British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Fluoride in groundwater from high-fluoride areas of Ghana and Tanzania

Groundwater Systems & Water Quality Programme

Commissioned Report CR/02/316

'Minimising fluoride in drinking water in problem aquifers' (R8033) Phase I Final Report

BRITISH GEOLOGICAL SURVEY

COMMISSIONED REPORT CR/02/316

Fluoride in groundwater from high-fluoride areas of Ghana and Tanzania

'Minimising fluoride in drinking water in problem aquifers' R8033. Phase I Final Report.

P L Smedley, H Nkotagu, K Pelig-Ba, A M MacDonald, R Tyler-Whittle, E J Whitehead and D G Kinniburgh

Key words

Fluoride, groundwater, aquifer, health, fluorosis, water quality

Front cover

A young girl from central Tanzania (R. Tyler-Whittle, BGS).

Bibliographical reference

P L SMEDLEY, H NKOTAGU, K PELIG-BA, A M MACDONALD, R TYLER-WHITTLE, E J WHITEHEAD AND D G KINNIBURGH. 2002. Fluoride in groundwater from high-fluoride areas of Ghana and Tanzania.

British Geological Survey Commissioned Report, CR/02/316. 72 pp.

Keyworth, Nottingham British Geological Survey 2002

BRITISH GEOLOGICAL SURVEY

The full range of Survey publications is available from the BGS Sales Desks at Nottingham and Edinburgh; see contact details below or shop online at www.thebgs.co.uk

The London Information Office maintains a reference collection of BGS publications including maps for consultation.

The Survey publishes an annual catalogue of its maps and other publications; this catalogue is available from any of the BGS Sales Desks.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as its basic research projects. It also undertakes programmes of British technical aid in geology in developing countries as arranged by the Department for International Development and other agencies.

The British Geological Survey is a component body of the Natural Environment Research Council.

Keyworth, Nottingham NG12 5GG

☎ 0115-936 3241 Fax 0115-936 3488
e-mail: sales@bgs.ac.uk
www.bgs.ac.uk
Shop online at: www.thebgs.co.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA

☎ 0131-667 1000 Fax 0131-668 2683
e-mail: scotsales@bgs.ac.uk

London Information Office at the Natural History Museum (Earth Galleries), Exhibition Road, South Kensington, London SW7 2DE

☎ 020-7589 4090 Fax 020-7584 8270
☎ 020-7942 5344/45 email: bgslondon@bgs.ac.uk

Forde House, Park Five Business Centre, Harrier Way, Sowton, Exeter, Devon EX2 7HU

☎ 01392-445271 Fax 01392-445371

Geological Survey of Northern Ireland, 20 College Gardens, Belfast BT9 6BS

☎ 028-9066 6595 Fax 028-9066 2835

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB

☎ 01491-838800 Fax 01491-692345

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU

☎ 01793-411500 Fax 01793-411501
www.nerc.ac.uk

Foreword

This report is the product of a study by the British Geological Survey (BGS) as a part of the UK DFID-funded project 'Fluoride in groundwater from high-fluoride areas of Ghana and Tanzania', project code R8033. The report contains the results obtained for Phase I of the project and describes the work carried out during the interval August 2001 to December 2002. The report findings form the basis for the initiation of Phase II which is anticipated to be carried out during January 2003 to May 2004. The findings are therefore of an interim nature.

Acknowledgements

We would like to acknowledge the considerable help given by WaterAid staff in Accra, Ghana, notably by Gordon Mumbo and in Tabora, Tanzania, especially by Herbert Kashililah. Without this, the fieldwork and data collection in each country would not have been possible. We also acknowledge Kezia Mbwambo and Radhia Ideva for assistance with the fieldwork in Tanzania and Atenyose Ignatius Azoms (Ghana Water Co. Ltd) for assistance with fieldwork in Ghana. Chemical analysis of water samples in the BGS laboratories was carried out by Debbie Allen, George Darling, Sarah Hannay, Daniel Lapworth, Daren Gooddy and Janice Trafford. Help with the production of GIS maps has also been provided by Jenny Cunningham and Rose Hargreaves.

Contents

Foreword i

Acknowledgements i

Contents ii

Executive summary 1

1 Introduction 2
- 1.1 Water quantity and quality issues 2
- 1.2 Fluoride and its impact on health 2
- 1.3 Fluoride standards and guidelines for drinking water 3

2 Objectives of the project 4

3 Previous studies on fluoride in groundwater 6
- 3.1 Focus of research 6
- 3.2 Research findings 6

4 WaterAid activities and collaboration 7

5 Study areas 8
- 5.1 Northern Ghana 8
- 5.2 Central Tanzania 12

6 Results 17
- 6.1 Ghana 17
- 6.2 Tanzania 24
- 6.3 General conclusions from Ghana and Tanzania 34

7 Institutional and social factors 35
- 7.1 Fluoride and water supply 35
- 7.2 The impact of fluorosis on communities 36

8 In-project training 37

9 Conclusions and implications 37
- 9.1 Water quantity versus water quality 37
- 9.2 Role of geology 38
- 9.3 Preliminary guidelines 38
- 9.4 Decision point on Phase II 39
- 9.5 Principal objectives and activities of Phase II 40

10 Reports and articles produced from the project 42

11 References 42

Appendix 1 MSc student thesis plan ... 45

1 Introduction ... 46
1.1 General introduction ... 46
1.2 Study area ... 46

2 Statement of the research problem ... 47

3 Objectives ... 47

4 Significance of the study ... 48

5 Literature review ... 48
5.1 Fluoride in groundwater ... 48
5.2 Fluoride occurrence and geochemistry ... 49

6 Hydrogeochemistry of fluoride and stable isotopes ... 50

7 Materials and methods ... 51
7.1 Existing data compilation ... 51
7.2 Field work ... 51

8 Data analysis and presentation ... 51

9 Other relevant information ... 52
9.1 Sponsorship ... 52
9.2 MSc timetable ... 52

Appendix 2 Water-quality data for samples from Bolgatanga area, northern Ghana ... 53

Appendix 3 Water-quality data for samples from north-central Tanzania ... 61

FIGURES

Figure 1 A view of one of the boreholes in the Tongo Granite area near Bolgatanga, northern Ghana 8

Figure 2 A typical borehole in the Bolgatanga area fitted with an Afridev handpump........... 10

Figure 3 The location of the study area in Tanzania. The simplified geological map is from MacDonald and Davies (2001) and the rainfall information from New and Hulme (1997). . 13

Figure 4 A queue at one of the widely-spaced boreholes in central Tanzania. 14

Figure 5 Dug pit in central Tanzania. During the dry season, many of the shallow boreholes in the region dry up and local people have to resort to muddy water from such sources. 15

Figure 6 Comparisons of fluoride analyses measured by automated colorimetry (AC), ion chromatography (IC) and ion selective electrode (ISE) in the field.................................... 16

Figure 7 Map showing the distribution of fluoride in the northern Ghana study area 19

Figure 8 Box and whiskers plot showing the variation in fluoride concentration in water from various sources in the study area in northern Ghana. 19

Figure 9 Fluoride concentration in water versus the depth of the middle of the screened interval of boreholes (where known) or dug well depth.. 20

Figure 10 Scatter plots showing the variation of fluoride concentration in Ghanaian water samples with other water quality parameters. 21

Figure 11 Map showing the distribution of sodium in the northern Ghana study area 21

Figure 12 Map showing the distribution of alkalinity (bicarbonate) in the northern Ghana study area.. 22

Figure 13 Map showing the distribution of calcium in the northern Ghana study area 22

Figure 14 Map showing the distribution of fluoride in the Igunga-Iramba-Singida study area of north-central Tanzania. 26

Figure 15 Box and whiskers plot showing the variation in fluoride concentration in water from various sources from the study area.. 27

Figure 16 Scatter plots showing the variation of fluoride concentration in Tanzanian water samples with other water quality parameters. In the case of the Ca vs F plot, the samples in which the fluoride saturation index has been exceeded (SI>0) have been distinguished from those where it has not (SI<0)... 28

Figure 17 Electron microprobe element maps for fluorine and phosphorus for a granite from central Tanzania (sample TZ4). The close association between fluorine and phosphorus indicates that the fluorine is present in the mineral fluorapatite. The scale at the bottom left-hand corner is 500 µm. 29

Figure 18 Map showing the distribution of sodium in the Igunga-Iramba-Singida study area of north-central Tanzania.. 30

Figure 19 Map showing the distribution of alkalinity (bicarbonate) in the Igunga-Iramba-Singida study area of north-central Tanzania. 30

Figure 20 Map showing the distribution of calcium in the Igunga-Iramba-Singida study area of north-central Tanzania. 31

Figure 21 Variation of dissolved oxygen concentration with the percentage of modern recharge estimated by the CFC-11 content of the water. 31

Figure 22 Map showing the distribution of uranium in the Igunga-Iramba-Singida study area of north-central Tanzania. 33

Figure 23 The saturation index of the mineral fluorite plotted against the fluoride concentration in waters from Ghana and Tanzania. 34

TABLES

Table 1 Various international guidelines and national standards for fluoride in drinking water 4

Table 2 'Logical framework' for the DFID KaR project. 5

Table 3 Percentage of wells that fall within a given fluoride concentration class (mg L^{-1}) as a function of water source. 18

Table 4 Variation of fluoride concentration with surface geology in the Ghana project area... 18

Table 5 Percentage of exceedances of WHO guideline values found in the Ghanaian water samples listed in decreasing order of frequency of exceedances 23

Table 6 Fluoride concentrations in various waters from Tanzanian regions arranged in terms of decreasing median fluoride concentration (from Bardecki, 1974). 24

Table 7 Variation of fluoride concentration (mg L^{-1}) with surface geology in Tanzania 25

Table 8 Percentage of wells that fall within a given fluoride concentration class (mg L^{-1}) as a function of water source. Sample set includes water analyses from the MSc study of Iramba District by R. Ideva.. 26

Table 9 Percentage of exceedances of WHO guideline values found in the Tanzanian water samples listed in decreasing order of frequency of exceedances 32

Executive summary

Naturally high concentrations of fluoride are found in groundwater from many parts of the world, including Africa, and can have an important impact on human health. Chronic ingestion of high concentrations gives rise to dental fluorosis and in extreme cases, skeletal fluorosis. While not life-threatening, these can impair quality of life and affect livelihoods, particularly in rural areas. They also pose a considerable constraint on groundwater development. As donors become increasingly concerned over groundwater-quality issues, groundwater-development projects may be halted through concerns over excessive fluoride concentrations. Fluoride problems tend to be more prevalent in the more arid parts of the world, where water is already a scarce resource.

Groundwater fluoride concentrations have been investigated in two study areas in Africa: the Bolgatanga area of northern Ghana (Upper East Region) and the Tabora-Singida areas of central Tanzania. Both study areas have notable groundwater fluoride problems, with Tanzania being particularly badly affected. Fluoride concentrations were found to exceed 20 mg L^{-1} in central Tanzania and 4 mg L^{-1} in northern Ghana. Both these extremes are in excess of the WHO guideline value for fluoride in drinking water of 1.5 mg L^{-1}. In Ghana, 23% of samples analysed exceeded the WHO guideline value, while in Tanzania 57% were in excess. Dental fluorosis is common in both areas, particularly in children, and is clearly related to the water supply.

A geological control on fluoride concentrations in groundwater is clear in both study areas. High-fluoride groundwaters in northern Ghana are found in areas of granite. In central Tanzania, fluoride concentrations are also high in granitic rocks, although some relationship with local NE-SW-trending faults is also apparent. Whether this influences the fluoride concentrations in the Tanzania study area significantly is currently unclear. The influence of geothermal fluids from the East African Rift Valley, concentrated along fault lines, may be a factor in producing the high fluoride concentrations, although fluoride build-up through rock weathering is also a likely control. Further data interpretation, water sampling and mineralogical investigation are required to resolve the relative influence of such sources. Preliminary results suggest that the minerals apatite, biotite and fluorite are the most likely mineral sources for fluoride. There is little evidence in most of the waters for control of dissolved fluoride concentrations by dissolved calcium (as would be expected if fluorite were present).

The variation of fluoride concentration with depth is uncertain and requires detailed studies at particular sites. In Tanzania, some of the shallow water sources, including surface water, had high concentrations of fluoride. A generally increasing trend with depth might normally be expected if fluoride is derived from a geological source by time-dependent weathering. This depth versus concentration relationship, which has clear practical implications in terms of well construction, will be determined as part of Phase II of the project. The investigation will involve construction of observation boreholes (piezometers) at various depths and testing for fluoride and a range of other water-quality parameters. Where possible, the depth-fluoride relationship observed during the recent construction of a set of boreholes in the Singida area of Tanzania by WaterAid will also be investigated. In view of the larger regional extent of identified high-fluoride groundwaters in Tanzania, its more severe manifestation and the less clear-cut relationship with geology, the bulk of future work on the project will be concentrated in Tanzania.

1 Introduction

1.1 WATER QUANTITY AND QUALITY ISSUES

The supply of water in adequate quantity and of acceptable quality remains a major issue in arid areas of the developing world. Increasing demand and greater variability in climate may be exacerbating the problems. Quantity problems are well demonstrated in many arid regions of Africa. Some dug wells in central Ghana have become dry in recent years even after considerable investment has been made in deepening the wells by blasting. In central Tanzania, dug wells and shallow boreholes regularly dry up in the dry season, forcing villagers to resort to using muddy water from dugouts in dry river channels. SEMA, a Danish-supported NGO operating in Tanzania, has abandoned developing new dug wells in central Tanzania because they tend to fail during a drought, the most critical time for water supply.

There is also evidence that climate change may be impacting on the situation. For example, much of Tanzania suffered a serious drought in 1997. This was followed by damaging floods in early 1998 which led to an increased incidence of cholera and other waterborne diseases. These extreme conditions are believed to be related to El Niño events originating far away. Such El Niño events are likely to continue to affect central Africa with varying severity into the foreseeable future.

Superimposed on these water-supply problems are problems related to water quality. Surface water sources tend to be contaminated with pathogenic bacteria and parasites. Groundwater generally contains much lower concentrations of these contaminants as a result of natural processes such as filtration. From this point of view, groundwater is a preferable source of drinking water and often constitutes a relatively reliable source during times of scarcity. However, groundwater can also suffer from significant water-quality problems, foremost of which in Africa is the problem of naturally high fluoride concentrations resulting principally from interaction with fluorine in minerals and rocks.

Donors, who have traditionally played an important role in increasing the access of rural communities to safe drinking water in Africa and elsewhere, are becoming increasingly concerned with the quality of the water delivered by their projects. In the past, water-quality testing was often left to the drilling contractor to undertake. Many potential problems such as excessive fluoride went largely undiagnosed. This is no longer the case. Natural water-quality problems are now perceived as a real constraint on rural water supply and donors are no longer willing to fund projects where the risk of failing to comply with national quality standards or international drinking-water guidelines is high. Clearly, complying with such standards has significant cost implications, especially since natural water-quality problems are hard to predict and may only be identified positively once drilling has been completed. In Africa, with its dominance of hard basement rocks, drilling is expensive and to abandon new wells on account of poor water quality is seen as unattractive. This puts an added importance on the ability to predict the risks, or at least forewarn of the likelihood of any such problems occurring, and of devising approaches which might minimise such risks. This project aims to address some of these issues.

1.2 FLUORIDE AND ITS IMPACT ON HEALTH

Fluoride is an essential element for human health. Although both deficiency and excess of fluoride in the human diet can have detrimental effects, it is the excesses that are now of most concern since fluoride deficiencies can be minimised by using fluoridated toothpastes (and water fluoridation in developed countries). Drinking water is an important component of the dietary fluoride intake and concentrations in drinking water of around 1 mg L^{-1} are often taken to be optimal. Chronic ingestion of water with concentrations above around 1.5 mg L^{-1}, the WHO guideline value for fluoride in drinking water, is considered to be detrimental to health and this is borne out by field observations. There is a remarkably small margin of safety in drinking-water fluoride concentrations.

The most common consequence of exposure to excess fluoride is dental fluorosis ('mottled enamel'), a condition involving interaction of fluoride with tooth enamel, and causing staining or blackening, weakening and possible loss of teeth. Although not life threatening, dental fluorosis can adversely affect the quality of life as poor dental health compromises integration into society and in some developing countries can affect a woman's ability to marry.

With more extreme exposure to fluoride, skeletal fluorosis can result. This is manifested in the early stages as osteosclerosis, involving hardening and calcifying of bones, and causes pain, stiffness and irregular bone growth. At its worst, the condition results in severe bone deformation and debilitation.

Long-term exposure to fluoride in drinking water at concentrations above around 1.5 mg L^{-1} can result in dental fluorosis. Values above around 4 mg L^{-1} have been found to result in skeletal fluorosis and above about 10 mg L^{-1} in crippling fluorosis (Dissanayake, 1991). However, in practice, the links between concentrations and observed disease vary regionally and are dependent on additional factors, particularly nutrition. Dietary deficiencies in calcium (e.g. dairy produce) and vitamin C are recognised as important exacerbating factors in the onset of fluorosis disease. Young children are particularly at risk from fluorosis as ingested fluoride affects the development of growing teeth and bones. Once developed, the symptoms of fluorosis are irreversible. Links have also been made between high fluoride and other health problems, including birth defects (Hamilton, 1992) and cancer (Marshall, 1990), although these are less clearly defined.

Estimates are not well-established, but more than 200 million people worldwide are thought to be drinking water with fluoride in excess of the WHO guideline value. Most are in developing countries. Groundwater is particularly vulnerable to fluoride contamination. In terms of the populations affected, fluoride is by far the most important and detrimental contaminant in groundwater and is recognised as a significant health issue by agencies involved in water supply. Of 30 countries identified with serious fluoride problems, around half are in Africa (Kloos and Haimanot, 1999).

1.3 FLUORIDE STANDARDS AND GUIDELINES FOR DRINKING WATER

There are no minimum standards or guidelines for fluoride in drinking water but most countries have a maximum recommended or allowable limit. These vary from 1.5 mg L^{-1} recommended by WHO and enforced by many countries, to 8 mg L^{-1} adopted by Tanzania (Table 1). This high value was adopted in 1974 and reflects a desire to reduce the limit in line with the WHO value, while indicating difficulties with compliance in a country with regionally high fluoride concentrations and problems with water scarcity. The limit remains in force today.

While the exact concentration of fluoride at which fluorosis symptoms appear is not known precisely and probably depends on other factors such as diet and age, our observations suggest that dental fluorosis in children is commonly observed where fluoride concentrations exceed around 3 mg L^{-1}. Therefore, complying with the WHO guideline value provides a small margin of safety while complying with the Tanzanian standard in an area of high fluoride waters could lead to considerable incidence of dental fluorosis and even skeletal fluorosis. In practice, while the Government of Tanzania upholds its temporary standard, donors involved in the water sector often prefer to adopt their own stricter national standard or that of WHO.

In Ghana, the WHO guideline value (1.5 mg L^{-1}) has been adopted as the national standard for drinking water.

Table 1 Various international guidelines and national standards for fluoride in drinking water

Organization or country (date)	Name	Fluoride concentration (mg L^{-1})
WHO (1993)	Guideline value	1.5
EU (1998)	Maximum permissible value	1.5
USA (1999)	Secondary (recommended) standard	2
USA (1999)	Maximum contaminant level (MCL)	4
Ghana	National standard	1.5
Tanzania (1974)	Temporary national standard	8

2 Objectives of the project

Although many investigations of groundwater quality have been reported from high-fluoride areas across the world, there have been few detailed accounts of the spatial variations in and controls on fluoride occurrence in aquifers. This project aims to address these uncertainties by assessing whether it is possible to predict the spatial variation in concentrations and make use of this to define basic guidelines for well siting and construction that can be of use to water providers and policy makers.

Two countries with recognised fluoride problems, Tanzania and Ghana, have been chosen as areas of investigation. Tanzania has a large area of crystalline basement rocks and also lies within the East African Rift Valley. The geology of Ghana is also dominated by hard crystalline basement rocks. Both have large areas with arid climatic conditions. High fluoride concentrations have been identified in groundwater sources from parts of both countries. Communities living in the Tabora and Singida regions of central Tanzania show abundant evidence of dental fluorosis. Residents of parts of the Upper East Region of Ghana also show evidence of dental fluorosis. There is currently no information available in either country to assess whether skeletal fluorosis is an additional problem in these areas.

This project aims to provide a detailed picture of the scale and impacts of fluoride occurrence in drinking-water supplies and the links between water use and health outcomes. This will be achieved in particular through groundwater-quality surveys in selected study areas, analysis of a range of rock and mineral samples and installation and testing of piezometers drilled to predefined depths. Results produced will be used where possible to provide rule-of-thumb guidelines for the optimal siting and construction of water wells in order to minimise the risk of drawing water with unacceptably high fluoride concentrations. The project also aims to assess the institutional capability and willingness of regional water providers to implement guidelines produced and maximise take-up. The project is being carried out in collaboration with University researchers (Department of Geology, University of Dar Es Salaam, Tanzania and University for Development Studies, Tamale, Ghana) as well as WaterAid in both countries. WaterAid and its local NGO partners have significant rural water-supply interests in both study areas.

The project has been divided into two parts: an initial phase, Phase I (August 2001 to December 2002), involved initiating collaborative links with local partners, setting up field study sites, taking reconnaissance groundwater and geological samples and discussing water-quality issues with regional water providers and policy makers. Phase II (intended timetable January 2003 to May 2004) will involve consolidation of research findings, field testing of preliminary conclusions and guidelines produced in Phase I, installation and testing of piezometers in study areas and compilation and dissemination of results, including end-of-project workshops in each country. This report outlines the work carried out to date during Phase I of the project and describes the interim results produced.

The objectives of the project as laid out in the original 'logical framework' are given in Table 2.

Table 2 'Logical framework' for the DFID KaR project.

Narrative summary	Measurable indicators	Means of verification	Important assumptions
Goal: W3: Combating degradation of water resources	Significant decrease in the incidence of dental fluorosis in children, over 10 years or so.	National health statistics (Tanzania, Ghana)	
Purpose: Improve approaches for the siting and construction of wells for provision of sustainable supplies of low-fluoride drinking water.	Guidelines incorporated into strategy documents of water providers.	Inspection of water-supply strategy documents (national, and relevant NGOs, multilateral agencies).	Fluoride problems are recognised as a national priority. Guidelines produced are followed and prove effective in reducing prevalence of disease.
Outputs: 1. Improved generic understanding of fluoride distribution and controls in high-fluoride aquifers. 2. Decision point on implementation of Phase II. 3. Guidelines provided for identified users on borehole siting and completion in fluoride-prone areas. 4. Trained student and partners. 5. Informed NGOs and other water providers.	1. Review published in the international literature, submitted by month 12. 2. Interim report produced by end of Phase I. 3. Manual of guidelines and publicity leaflet produced by end of project. 4. MSc awarded and outputs co-authored by local partners, both by end of project. 5.1 Hydrochemical databases for Tanzania, Ghana by month 26. 5.2 Seminars held at project start (Tanzania, Ghana), workshops at project end, website active; reports, publicity leaflets, publications produced by project end.	1. Review copied to DFID, accessible in open literature, by month 24. 2. Report sent to DFID by month 14 and DFID response given. 3. Manual and publicity leaflet, copies of databases sent to DFID by end of project. 4. University records; partner questionnaire after project completion. 5. Workshop timetables and reports; website inspection.	(Output to purpose) Water providers are willing to adopt the guidelines. Guidelines developed are of generic application. Issues of water quality in arid areas are not outweighed by issues of quantity and hence ignored.
Activities: **Phase I:** 1. Collate existing data/ information on fluoride in groundwater worldwide. 2.1 Carry out inception visits to Tanzania and Ghana. 2.2 Complete inception report. 2.3 Survey water quality in parts of each country	1. Database of reference documents produced by end of Phase I; updated throughout project lifetime. 2.1 Detailed project work plans, including selected field areas, work schedules by month 7. 2.2 Inception report provided by month 7. 2.3 Preliminary hydrochemical databases for each study area	1. Bibliographic database available to DFID on request. 2. Travel and subsistence invoices; back-to-office notes, DFID inception and progress report(s)	(Activity to output) Existing external reports and publications are of sufficient quality and detail to be useful. Local drilling contractors are available and reliable. NGOs etc are willing to attend seminars,

Narrative summary	Measurable indicators	Means of verification	Important assumptions
(sampling and analysis). **Phase II:** 3.1 Install piezometers to discrete depths and test water levels and quality. 3.2 Field test guidelines in selected areas. 3.3 Analyse samples and database results. 3.4 Assess user needs and institutional capabilities. 4. Supervise MSc student (Tanzania) and train partners. 5. Prepare and disseminate results.	available by end of Phase I. 3.1-3.3 Hydrochemical databases produced by end of project. 3.4 User needs assessments incorporated into progress report by month 21. 4. University progress reports/assessments. 5. DFID progress reports, website active by month 9, DFID Summary Report available by end of project.	3.1 Drilling contract 3.2 Travel and subsistence invoices 3.3 Inspection of databases 3.4. DFID progress report and subsequent reports. 4. Student/university questionnaire. 5. Reports, invoices from seminars, workshops. DFID Summary Report. BGS Financial records submitted to DFID.	workshops. Travel to, and work in, the countries under investigation is not restricted by external factors (e.g. air travel restrictions, terrorist threats).

3 Previous studies on fluoride in groundwater

3.1 FOCUS OF RESEARCH

There have been many investigations of high fluoride concentrations in groundwater in many areas of the world and a large body of information exists on fluoride problems and fluorosis occurrence. Many of the published studies relate to epidemiology or are simple accounts of the ranges of fluoride found in various water bodies. Rather less information is available on the hydrogeochemical controls on fluoride distribution. Few studies have carried out assessments of groundwater quality in relation to geology, well depth, or well construction for example.

Many of the problems with high fluoride concentrations in groundwater are found in Africa. In Ghana, relatively few occurrences of high-fluoride groundwater have been reported despite the fact that much of northern Ghana is semi-arid with basement rocks of granitic or gneissose composition. From discussions with government departments, it is not clear whether this reflects a problem which is only of local extent or results from a lack of systematic testing for fluoride on a national basis. Certainly, gaining access to national water-quality data during discussions with government departments and NGOs proved very difficult. In Tanzania, a widespread problem of high-fluoride water occurs, although most scientific research on the problem has so far focused on the Arusha area within the Rift Valley and again there are few systematic data to assess the scale and spatial distribution of the problem.

3.2 RESEARCH FINDINGS

High-fluoride groundwater provinces have been recognised in many parts of the world, particularly northern China, India, Sri Lanka, Mexico, western USA and Argentina as well as many countries in Africa. Many of these affected regions have been described in the Inception Report produced earlier in this project (Smedley, 2002). Fluoride removal by water treatment is carried out in some countries. However, as many of the high-groundwater provinces occur in developing countries, fluoride removal practices vary widely and many high-fluoride water sources are used without treatment. As a result, large populations throughout parts of the developing world suffer the effects of chronic endemic fluorosis. This includes around

70 million people in India, 45 millions in China (Wuyi et al., 2002) and some 5 millions in Mexico (Diaz-Barriga et al., 1997). The population at risk in Africa is unknown but is also likely to be tens of millions.

The two chosen study areas are in Ghana and Tanzania. In each country, groundwater is the most widely used and appropriate source of drinking water for rural communities, particularly in the arid areas. Increased groundwater development has been seen as a significant contributor to the greater provision of a bacterially safe and secure water supply in both countries, although fluoride is an unwelcome problem.

A BGS study of iodine deficiency in the Bolgatanga area of northern Ghana in the mid 1990s (Smedley et al., 1995) identified by chance high-fluoride waters in parts of the area. However, the source of the fluoride was not clear and the extent of the area affected remained uncertain. Therefore, an extended part of this region was included in the present project. North central Tanzania was also chosen for study because although parts of the country, especially the Arusha and Kilimanjaro areas in the north, were well known to have high-fluoride waters, other areas have been much less studied and in the country as a whole, there had been few detailed geological investigations of the factors controlling fluoride concentrations. The fluoride problem in central Tanzania is potentially extensive and therefore merits study.

4 WaterAid activities and collaboration

WaterAid are active in both Ghana and Tanzania, and work through local NGOs to implement rural water supply and sanitation programmes. WaterAid’s funding in Ghana has in the past come in part through the British High Commission but this funding has recently been stopped and the overall WaterAid country budget for Ghana has been reduced. Nevertheless, WaterAid remain very active in Ghana. They have helped supply around 2600 wells. Projects include construction of hand-dug wells, handpump maintenance programmes, promotion of latrines and training of village health co-ordinators. These are carried out through various local partners. In return, WaterAid offers its partners financial support, training and technical advice as well as assistance with planning, budgeting and institutional development. WaterAid helps its partners to develop and grow into independent organisations which then contribute to the wider water and sanitation debates. Visits were made during the project to WaterAid in Accra (representative Mr Gordon Mumbo) and WaterAid’s NGO partners in both Tamale (New Energy) and Bolgatanga (Rural Aid).

WaterAid representatives were also met in Tanzania (Mr Herbert Kashilila and Mr David Mather). WaterAid partners in Tanzania include the Anglican Church of Tabora. Mr Kashilila arranged a meeting in Tabora between the project team and five local stakeholders in the water and sanitation field in which the aims of the project and the local water-supply situation were discussed. WaterAid have recently begun a major DFID-funded project to drill boreholes in the Singida peri-urban area. BGS provided some technical advice and help on the measurement of fluoride in the field so that WaterAid would be able to keep a ‘real-time’ assessment of water quality during the drilling of a new borehole. If unacceptably high concentrations of fluoride persisted, then drilling would be halted and the borehole abandoned, thus saving valuable time and resources. As a result of our visit to WaterAid in Singida, Mrs K Mbwambo (Tanzanian Bureau of Standards) has agreed to provide WaterAid with further training in the measurement of fluoride. BGS has also agreed to provide a comprehensive water-quality analysis of all completed WaterAid wells as part of the current DFID project.

WaterAid provided valuable logistical help for the field work in both Ghana (Mr Gordon Mumbo) and Tanzania (Mr Herbert Kashilila).

The experience gained during this phase of the project has been valuable in helping us to gain a broader view of natural groundwater-quality problems in Africa and elsewhere. This has proved useful during the preparation of Groundwater Quality and country-specific briefing sheets for WaterAid (www.wateraid.org.uk/site/in_depth/research_centre/groundwater/) including a fact-sheet about fluoride in groundwater and country sheets for Ghana and Tanzania.

5 Study areas

5.1 NORTHERN GHANA

5.1.1 Regional setting

The Upper East Region lies in the north-eastern part of Ghana, adjacent to the Burkina Faso border in the north and the Togo border in the east. The main town is Bolgatanga, although the communities in the study area are largely rural. The region has a semi-arid climate, with average annual rainfall of around 1000 mm and a single rainy season from May to October, most of the rain falling between July and September. There is a pronounced dry season during the rest of the year. Maximum temperatures range between 20 and 40ºC (Murray, 1960). It is therefore hot and dusty for much of the year (Figure 1).

The area investigated is bordered to the north-east by the Red Volta River 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. Drainage of minor rivers is towards the south and south-west, largely controlled by the geological strike. The Red Volta and most of the minor streams frequently dry up during the dry season (Murray, 1960).

Figure 1 A view of one of the boreholes in the Tongo Granite area near Bolgatanga, northern Ghana.

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

5.1.2 Geology and geomorphology

The geology of the region is dominated by crystalline basement rocks. Upper Birimian (Precambrian) strata are divided into metavolcanic rocks (greenstone, lava, amphibolite, tuff) and metasedimentary rocks (sheared conglomerate, greywacke, quartzite, grit, arkose, phyllite and schist), as well as meta-igneous lithologies (hornblende- and biotite-granodiorite, tonalite, adamellite, biotite-gneiss and migmatite). The Birimian rocks form a folded, steeply-dipping, complex group of formations, metamorphosed to greenschist grade. These have not been dated clearly.

Post-Birimian magmatic activity produced a suite of coarse-grained granites, the Bongo Granite suite, and associated minor intrusions (now largely amphibolite as well as porphyry). The precise age of these intrusions is unknown. 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, sodic plagioclase 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 (Murray, 1960). The central portion of the outcrop comprises coarse biotite-granite and in general, 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 in 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).

The Sekoti Granodiorite in the east forms rounded tors resembling those of the Bongo Granite. Coe (1953) grouped the intrusion with the Bongo suite, although Murray (1960) 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 Sekoti Granodiorite comprises mainly plagioclase and quartz with biotite as the dominant mafic mineral, often replacing 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. 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 gold-bearing, 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 in the recent past. Sulphide minerals are widely dispersed, principally comprising pyrite and chalcopyrite (minor arsenopyrite) associated with the gold-bearing 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 erosion caused by 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 agricultural quality but since many are on hill slopes, 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 potassium content of the bedrock (Murray, 1960). Soils are lateritic in places.

Figure 2 A typical borehole in the Bolgatanga area fitted with an Afridev handpump.

5.1.3 Hydrogeology and water supply

Groundwater development began in Ghana during the 1940s with the installation of dug wells. These have frequently been superseded by boreholes which have been installed over large parts of the country, mainly since the 1970s. Various water supply projects have led to groundwater development in Ghana. Drilling has been achieved through the 3000 Tubewell Project carried out in southern Ghana, and the CIDA (Canadian)-funded programme which installed some 2700 boreholes in the north of the country (1974–1981). Many of the boreholes sampled in this project were CIDA boreholes constructed at this time.

Numerous other boreholes have also been installed by NGOs and today, there are an estimated 20,000 boreholes across the country. Boreholes are equipped mostly with India Mark II or III handpumps, with some using Afridev or Nira pumps. There has also been a WaterAid initiative to cover dug wells and install handpumps in order to minimise contamination from surface pollutants. Newly installed dug wells funded by CIDA are also now sealed and equipped with handpumps. A number of wells drilled in the mid 1990s were capped because fluoride concentrations exceeded 1.5 mg l^{-1}.

The Vea reservoir north of Bolgatanga provides water supply after treatment for the residents of the Bolgatanga urban area, but for the majority of residents, water is supplied at family or community level. Most obtain water from individual wells and boreholes, the latter mostly equipped with handpumps (Figure 2).

High evapotranspiration rates mean that groundwater recharge in the area is limited. Average recharge is estimated at about 4% of annual rainfall, or about 40 mm a^{-1} (Apambire et al., 1997). Recharge is thought to be greatest in the north and the regional pattern of groundwater flow is southwards (Apambire, 1996), although detailed information about groundwater flow and local variations is not available. Likewise, few data are available for current borehole pumping rates. Water levels generally vary between 1–20 m below ground level and measurements from a limited number of dug wells in this study were typically around 2–7 m below surface.

Groundwater flow and storage in the crystalline aquifers of the Bolgatanga area take place principally in fractures in the bedrock and in the upper weathered zone ('regolith'). The basement rocks have little or no primary porosity or permeability. Boreholes abstracting from the fractured basement usually rely on storage in the overlying or adjacent weathered zone for a sustainable yield. Approximately 95% of wells in the Upper East Region are completed within the weathered material. The thickness of this weathered zone depends upon lithology, being greatest in fractured horizons and close to quartz veins and pegmatites (Apambire, 1996). The weathered zone is around 3–40 m thick, with the highest average thicknesses occurring in the Birimian metasediments (average 27 m, Apambire, 1996). The regolith is typically clay-rich and has variable permeability, in some places forming lateral boundaries to groundwater flow. Aquifers in the weathered zone therefore tend to be irregular in configuration and of limited extent.

Groundwater yields are typically low from the basement rocks, and a large proportion of wells fail to yield a usable supply. Borehole success rates in the Upper East (yields of 0.1 L s^{-1} or greater) vary between around 50% and 95%. Greatest success rates are generally found in weathered granite and poorest in schist and granite gneiss (Horatio-Larbie, 2000). Hence, although groundwater is the main source of water in the study area as a whole, available resources are limited.

5.1.4 Sampling and analysis

Groundwater sampling in the Bolgatanga-Bongo area was carried out during February 2002. Data have also been included from a sampling campaign carried out during an earlier DFID-funded project in the region (Smedley et al., 1995). A key objective of the 2002 campaign was to obtain samples from the area surrounding that covered by the earlier BGS study, where fluoride concentrations in groundwater were observed to be high. Emphasis was placed on sampling areas of granitic rock which were suspected to have the worst fluoride problems. Hence, samples were collected in particular from the Bongo and Tongo Granites and the Sekoti Granodiorite.

Samples were taken from dug wells and from deeper boreholes, so that we could examine the relationship between well depth and fluoride concentration. Where possible samples were taken from dug wells and boreholes in close proximity for comparison. Sampling in some areas was restricted due to accessibility problems or lack of wells in sparsely populated areas. Few wells exist in parts of the Sekoti Granodiorite and also in the west of the study area. However, wells were present in sufficient numbers in most of the areas sampled. The Vea reservoir, which serves as the main water supply for Bolgatanga town and local irrigation projects, was sampled for comparison with groundwater.

Some measurements of well parameters were carried out in the field. These included groundwater pH, dissolved oxygen, specific electrical conductance (SEC), alkalinity and temperature. Where possible, pH and dissolved oxygen were measured by pumping groundwater through a flow-through cell in order to prevent aeration. Alkalinity was determined by titration and is quoted as HCO_3. Where possible (in practice, only at dug wells) the well depth and the water level were measured. Water samples were also taken at each site for subsequent laboratory analysis in Tamale and the UK. A number of rock samples were also taken at some sites. Analysis of water samples for fluoride was carried out in batches during the course of the fieldwork.

At each sampling site, three aliquots were taken of 0.2 μm-filtered water in polyethylene bottles. One was acidified to 1% (v/v) with pure HNO_3 for the analysis of major elements (including total sulphur as SO_4) and a number of trace elements. A second was acidified with 2% pure HCl for the analysis of total arsenic (As) and a third was left unacidified for the analysis of nitrogen species, Cl, Br, F and I. Additional filtered samples were taken for F analysis by ion-selective electrode at the University for Development Studies in Tamale. The analysis of a range of trace elements besides F was carried out in order to investigate other potential water-quality problems and to provide a broader assessment of the hydrogeochemical processes active in the aquifers.

Additional notes at sampling sites were made of the condition of the well and its surroundings. In most cases, the wellheads were in good condition and equipped with a concrete apron. At the sampling sites, observations were also made of the dental health of the local residents.

A listing of the samples collected and summary chemical data are given in Appendix 2. This includes those samples collected during our earlier study of the area.

5.2 CENTRAL TANZANIA

5.2.1 Regional setting

Project investigations have been centred on the Singida and Tabora regions (Iramba, Singida Urban, Singida Rural and Igunga districts) of central Tanzania. The region is hot and arid with an average annual rainfall of between 600 and 800 mm (Figure 3), falling mainly in November to April. Rainfall records show virtually no rainfall between June and September (although several hours of heavy rainfall occurred in Singida during sampling for the project). The area is high plateau of around 1500 m altitude and average monthly temperatures lie in the range 20–26ºC.

5.2.2 Geology and geomorphology

Much of Tanzania is underlain by Precambrian basement rocks, mainly of granite, gabbro and metasediments (Figure 3). Sedimentary basins to the south of the country are mainly of Karroo age. Volcanic rocks of the region are associated with the East African Rift Valley which splits in Tanzania, the western limb passing through Lake Tanganyika and the eastern limb running via Arusha and Moshi to Morogoro. Young, mainly unconsolidated alluvial and lacustrine sediments are also present as a surface cover in many parts of the country. These are typically formed of weathered granitic and metasedimentary rocks from the basement and often infill depressions and grabens associated with the rifting.

The study area (Figure 3) can be split into two main geomorphological units. A high plateau in the south-east (approximately 1500 m) is underlain by granitic and metasedimentary basement rocks. These often occur at shallow depths below the surface and many outcrops of weathered granite are evident as tors across the region. The plateau also has rolling countryside where the granite is highly weathered. The soil is generally sandy, although ferricrete is occasionally present on hill sides with heavy mbuga clay (black vertisol soils) in valleys.

The north-west comprises a flat plain formed by surface alluvial and lacustrine deposits, with some metasedimentary basement rocks. The plain forms the old surface of the proto Lake Eyasi and possibly proto Lake Victoria. Alluvial fan deposits occur at the edge of the plain. Much of the surface of the plain is covered with mbuga clay which is typically several metres thick. Rivers dissect the plains and the incised valleys are filled with alluvium.

The lithologies can be classified as follows:

Archean Granite Shield: much of the study area is underlain by granite with variable grainsize and composition. Pegmatite is found in some areas. The granite has also been intruded by many dykes and sills of doleritic composition, dating from both the Palaeozoic and Proterozoic. Younger (Cenozoic) intrusions may also be present in the area, though reliable dating has not been carried out.

Archaean Greenstone Belt: the Greenstone Belt within the study area comprises a complex mixture of metasediments and acidic and basic volcanic rocks. The rocks are undergoing exploration for gold and some areas have small-scale mining activities. The metasediments comprise metamorphosed shale, greywacke, quartzite and schist. One quartzite unit is easily distinguishable and is named the ‘Banded Ironstone Formation’ due to its characteristic iron cementation. Acidic volcanic rocks (e.g. rhyolite, dacite) and associated tuffs are present along with basic volcanic rocks and tuffs. Some of the basic rocks have been altered to form greenschists which give the formation its name.

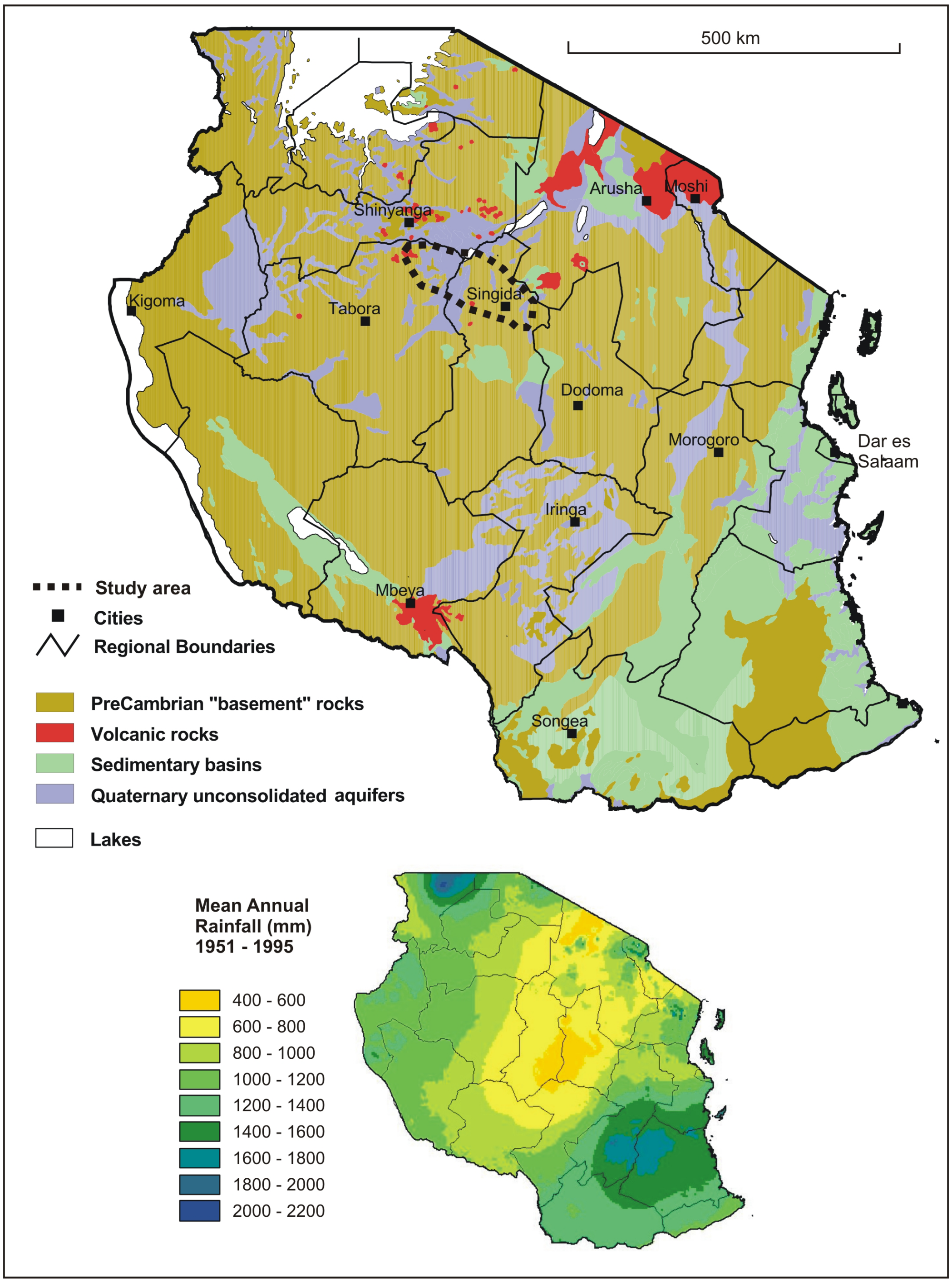

Figure 3 The location of the study area in Tanzania. The simplified geological map is from MacDonald and Davies (2001) and the rainfall information from New and Hulme (1997).

Cenozoic lacustrine deposits: the lake deposits of the former Lake Eyasi comprise consolidated and unconsolidated sand, gravel, clay, limestone and tuff. Some evaporite deposits are also thought to be present

Holocene alluvial fans and lake deposits: alluvial fans around the eastern escarpment of the plain form shallow slopes and comprise poorly-sorted and cross-bedded alluvium. No detailed profiles are available for the sequence, but the sediments are likely to be up to 50 m thick. Mbuga clay can be present at depth. Mapped as the same formation are the lake deposits of the forerunner of

Lake Victoria. These are present in the Igunga area and comprise cemented limestone, sandstone and conglomerate.

5.2.3 Hydrogeology and water supply

In the rocks of the Archaean Granite Shield, groundwater occurs in both the fractured and weathered zones of the granite. Drilling records indicate that groundwater is often found at the base of the weathered zone, typically 20–40 m below ground surface. Drilling success rates are of the order of 50–70% (with 5 or 6 boreholes being drilled for 3 completed boreholes). Yields tend to be sufficient for hand pumps (generally less than 30 $m^3 day^{-1}$), and occasionally for higher-yielding motorised pumps. Shallow boreholes and wells that only penetrate 10 m of the weathered zone can decline in yield significantly towards the middle of the dry season. Boreholes tend to be few and far between (Figure 4) and queues are common. A significant number of borehole pumps are not working, mainly through lack of maintenance. Little information is currently available concerning groundwater pumping rates.

In the Archaean Greenstone Belt, lithology and fracturing control the occurrence of groundwater. However, due to the complexity of the geology and the lack of data, it is difficult to make robust generalisations about groundwater availability. Weathered and fractured siltstone and quartzite are likely to have the highest potential for groundwater development; fractured lavas may also allow significant groundwater movement.

Cenozoic lacustrine sediments contain groundwater mostly within units of sand and gravel. Groundwater is generally exploited at shallow depths (1–5 m) and from dugouts in river beds. In some areas, these dugouts provide the main source of water during the dry season (Figure 5). Some deeper boreholes drilled into these deposits have produced saline water. The thick mbuga clay, present in much of these areas, has poor groundwater yields.

Where present in quantity, the Quaternary alluvial deposits form a good aquifer. Boreholes drilled at the foot of the escarpment have good sustainable yields and low-salinity water. However, in some of the smaller alluvial aquifers (e.g. to the south-east of Kiombio) the alluvium can be thin and patchy and groundwater availability is controlled by bedrock geology.

Figure 4 A queue at one of the widely-spaced boreholes in central Tanzania.

Figure 5 Dug pit in central Tanzania. During the dry season, many of the shallow boreholes in the region dry up and local people have to resort to muddy water from such sources.

Few data are available to characterise the hydrogeology of the lacustrine deposits of the proto Lake Victoria in this area. Conditions are likely to be similar to those of the proto Lake Eyasi.

5.2.4 Sampling and analysis

Groundwater sampling was carried out during two campaigns, the first in March 2002 and the second in August 2002. In total, 85 water samples were taken. A summary of the samples collected is given in Appendix 3. The sample sources included 50 boreholes, 24 large-diameter wells and dugouts, 6 dams and lakes (including 'charco dams'), 1 spring and 4 samples of rainfall. In each district, we were accompanied by an engineer from the local water department.

Efforts were made to take samples from different hydrogeological environments. A rough transect was followed moving north-west from the granite plateau across the metasediments and down onto the lacustrine plain. At seven of the sites, samples were taken from both shallow and deep sources (e.g. boreholes and shallow dugouts). A brief survey of the hydrogeological conditions was also taken at each site, including depth and nature of wells, approximate yields and local geology.

On-site water sampling was carried out as in Ghana, with dissolved oxygen and redox potential (Eh) being measured where possible using a flow-through cell. Water samples were collected for subsequent laboratory analysis at the University of Dar Es Salaam and at BGS Wallingford, UK. Samples for chlorofluorocarbon (CFC) analysis were also taken at 16 of the sites. CFC samples were only collected where an airtight connection to the wellhead could be achieved. Measurements were made of CFC-11 and CFC-12 and results are given as percent modern recharge based on CFC-11 at 25ºC and with individual pressure corrections according to sampling altitude.

Rock samples were collected from various sites during the sampling campaigns. In-situ samples were taken as close as possible to the sampled water source. A total of 35 rock samples were taken from 23 sites. Of these, 17 were granite, 4 were pegmatite, 6 metasediments, 4 dolerite samples, and 1 each of tuff, gabbro, ferricrete and lacustrine clay. These are currently being investigated petrographically and chemical analysis is also underway. Full results of the mineralogical and geochemical work carried out on these samples will be reported in Phase II of the project.

A more detailed investigation of fluoride was undertaken for the Tanzanian samples. Fluoride was measured by three commonly-used methods in order to compare the results and assess reliability. In most samples, fluoride was only measured by two of the three methods. The methods were ion-selective electrode (ISE), ion chromatography (IC) and automated colorimetry (AC). The first method was undertaken in the field and the last two in the BGS Wallingford laboratories. Comparison of fluoride methods is given in Figure 6. The results indicate good agreement between all three methods, with no systematic errors. Each of the methods is therefore considered to be reliable for fluoride analysis of water. Analyses discussed in this report were usually carried out by AC where available.

We also tested one of the simple fluoride field-test kits currently available (Machery-Nagel fluoride test papers). While this kit appeared to distinguish between very high and low fluoride concentrations, we do not recommend its use other than where no other options are available. The kits tend to be based on the bleaching of a test paper (zirconium dye lake method), with a visual assessment of the strength of this effect or its progression from a central point against a comparator. The difference between acceptable and unacceptable fluoride concentrations is quite narrow and so requires quite a precise and reliable measurement, especially when important decisions are to be based on the results. Also the kits tend to be date-stamped with a limited shelf-life which further reduces their usefulness. We saw a number of unused and out-of-date kits in Tanzania.

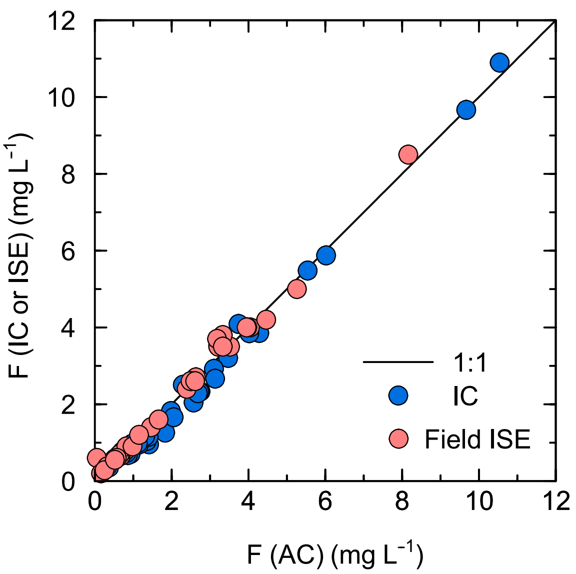

Figure 6 Comparisons of fluoride analyses measured by automated colorimetry (AC), ion chromatography (IC) and ion selective electrode (ISE) in the field.

The availability of a range of reliable analytical methods for fluoride is helpful for developing countries. The ISE method is a reliable and accessible method for laboratory and even field use providing that it is used by trained technicians. The other two laboratory methods require relatively expensive equipment. The fluoride electrode is a solid-state electrode and unlike a pH electrode, is quite robust. The weakest link is the accompanying reference electrode which may be glass. In better and more modern systems this electrode is combined with the fluoride electrode into a single 'combination' electrode. A high-precision ion meter is required to take the reading. These are available in both hand-held and laboratory benchtop versions. In order to avoid complications with complexation in solution and ion-activity corrections, a buffer needs to be added so that fluoride concentrations can be read directly from the calibration curve. TISAB (Total Ionic Strength Adjustment Buffer) is normally used for this. This solution can be easily prepared in most chemical laboratories or bought already prepared. With this system, it is possible for a fluoride measurement to be made in a couple of minutes.

Training in the use of the ISE should include a description of how to operate the equipment, how to prepare a calibration curve and how to check that everything is functioning properly. More advanced training would include some theory, including the difference between ion activities and concentrations and a more detailed explanation of the function of the TISAB buffer. A QA standard should be run regularly as a check on the proper functioning of the equipment. This could be a locally-prepared fluoride standard (to save money) but its value should be traceable back to a recognised reference standard.

6 Results

6.1 GHANA

6.1.1 Fluoride

The results from the present project have been combined with those of the earlier BGS study in the area (Smedley et al., 1995) to provide a more regional view of water quality.

Dental fluorosis was commonly seen amongst the children of the area although not all children showed evidence. A random survey of school children at Tarongo school showed that between 25 and 50% of them showed some signs of dental fluorosis. The nearby school well, a CIDA-installed borehole, contained 2.9 mg L^{-1} fluoride. It was difficult to determine whether the difference in the incidence of dental fluorosis amongst children in a particular area was due to the children using water with different fluoride concentrations or for some other reason.

The concentration of fluoride in the sampled waters ranged from 0.09 to 4.37 mg L^{-1} with a mean of 1.00 mg L^{-1}. Of the water samples collected, 23% exceeded the WHO guideline value of 1.5 mg L^{-1} and 16% exceeded 2 mg L^{-1} (Table 3). However, some 67% of samples were also less than 0.7 mg L^{-1} which indicates that in many areas, the water is, if anything, deficient in fluoride.

There is a strong geological control on the fluoride concentration (Figure 7). When all water sources (boreholes, dug wells) are considered together, high fluoride concentrations tend to be found in groundwaters from the Bongo and Tongo Granites and the Sekoti Granodiorite (Table 4). Not all wells in the granite exceeded the WHO guideline value for fluoride, but more than half did.

The Vea reservoir, which supplies drinking water for Bolgatanga town, has a particularly low fluoride concentration (0.22 mg L^{-1}), even though it is situated on the Bongo granite. This is because the reservoir is fed by rainwater and surface runoff during the rainy season. Both of these have low fluoride concentrations through lack of water-rock interaction

There was little difference in fluoride concentration between dug wells and boreholes (Figure 8). The fluoride concentrations in dug wells from the granite terrain were particularly variable. Many on the Bongo Granite were low while several, particularly from the Tongo area, had high fluoride concentrations. These latter wells were almost dry when sampled and there had probably been a considerable amount of evaporation directly from the water surface (the Cl concentrations were correspondingly high). These high-F dug wells were not being used as the primary source of drinking water at the time of sampling and the measured water quality may not be representative of the wells at other times of the year. Many of the dug wells tended to dry up completely during the dry season, limiting their overall use and usefulness.

Table 3 Percentage of wells that fall within a given fluoride concentration class (mg L^{-1}) as a function of water source.

Source of water	%age of wells in concentration class				n
	<0.7	0.7–1.5	1.5–2	>2	
Reservoir	100	0	0	0	1
Dug well	67	16	6	11	18
Borehole	66	10	7	17	166
All types	67	10	7	16	185

n = number of samples

Table 4 Variation of fluoride concentration with surface geology in the Ghana project area

Geology	n	Minimum	Mean	Maximum	% age >WHO GV
			mg L^{-1}		
Bongo & Tongo Granite	46	0.09	1.88	4.4	54
Sekoti Granodiorite	8	0.86	1.56	3.2	38
Birimian granodiorite, adamellite and gneiss	85	0.15	0.72	3.6	13
Birimian greenstone (metavolcanic and metasediment)	46	0.13	0.55	3.6	9

There were no multi-screened observation wells with which to gain a measure of the variation of fluoride concentration with depth for a particular well but some idea could be obtained by looking at the variation of fluoride concentration in different wells of varying depth (Figure 9). The well depth was taken as the central point of the screened or open interval (when known) for a borehole or as the total depth for dug wells. There was little consistent variation in fluoride concentration with the depth of well (Figure 9) which again demonstrates that dug wells and boreholes show a similar range of concentrations.

6.1.2 Source of the fluoride

There was a clear association of high-fluoride waters with the Bongo and Tongo Granites and the Sekoti Granodiorite but some high-fluoride waters were also found in wells on the Birimian meta-igneous rocks. Further, some wells on the granites and granodiorite were low in fluoride and so the geological classification is not a perfect predictor of high-F waters. This may in part reflect misclassification of the well geology, especially for wells close to a geological boundary. Also, the surface geology is not necessarily a reliable guide to the subsurface geology, again especially close to geological boundaries.

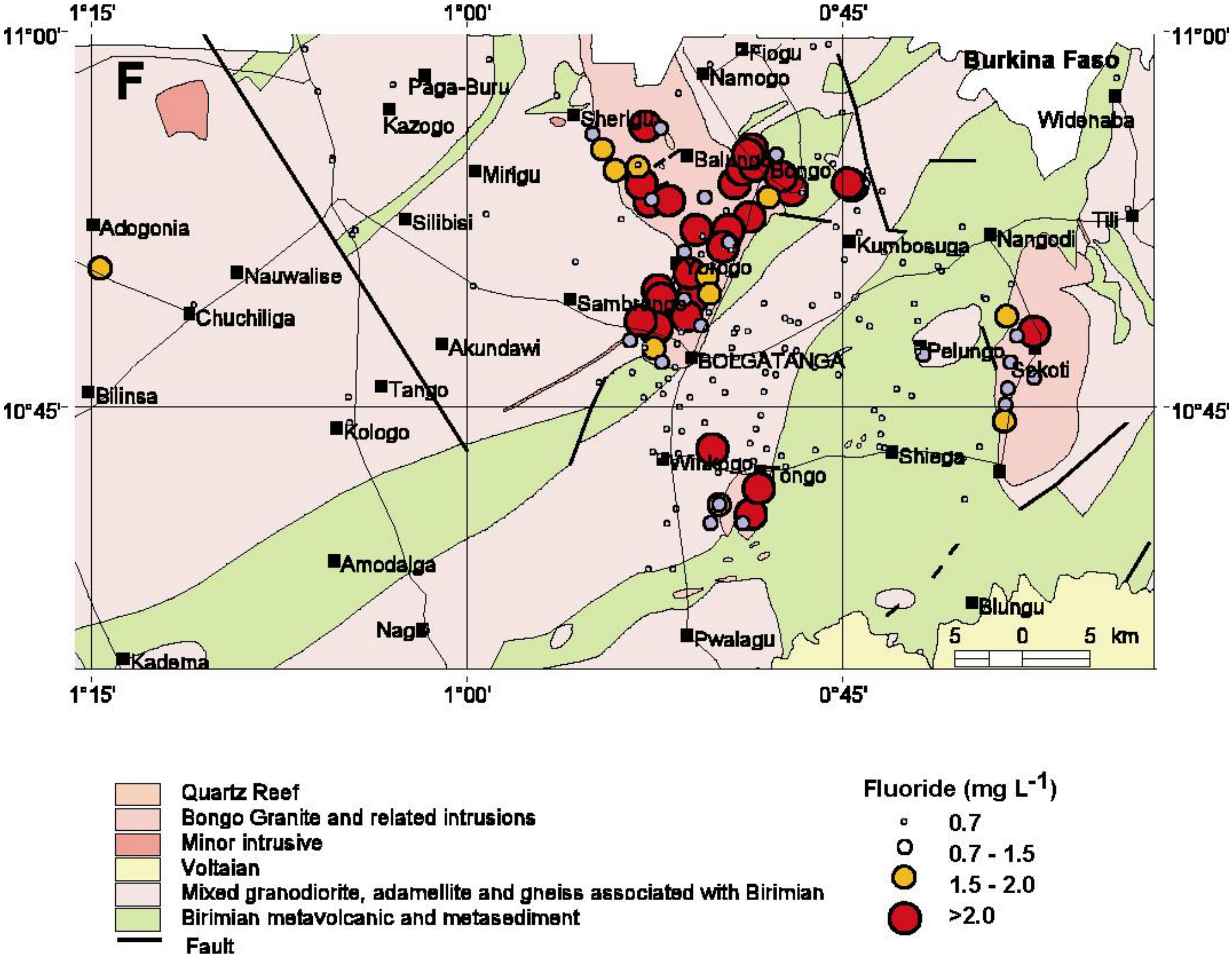

Figure 7 **Map showing the distribution of fluoride in the northern Ghana study area**

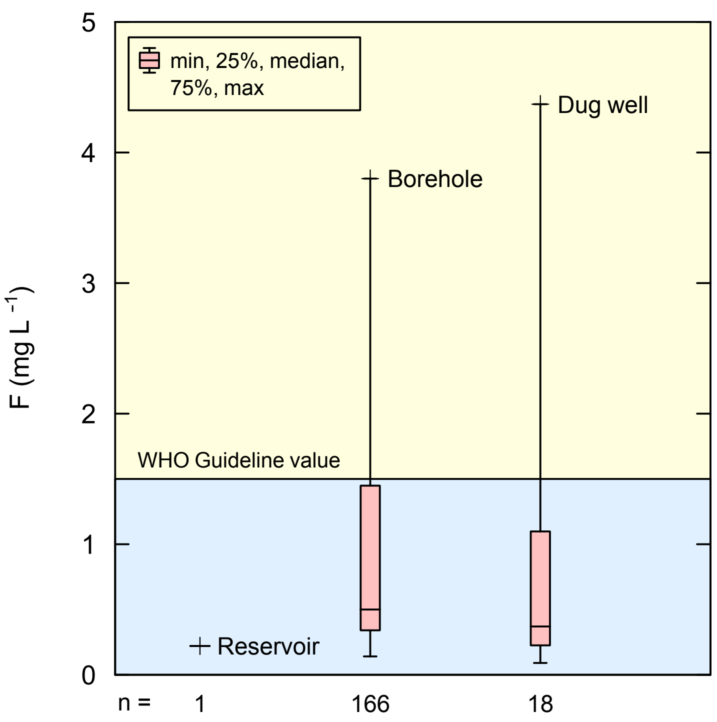

Figure 8 **Box and whiskers plot showing the variation in fluoride concentration in water from various sources in the study area in northern Ghana.**

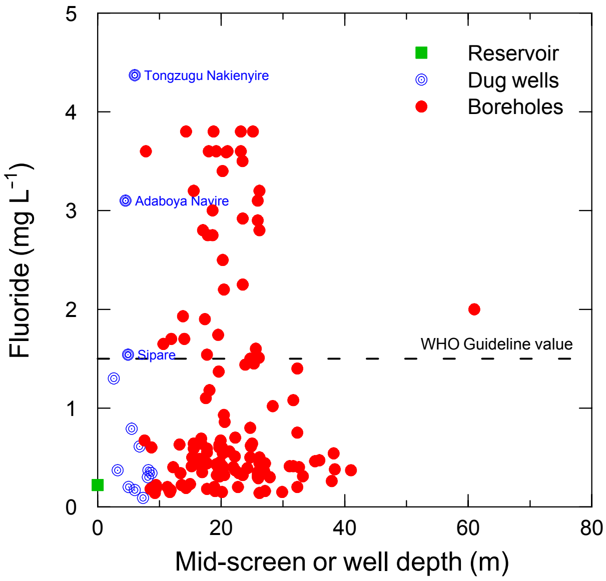

Figure 9 Fluoride concentration in water versus the depth of the middle of the screened interval of boreholes (where known) or dug well depth.

The granites and granodiorite are formed from igneous melts at a late stage of crystallisation and are hence relatively concentrated in residual incompatible elements such as the halides, including fluoride. Late-stage minerals such as amphiboles and biotites and abundant accessory minerals such as apatite and sphene can therefore contain relatively high concentrations of fluoride and other halide elements. The biotites from the Bongo Granite contain 2–3% fluoride (Smedley et al., 1995), which is not unusual for biotite, but in the low-recharge environment of northern Ghana could be a major source of fluoride to the waters. Samples of apatite from the area also contain 5–7% F and while apatite is normally less abundant than biotite it could also be a significant source of fluoride (Smedley et al., 1995). The mineral fluorite, another common source of fluoride in groundwaters, is only rarely found in the area and does not appear to be the major source of fluoride. The waters are mostly unsaturated with respect to fluorite indicating that there is insufficient fluorite in the rocks for this to be normally controlling the fluoride concentrations in the groundwaters.

6.1.3 Other elements of geochemical interest

Despite the strong geological control on fluoride concentrations, there was no useful correlation between fluoride and other major water-quality parameters (Figure 10). Most samples were undersaturated with respect to the mineral fluorite (CaF_2). This explains the lack of an inverse correlation with Ca concentration. There was also no correlation between fluoride and phosphate.

The sodium concentrations were generally low and showed little relationship with geology (Figure 11) or with chloride concentration. The most significant correlations between sodium were with the alkaline earth cations, Ca, Mg and Sr. This suggests that the sodium is mostly derived from the weathering of rocks rather than being derived from rainfall. The compositions are not believed to be affected by evaporation significantly.

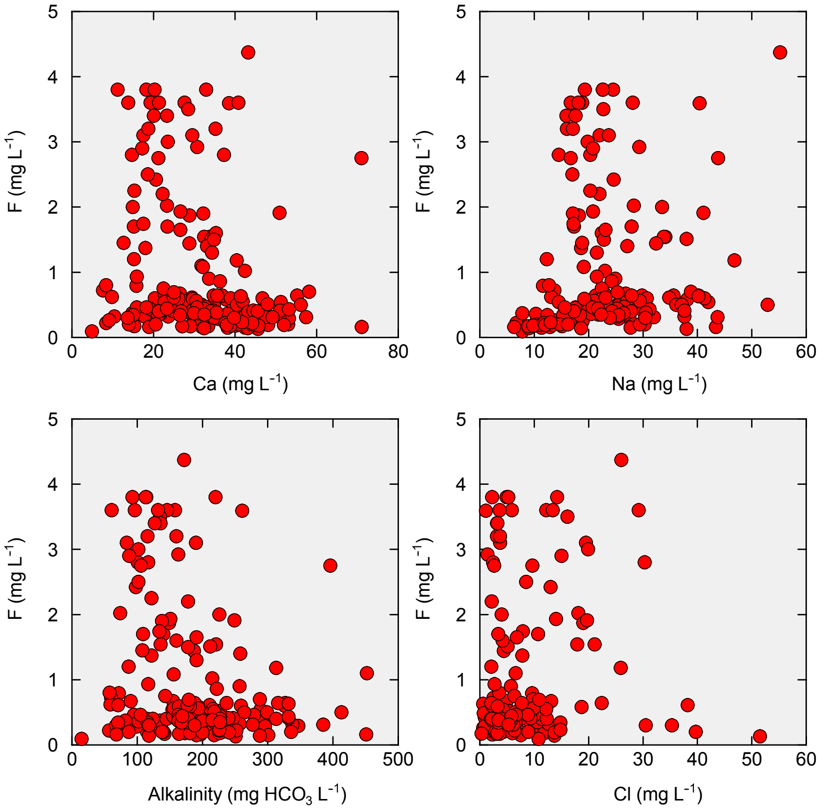

Figure 10 Scatter plots showing the variation of fluoride concentration in Ghanaian water samples with other water quality parameters.

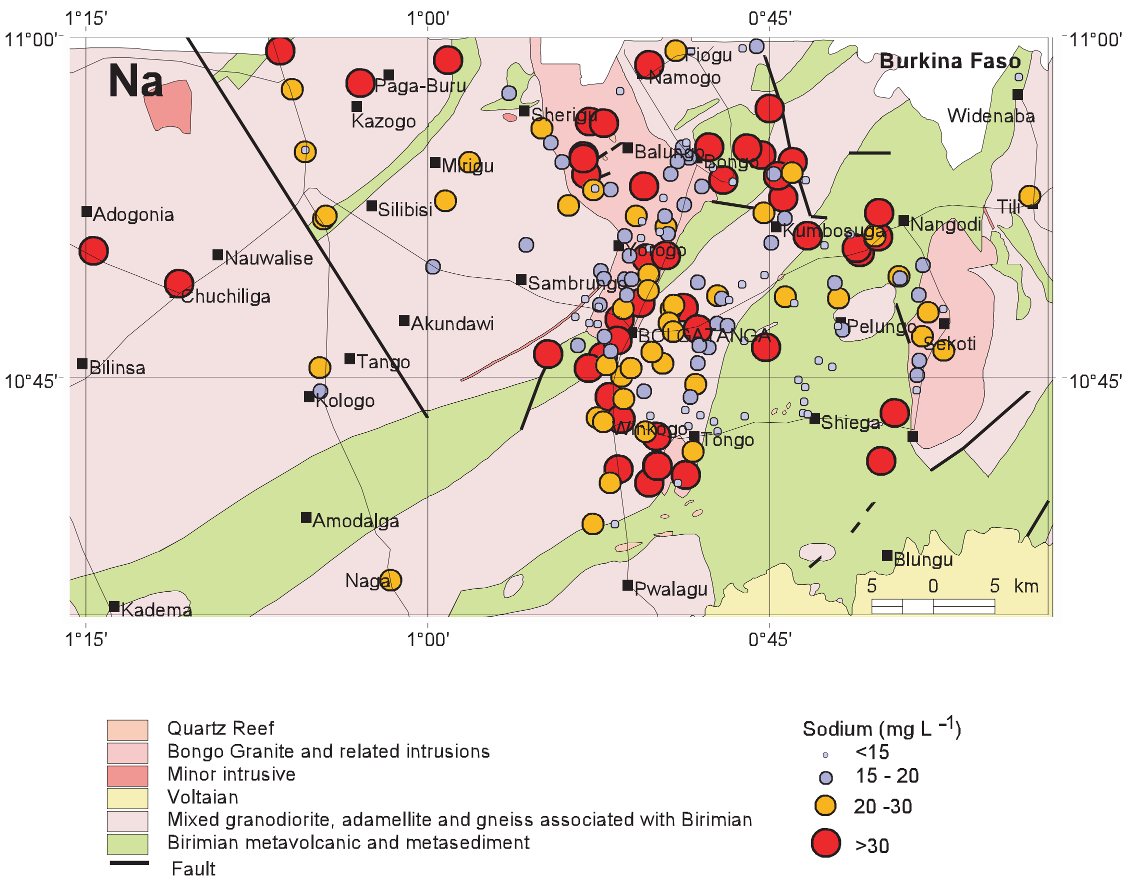

Figure 11 Map showing the distribution of sodium in the northern Ghana study area

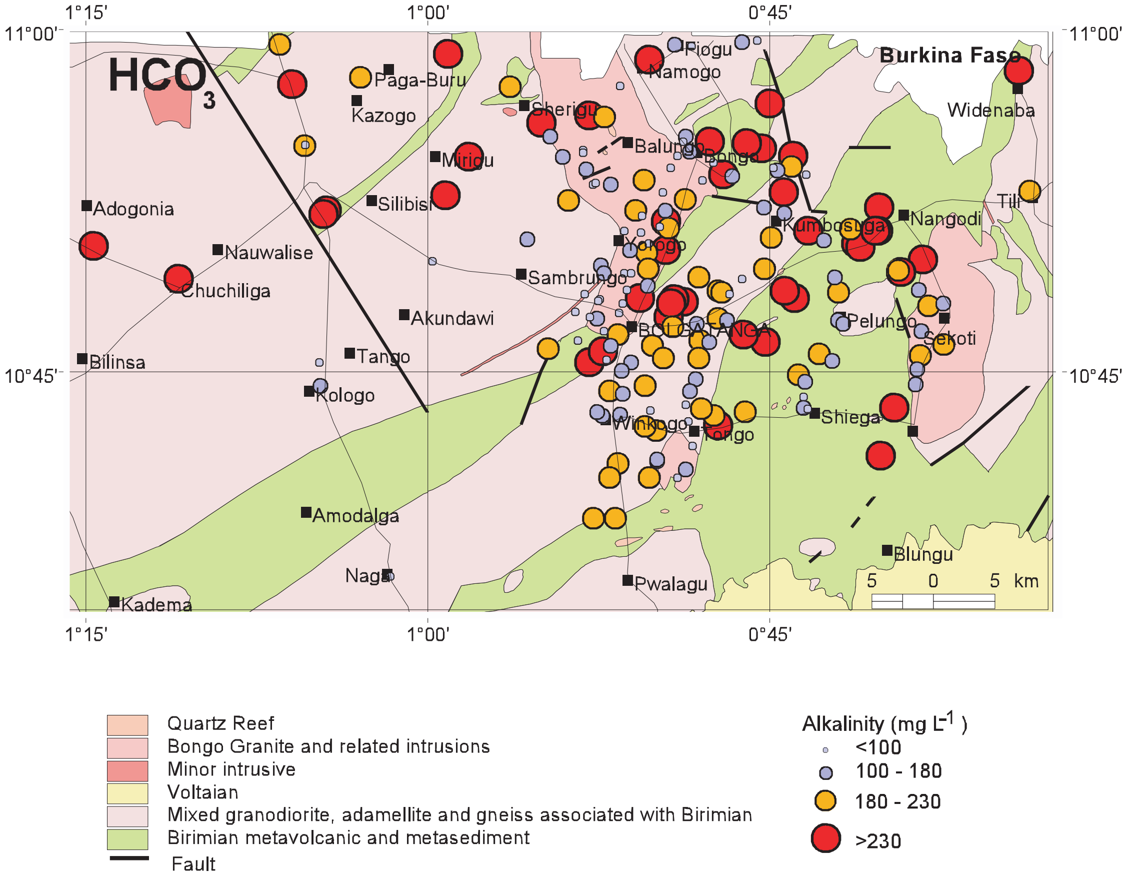

Figure 12 Map showing the distribution of alkalinity (bicarbonate) in the northern Ghana study area

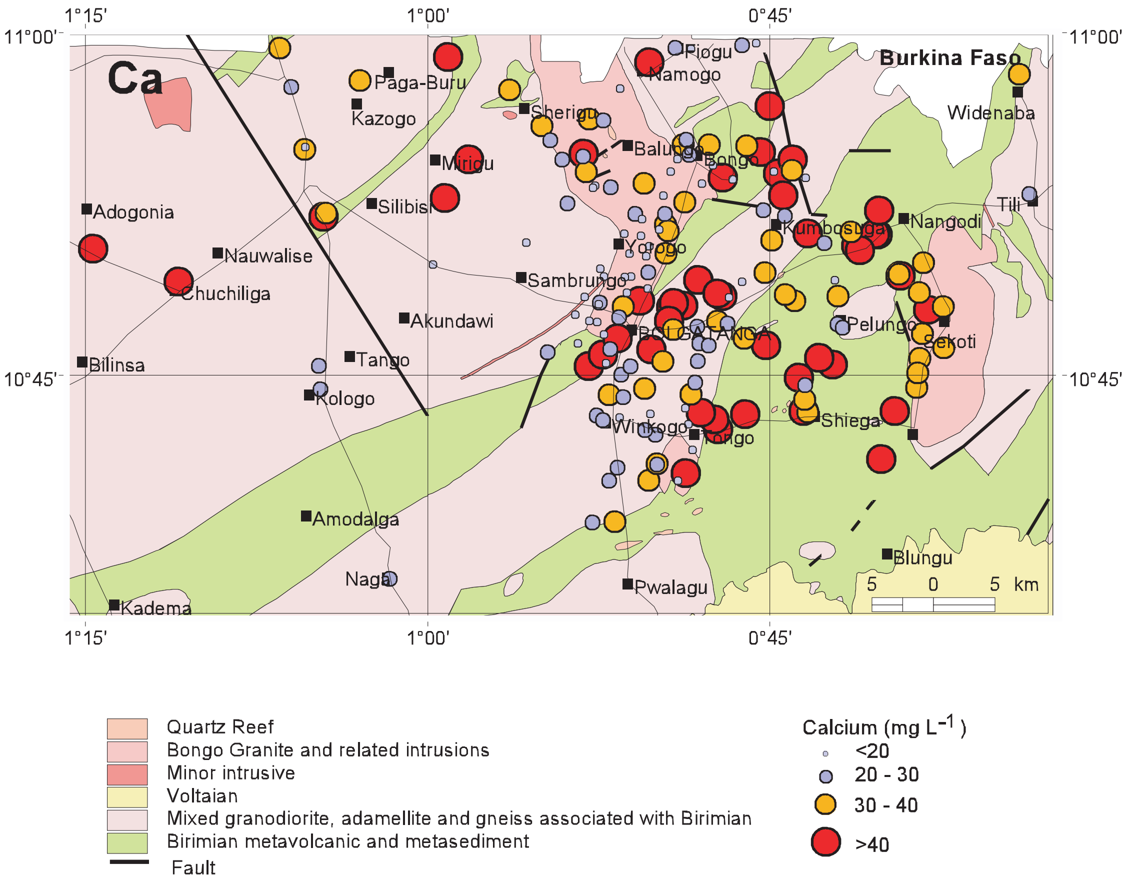

Figure 13 Map showing the distribution of calcium in the northern Ghana study area

Not surprisingly, bicarbonate alkalinity and calcium concentrations tended to be lowest for the wells overlying the Bongo and Tongo Granites (Figure 12 and Figure 13). Calcium is weakly positively correlated with magnesium but shows few other significant correlations. There is a cluster of relatively Ca-rich waters south of Bolgatanga reflecting the relatively high Ca concentrations for wells developed in the Birimian rocks.

6.1.4 Other elements relevant to health

Comprehensive analyses of the water for a wide range of major and trace elements (by ICP-MS) have shown that the major water-quality problem in the area is, not surprisingly, excessive fluoride (Table 5), at least judging by the WHO guideline values for health-related inorganic parameters. There were also occasional exceedances of uranium, nitrate and nitrite. Some 10% of waters sampled exceeded the WHO provisional guideline value for uranium of 2 µg L^{-1}. As with fluoride, the highest concentrations and greatest percentage of exceedances came from wells in granitic areas. This is not surprising as granites often contain enhanced concentrations of uranium as well as a range of other incompatible elements (Section 6.1.2).

The occasional high nitrate and nitrite concentrations are probably related to pollution. Occasional very high nitrite concentrations were found (up to 11.6 mg NO_2-N L^{-1}) but these are unlikely to be persistent. All of the high nitrite concentrations were found in the earlier (October 1993) survey and so may be seasonal.

Two of the waters with the greatest As concentrations, not unexpectedly, came from the Nangodi gold mine. Arsenic is often used as a ‘pathfinder’ element to help to locate sources of gold. One water was from the Nangodi clinic and the highest, which was mine drainage pumped directly from the base of the mine, exceeded the WHO guideline value of 10 µg L^{-1} by a factor of more than 40. This water was being used for domestic purposes at the time of sampling although it was not believed to be used for drinking water. It is important that this remains the case. No other elements analysed were found to be in excess of the WHO guideline values.

Table 5 Percentage of exceedances of WHO guideline values found in the Ghanaian water samples listed in decreasing order of frequency of exceedances

Element		WHO GV mg L^{-1}	Maximum mg L^{-1}	n	n>GV	% exceeding GV
F		1.5	4	185	43	23.2
U	(P)*	0.002	0.032	185	18	9.7
NO_3-N		11.3	33	185	12	6.5
NO_2-N	(P)	0.06	11.6	185	11	5.9
As	(P)	0.01	0.434	185	5	2.7
B	(P)	0.5	0.13	185	0	0.0
Ba		0.7	0.59	185	0	0.0
Cd		0.003	0.0002	185	0	0.0
Cr		0.05	0.010	185	0	0.0
Cu		2	0.030	185	0	0.0
Mn	(P)	0.5	0.406	185	0	0.0
Mo		0.07	0.015	185	0	0.0
Ni	(P)	0.02	0.004	185	0	0.0
Pb		0.01	0.004	185	0	0.0
Sb	(P)	0.005	0.0017	185	0	0.0

*(P) = Provisional value; GV = guideline value; n = number of samples; n>GV = number of samples exceeding guideline value. Only health-related analysed inorganic parameters are listed.

6.2 TANZANIA

6.2.1 Fluoride

It has been known for a long time that there is a serious groundwater fluoride problem in parts of the Tanzanian Rift Valley, particularly in the Arusha region (Mambali and Kilham, 1982). However, the distribution of fluoride in other parts of Tanzania is less well known. The only systematic, nationwide survey of fluoride in Tanzanian waters was that carried out by Bardecki (1974) (Table 6). This survey demonstrated that extremely high F concentrations could be found in waters in many regions of Tanzania and that no region was free from high F concentrations. Although the survey was based on quite a small number of samples, and the nature of the samples collected and precise spatial distribution is unclear (borehole, spring, dug well, etc.), the scale of the F problem in Tanzania is clearly large. Four regions (Singida, Shinyanga, Mwanza and Arusha) were found to have a median F concentration in excess of the WHO guideline value.

Table 6 Fluoride concentrations in various waters from Tanzanian regions arranged in terms of decreasing median fluoride concentration (from Bardecki, 1974).

Region	n	Min	Mean	Max	Median
			mg L^{-1}		
Singida	78	<0.1	5.85	67	3.2
Shinyanga	38	0.28	3.22	14.8	2.0
Mwanza	52	0.2	3.43	18	1.9
Arusha	124	0.1	7.11	78	1.8
Mara	58	0.2	2.02	9.6	1.45
Dodoma	391	<0.1	1.45	92	0.90
Tabora	44	<0.1	1.2	7.6	0.74
Kilimanjaro	98	<0.1	1.91	25	0.56
Morogoro	93	<0.1	0.6	4	0.48
West Lake	27	<0.1	0.93	4.4	0.48
Tanga	116	<0.1	0.94	20	0.47
Mbeya	79	<0.1	0.74	10	0.42
Mtwara-Ruvumu-Lindi	90	<0.1	0.55	7	0.39
Iringa	68	<0.1	0.61	6.1	0.36
Kigoma	30	<0.1	0.52	3.21	0.34
Coast	204	<0.1	0.56	20.4	0.32
All Tanzania	***1590***	***<0.1***	***1.91***	***92***	***0.68***

The regional distribution of fluoride in the various water sources sampled in this study (Figure 14) shows that while there is significant variation across the area, there is not a very clear pattern either geographically or geologically. High-fluoride waters are broadly scattered over the entire study area, although there appears to be a somewhat greater density of such sources in the north. The reasons for this are not currently clear, but geology (the predominance of granite) or the greater degree of faulting in this area could be responsible (Figure 14). South of Singida, the water quality seems to be better but there were not many wells to be found in this area.

High fluoride concentrations can be found in all types of water (except rainfall) in the study area. Streams, rivers, lakes, pits or dug outs, dug wells and boreholes can all potentially contain excessive fluoride (Figure 15). Overall, 57% of water sources sampled exceeded the WHO guideline value for fluoride in drinking water. Dental fluorosis was widely observed in the area both amongst children and adults.

A similar scale of fluoride contamination was observed from groundwater-quality studies carried out by JICA (1998). They carried out tests of boreholes in 284 villages in the Hanang, Singida Rural, Manyoni and Igunga Districts of Tanzania, including 583 fluoride analyses. They observed that high fluoride concentrations were often associated with boreholes in granitic rocks. They also found no notable differences between the F compositions in different water types. In the case of both wells and boreholes sampled, around 50% were found to have fluoride concentrations >2 mg L^{-1}. In addition, around 30% of water holes and 40% of charco dams had F concentrations >2 mg L^{-1}.

For the samples collected in our survey, the relationship between surface geology, as given by the 1938 geological maps of the area, and fluoride concentration is given in Table 7. The highest frequency of high-F water sources is found on the Quaternary alluvium and Precambrian granite. The well with the highest fluoride concentration, 111 mg L^{-1}, was found at Isakamaliwa, located in the Quaternary lake deposits. Fortunately, this was very saline and was not used for drinking water. Field observations at the time of sampling identified volcanic tuffs in the local area and these may be the source of the unusually high fluoride concentration (and salinity) in the water sample. Evaporation of shallow groundwater may also have contributed to this increased salinity and fluoride. The mean concentration of fluoride in waters from both the alluvial deposits and the granite exceeded 2 mg L^{-1}, reinforcing the severity of the problem. The Greenstone provided the best source of low-fluoride water in terms of average F concentration.

There was not much difference between groundwaters from boreholes and shallower groundwater sources (dug wells and dugouts) but the lake or charco dam sources tended to be slightly better quality sources in terms of fluoride, albeit not by much. There was a large number, some 17–31%, of each water type, with a very high concentration of fluoride (>3 mg L^{-1}). The river and stream water sources were high in fluoride, as were some of the lakes. This reflects a significant high-F baseflow (groundwater) component at the time of sampling. Some evaporation of surface water may also have been responsible for increased F concentrations. The single spring sampled, Wembere spring (not represented in Table 8), and the single charco dam at Imalanguzu were both low in fluoride in comparison with regional standards.

Table 7 Variation of fluoride concentration (mg L^{-1}) with surface geology in Tanzania

Geology	n	Minimum	Mean	Maximum	%age>WHO GV
Quaternary alluvium	12	0.55	3.71	17.5	58
Quaternary lake deposits & alluvium*	10	0.65	3.46	14.3	30
Precambrian granite	82	0.16	2.40	8.7	62
Greenstone	12	0.67	1.45	4.2	33

* Excluding one exceptional well containing 111 mg L^{-1}

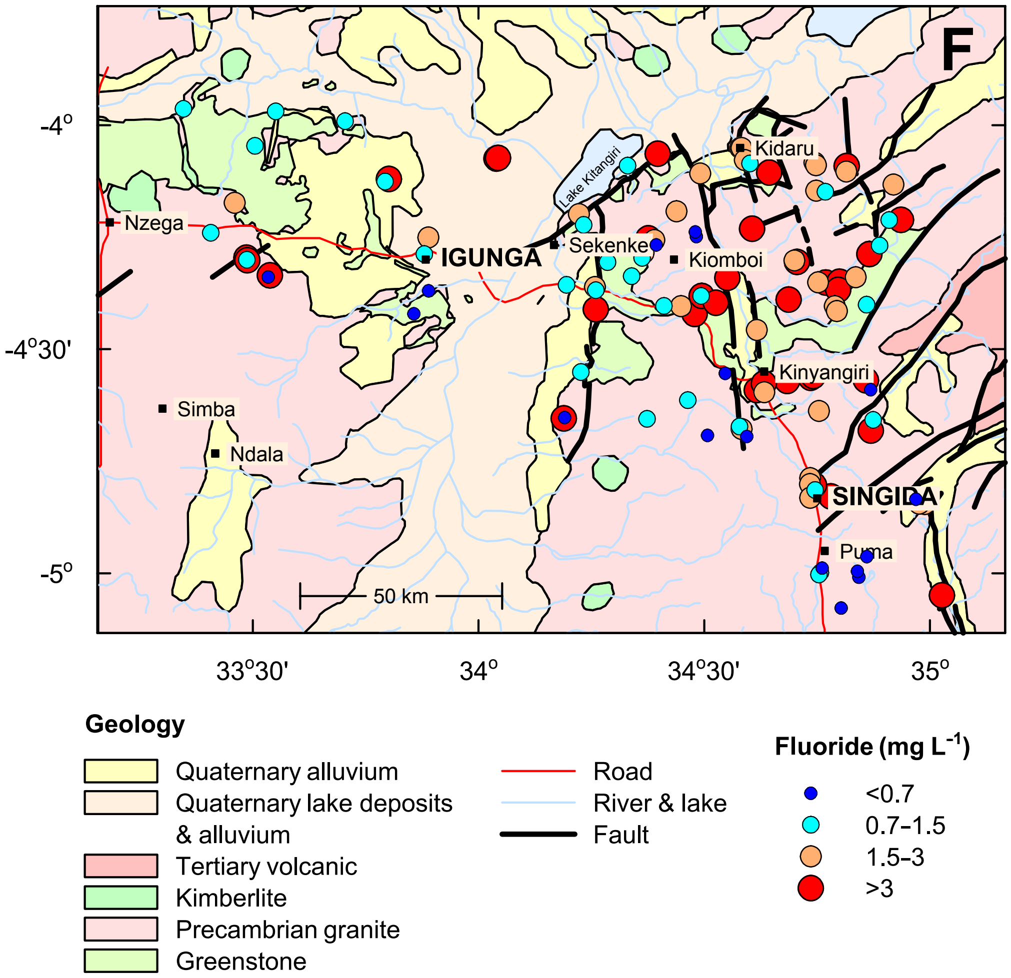

Figure 14 Map showing the distribution of fluoride in the Igunga-Iramba-Singida study area of north-central Tanzania.

Table 8 Percentage of wells that fall within a given fluoride concentration class (mg L^{-1}) as a function of water source. Sample set includes water analyses from the MSc study of Iramba District by R. Ideva.

Source of water	%age of wells in concentration (mg L^{-1}) class				n
	<0.7	0.7–1.5	1.5–3	>3	
River or stream	0	40	40	20	5
Lake or charco dam	33	33	17	17	6
Dug well and dugout	28	20	24	28	25
Borehole	11	29	29	31	80
All types	15	28	28	29	116

n = number of samples

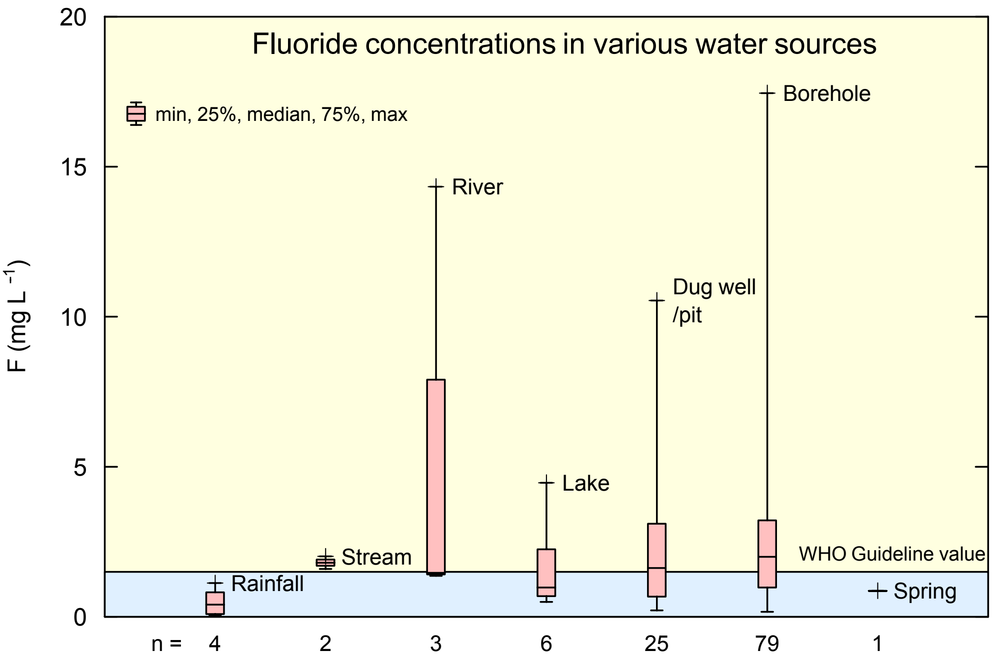

Figure 15 Box and whiskers plot showing the variation in fluoride concentration in water from various sources from the study area (excluding one exceptional well containing 111 mg L^{-1}).

Scatter plots showed that there was only a poor relationship between fluoride and calcium (Figure 16) but calculations indicated that the majority of waters were undersaturated with respect to fluorite. This explains the lack of the inverse relationship as this would only be expected of water in which fluorite saturation occurs. For the waters in which fluorite saturation was calculated to occur, there was a reasonable inverse relationship: i.e. high-Ca waters had low F concentrations, and *vice versa* (Figure 16).

There was a significant positive correlation with Na, and to a lesser extent with alkalinity, suggesting that high fluoride concentrations may be associated with strong water-rock interactions involving weathering of sodic igneous rocks. However, geothermal waters in the Rift Valley commonly also have high sodium and alkalinity concentrations (Kilham and Hecky, 1973; Lahermo and Nanyaro, 1981) and this is a potential extra source of high fluoride worthy of consideration. However, no correlation was observed between fluoride and other indicators of geothermal inputs such as temperature, silica or boron.

There was also not a good correlation between fluoride and chloride, indicating that simple evaporation of rainfall or even groundwater is not a predominant factor. However, the salinity in some of the samples was very high (more than 250 mg Cl L^{-1}) which suggests some evaporative influence. The high salinity makes them unpleasant to use for drinking water and so frequently, these sources are only used as a last resort.

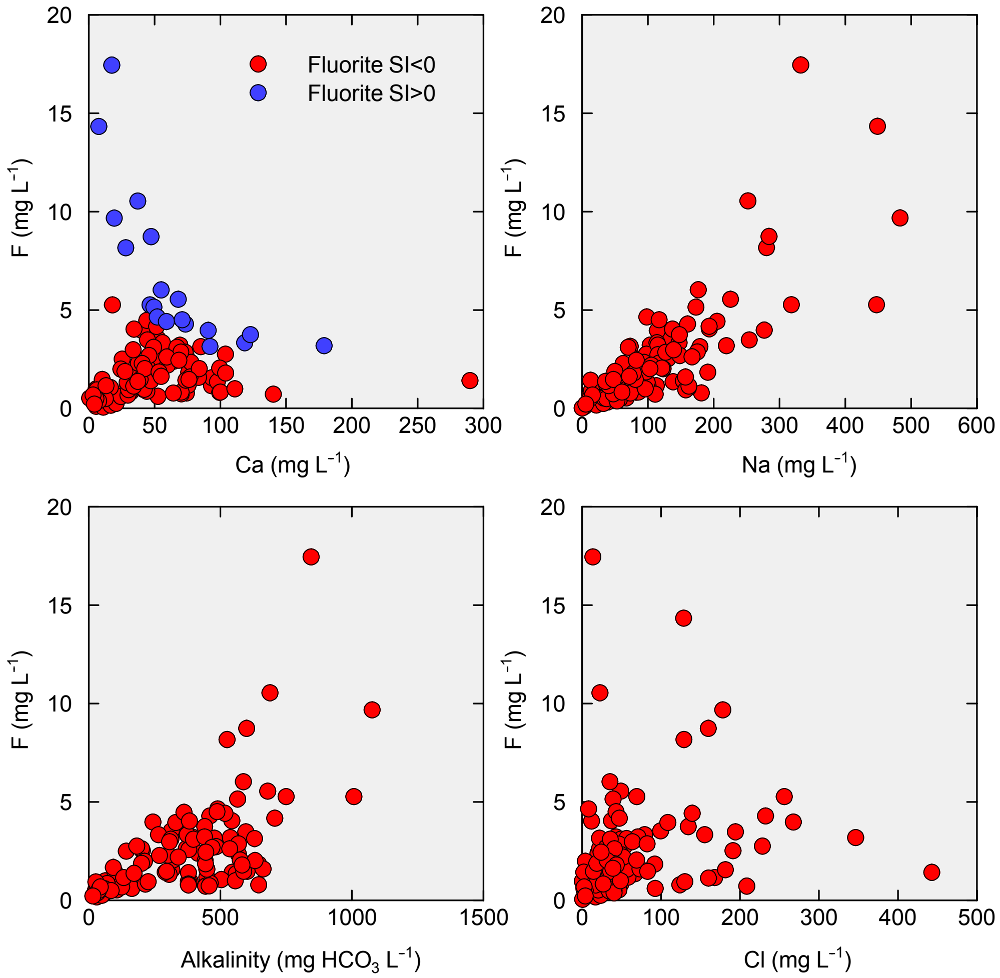

Figure 16 Scatter plots showing the variation of fluoride concentration in Tanzanian water samples with other water quality parameters. In the case of the Ca vs F plot, the samples in which the fluoride saturation index has been exceeded (SI>0) have been distinguished from those where it has not (SI<0).

6.2.2 Source of the fluoride

Some of the high-flouride waters found in the East African Rift result from the input of fluorine-rich geothermal waters (e.g. Gaciri and Davies, 1993; Ashley and Burley, 1994). This may also be true to some extent in north-central Tanzania, although whether it is an important source remains unclear. The apparent association between high fluoride concentrations and faulting in the study area may arise through invasion of geothermal solutions along fault zones. However, the data produced so far do not distinguish the sources of fluoride clearly. The positive correlation with Na and alkalinity described above (Section 6.2.1) could be achieved simply by water-rock reactions. Further investigation of collected data and field testing of other water sources (e.g. close to and remote from faults and in different rock types) is required to help discriminate between the potential sources.

Preliminary mineralogical analyses of the rocks from the study area suggest that three main mineral sources of fluorine are possible: (i) apatite, a Ca-F phosphate mineral, is one of the more common accessory minerals and was found to contain about 5–6% wt % F. There is a good correlation between F and P when mapped at sub-mm scale using an electron microprobe (Figure 17), supporting the presence of apatite; (ii) fluorite may be occasionally present but was difficult to observe; (iii) micas (biotite and muscovite) are also present in variable quantity. Fluorite is very soluble, apatite much less so. Biotite is more readily weathered than muscovite and could release fluorine on weathering.

No other major fluorine-containing minerals were observed. The biotites observed in the granites were K-deficient and appeared to be quite low in fluorine, about 0.2 wt %. Their low K contents indicate that they have been substantially weathered, suggesting the possibility of the simultaneous release of fluorine.

It is difficult to prove that a particular minor mineral is the major source without studying unweathered rocks since the source mineral might have dissolved completely during weathering. All the rocks examined so far were collected from the surface and so are likely to have been at least partially weathered.

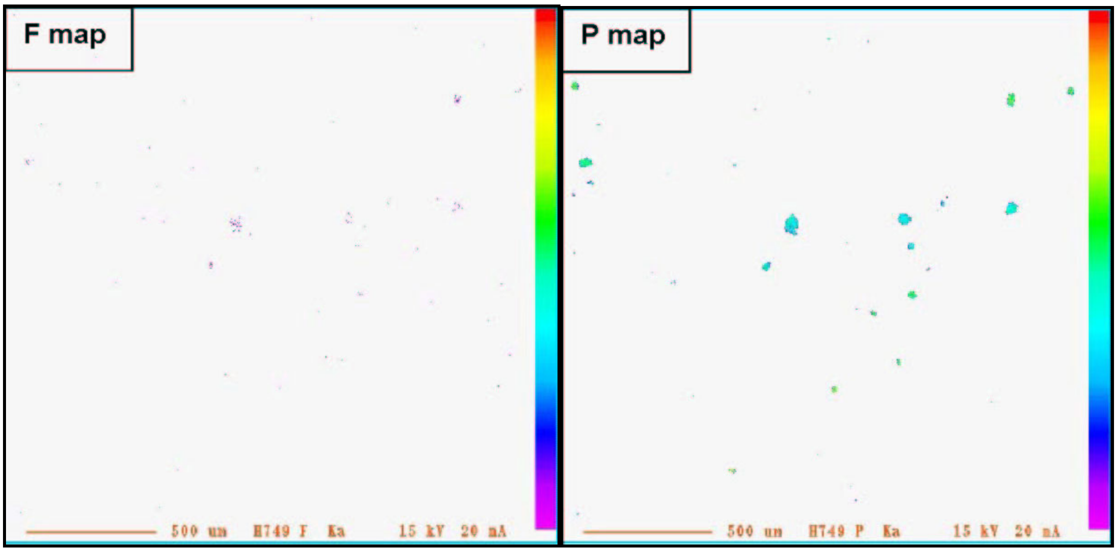

Figure 17 Electron microprobe element maps for fluorine and phosphorus for a granite from central Tanzania (sample TZ4). The close association between fluorine and phosphorus indicates that the fluorine is present in the mineral fluorapatite. The scale at the bottom left-hand corner is 500 µm.

6.2.3 Other elements of geochemical interest

The scatter plots (Figure 16) show how fluoride varies with some other water-quality parameters. Their spatial distribution is given in Figure 18–Figure 20.

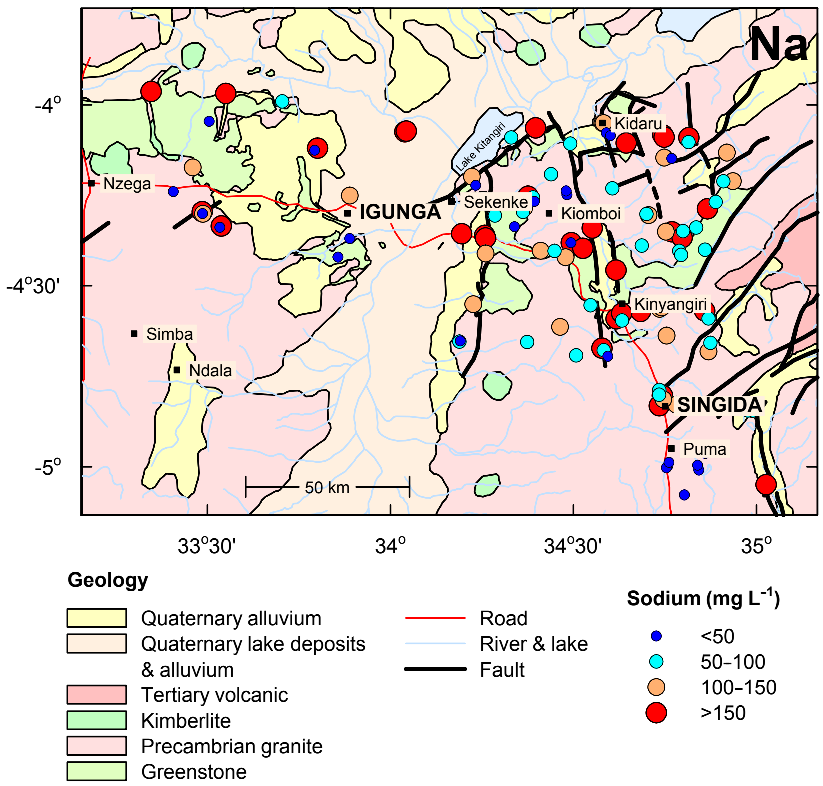

Figure 18 Map showing the distribution of sodium in the Igunga-Iramba-Singida study area of north-central Tanzania.

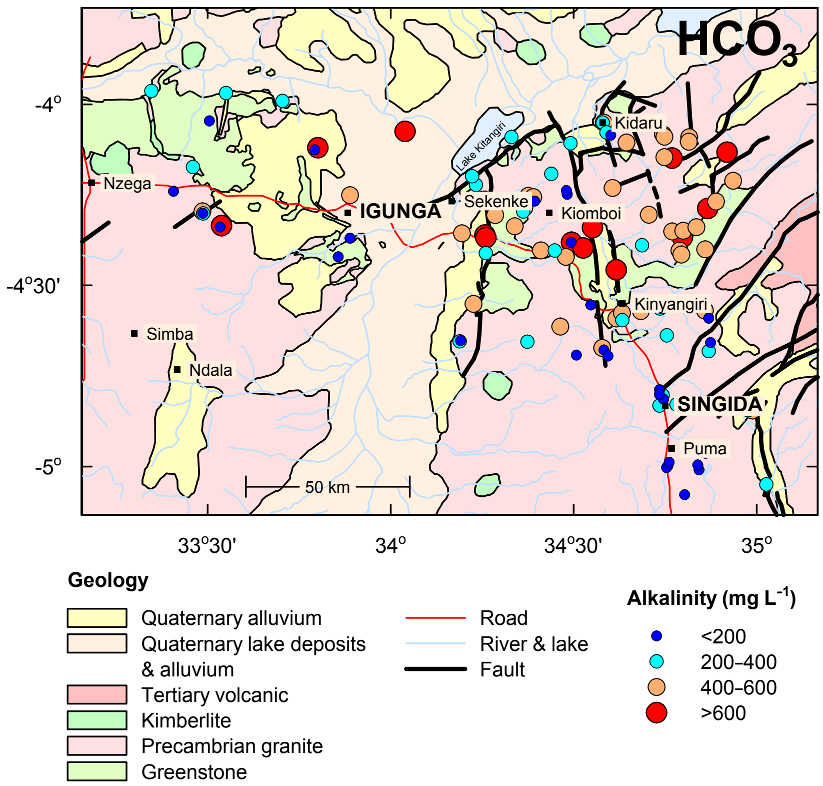

Figure 19 Map showing the distribution of alkalinity (bicarbonate) in the Igunga-Iramba-Singida study area of north-central Tanzania.

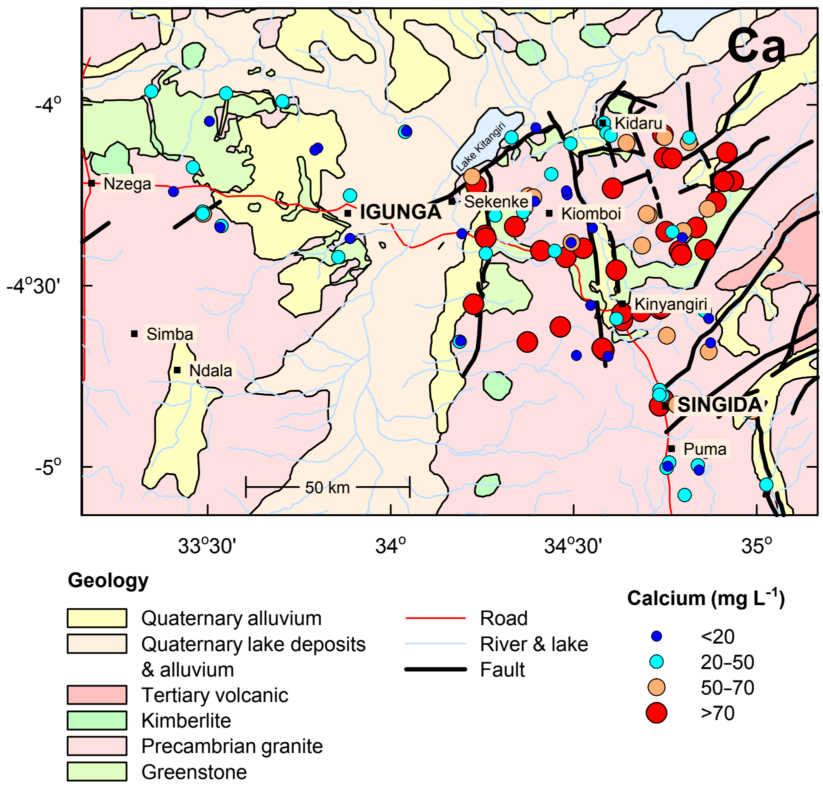

Figure 20 Map showing the distribution of calcium in the Igunga-Iramba-Singida study area of north-central Tanzania.

6.2.4 Dating of the groundwater

A novel method of 'groundwater dating' was tested in Tanzania. This involved the measurement of the concentration of various chlorofluorocarbons (CFCs) in the water. CFCs are almost entirely man-made and have only entered the atmosphere, and hence the groundwater, over the last few decades. Therefore the concentration of CFCs in groundwaters gives some clues as to the 'age' of the groundwater.

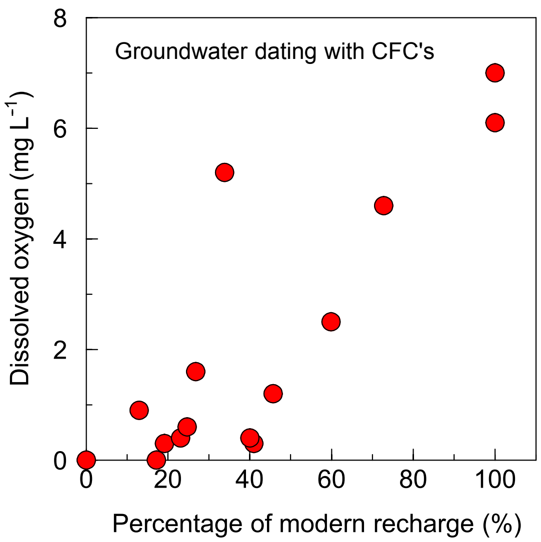

Figure 21 Variation of dissolved oxygen concentration with the percentage of modern recharge estimated by the CFC-11 content of the water.

Figure 21 shows the variation of percent modern recharge estimated from CFC-11 versus the dissolved oxygen concentration for selected water samples. It reveals a positive correlation (r^2=0.71). The relationship suggests that the oxygenated groundwaters from the study area are of a young age, representing water recharged for the most part in recent decades. This follows, as older groundwater will have had a longer residence time in the aquifers (away from the atmosphere) and hence longer for the dissolved oxygen to be consumed by various reduction reactions in the aquifer. Some oxygen-poor groundwaters from the Tanzanian study area are therefore likely to be relatively 'old', although many of those investigated represent modern recharge.

There is little apparent relationship between dissolved oxygen concentration and well depth. Hence groundwater 'age' does not increase clearly with depth in the aquifers. This is likely because of the dominance of fracture flow in the crystalline basement rocks which dominate the region with resultant complex flow patterns. Groundwater mixing is likely to be an important process in the fracture zones.

There is a slight relationship between percent modern recharge and groundwater fluoride concentrations, with some of the 'older' samples having relatively high fluoride concentrations. This might be expected as a result of slow fluoride build-up with increased groundwater residence time. However, the correlation between the two parameters is not statistically significant and not sufficiently good to be used in a predictive sense.

6.2.5 Other elements relevant to health

Analysis of the waters for a broad range of inorganic elements showed that some of the waters exceeded the WHO guideline values for parameters other than fluoride (Table 9).

Table 9 Percentage of exceedances of WHO guideline values found in the Tanzanian water samples listed in decreasing order of frequency of exceedances

Element		GV mg L^{-1}	max mg L^{-1}	n	n>GV	% exceeding GV
U	(P)*	0.002	0.647	116	80	69.0
F		**1.5**	**111**	**115**	**65**	**56.5**
NO_3-N		11.3	66.1	116	32	27.6
Ba		0.7	2.40	116	8	6.9
As	(P)	0.01	0.123	116	7	6.0
Mn	(P)	0.5	0.0058	116	6	5.2
Se		0.01	0.106	116	4	3.4
NO_2-N	(P)	0.06	0.35	32	1	3.1
B	(P)	0.5	2.85	116	2	1.7
Mo		0.07	0.255	116	1	0.9
Ni	(P)	0.02	0.333	116	1	0.9
Pb		0.01	0.085	116	1	0.9
Cd		0.003	0.0009	116	0	0.0
Cr		0.05	0.025	116	0	0.0
Cu		2	0.073	116	0	0.0
Hg		0.001	0.0019	116	0	0.0
Sb	(P)	0.005	0.0002	116	0	0.0

*(P) = Provisional value (1993); GV = guideline value; n = number of samples; n>GV = number of samples exceeding guideline value. Only health-related inorganic parameters listed.

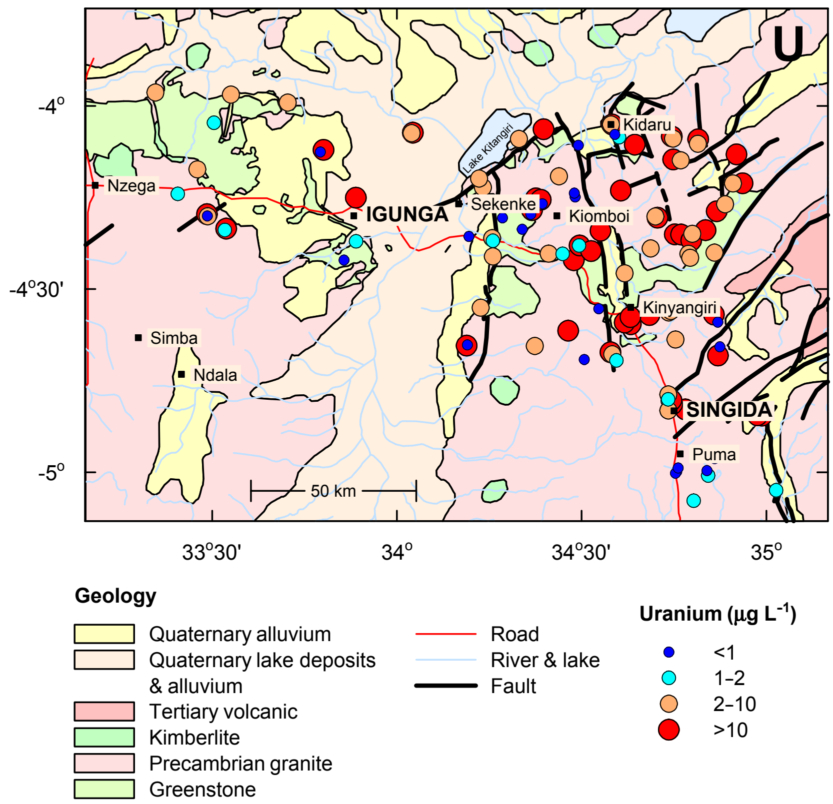

Figure 22 Map showing the distribution of uranium in the Igunga-Iramba-Singida study area of north-central Tanzania.

It can be seen from Table 9 that while some 56.5% of waters exceeded the drinking-water guideline value for fluoride, some 69% exceeded the provisional guideline value for uranium. Sixteen water samples (14% of the total), mostly from boreholes on the Precambrian granite (Figure 22), exceeded 30 $\mu g\ L^{-1}$, the US EPA maximum contaminant level. The highest U concentration observed, 647 $\mu g\ L^{-1}$, was from the very high-fluoride well at Isakamaliwa. This is not believed to be used for drinking water.

Nitrate also frequently exceeded the guideline value, sometimes greatly so. This probably reflects pollution from the surface. The boreholes tend to be quite shallow and derive a large proportion of their water from close to the groundwater table. This is likely to be the most polluted groundwater in terms of nitrate. Near-surface evaporation may also be responsible for some high nitrate concentrations, although correlations with other indicators of evaporation such as chloride, are poor.

There were also less frequent exceedances of quite a large number of other constituents (Table 9), including a variety of trace elements (Ba, As, Mn, Se, B, Mo, Ni and Pb). Again it was the Isakamaliwa sample that exceeded many of the guideline values. This water is clearly an extreme example of the poor water quality that can occur naturally in the area.

Aside from the parameters directly of concern to health, salinity is an important constraint on the use of water in the area. Surface waters can be as much a problem in this regard as groundwaters.

6.3 GENERAL CONCLUSIONS FROM GHANA AND TANZANIA

Fluoride problems clearly exist in the study areas of both northern Ghana and central Tanzania, although the proportion of exceedances above the WHO guideline value and maximum concentrations are greater in Tanzania (Figure 23). Most of the water samples tested were undersaturated with respect to the mineral fluorite (CaF_2) indicating that fluorite was generally not a major source of F. Saturation is the point at which the mineral fluorite should begin to precipitate and hence reflects the upper concentration limit of dissolved F. Saturation in groundwater types from both areas is achieved at around 5 mg L^{-1} F. Larger F concentrations (>5 mg L^{-1}) in fluorite-saturated samples from Tanzania (Figure 23) are linked to low dissolved calcium concentrations.

Although the fluoride problem is well-recognised in both Ghana and Tanzania, the lack of systematic assessment, databasing and mapping at national level has made it very difficult to gain a broad overview of the precise locations and scale of the problem. While the Bolgatanga area of northern Ghana is now recognised as a F-rich area (in part as a result of earlier BGS work), we also heard of possible F-rich groundwaters in other parts of Ghana, e.g. north-west Ghana. Without a systematic survey, it is difficult to assess the veracity of this anecdotal information. The lack of well-publicised cases of dental fluorosis suggests that the scale of the problem is not that common in other parts of Ghana.

Similarly in Tanzania, where the scale of the problem appears to be much greater, there is a lack of sufficient randomised testing on a national scale to assess the overall extent of the problem. The existing databases rely quite heavily on pre-1975 data and often on surveys carried out by donor organisations. There is a need for more random surveys of water quality in both Ghana and Tanzania. These could be organised on a regional basis. The scale of testing need not be that great but they must be random in order to capture the overall statistics properly. Mapping the results would provide a rapid visual assessment of the scale and severity of the fluoride problem.

While we did not observe any *skeletal* fluorosis during our field surveys, there was much evidence of *dental* fluorosis especially among children. This is very distressing for the individuals concerned, and should be preventable (see later).

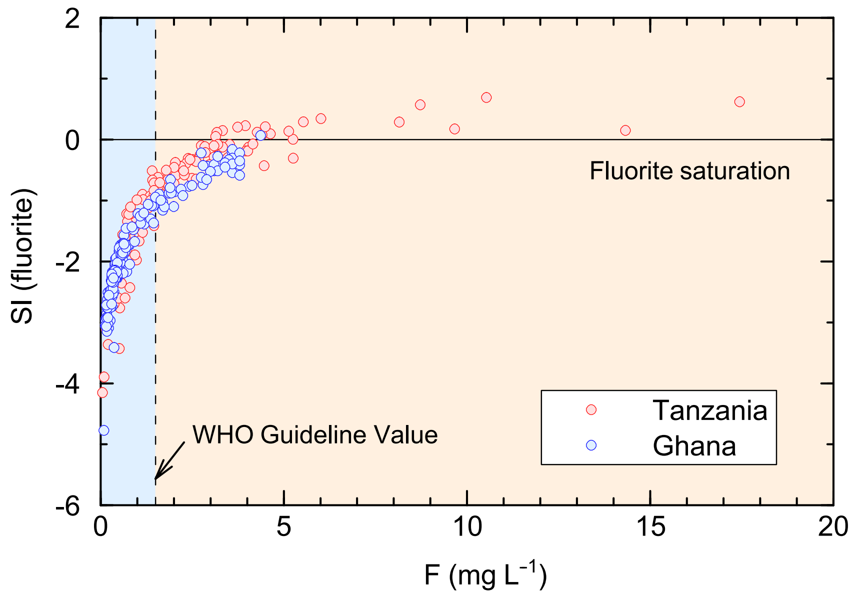

Figure 23 The saturation index of the mineral fluorite plotted against the fluoride concentration in waters from Ghana and Tanzania.

7 Institutional and social factors

A rigorous analysis of the socio-economic impact of high fluoride on communities in Ghana and Tanzania is beyond the scope of this study. However, it is vital that the research is rooted in the socio-economic conditions of the country in question and that recommendations provided are sensitive to those conditions. This is vital for maximising the chances of uptake of the research in the region. The findings outlined below are from discussions with a diverse range of stakeholders in each country, including community members, district commissioners, state and district water departments, NGOs, engineering consultants, university departments and government research organisations. In Tanzania, stakeholders include the Ministry of Water and Livestock Development and SEMA. In Ghana, discussions were held with the Water Resources Commission (WRC), the Water Research Institute (WRI), the Community Water & Sanitation Agency (CWSA) and the Ghana Geological Survey (GGS). NGOs consulted include WaterAid in both countries, and New Energy and Rural Aid in Ghana.

7.1 FLUORIDE AND WATER SUPPLY

7.1.1 Northern Ghana

In Ghana, the problem of high fluoride concentrations in drinking water appears a relatively localised phenomenon, centred on the Upper East Region. Anecdotal evidence suggests that isolated high-fluoride groundwaters occur in other areas but few data are currently available to support this. Water shortage is a major problem in northern and central Ghana, but despite this, water sources identified as having high fluoride concentrations are commonly not accepted by the affected user communities. Several high-fluoride wells in the Upper East Region have been capped. CIDA, the donor responsible for a major well installation programme in the region, has been concerned that some of the wells installed by them were delivering water with a high fluoride concentration. They instigated a comprehensive water-quality study of their wells and have been looking for alternative water supplies where high fluoride concentrations have been found.

Poor returns have been achieved from capital investments made by the various water development agencies including CIDA. Where functioning wells are abandoned, there is a risk of communities returning to surface-water sources where available, with consequent increased exposure to waterborne diarrhoeal disease (WRC, 2000).

7.1.2 Central Tanzania

Much of rural central Tanzania suffers from acute water shortage. In the study area, there are few working boreholes. People often have to travel large distances for water, carrying the water on ox-carts, bicycles or by head. In some communities, informal water markets have developed, the price for a 200 litre drum was commonly 500 TZS ($0.5 US). The scarcity of water in some areas has led to skin and eye infections, since water is used only for drinking and cooking. In communities where water is scarce (most of the communities visited) people told us that water was their main concern. The problem with the teeth was perceived as of much lower priority. This was reiterated by most of the Ministry officials, NGOs and district commissioners – water first, quality second.

However, fluoride does pose a considerable problem for those involved in developing water supplies in Tanzania. This is well-illustrated by the example of JICA in Singida region. JICA funded a large groundwater investigation programme in northern Tanzania during the mid to late 1990s. This was the preparatory work for a large-scale project to develop water supplies for several hundred communities across four districts. The groundwater investigations involved drilling investigation boreholes and carrying out hundreds of kilometres of geophysical surveys.

The state and district water departments were mobilised and expectations among communities in the districts were high. However, in the event the large-scale RWSS project has not materialised because of concerns over high fluoride concentrations. Only eight water sources are now to be developed in the region, these in areas where fluoride is known to be below the WHO guideline value. This has caused considerable confusion and disillusionment in the communities. It also highlights the need for a better understanding of fluoride distributions and their controls in groundwater.

During our investigations in central Tanzania, the Water Ministry (including those involved in the new World Bank rural water supply project) and Water Departments has expressed considerable interest in knowing the extent of the fluoride problem in central Tanzania. This knowledge would help to ensure that the JICA experience, where the project had progressed far and expectations had been raised before the problems of fluoride emerged, is not repeated.

7.2 THE IMPACT OF FLUOROSIS ON COMMUNITIES

From the field investigations carried out, it appeared that attitudes to fluoride excess in drinking water varied between the two study areas. In Ghana, the problem is seen as a serious one and in some cases steps have been taken to cap fluoride-affected wells. In Tanzania, the fluoride issue has a lower priority and less action has been taken to mitigate the problem. This in large part reflects the fact that fluoride occurrence is more widespread in Tanzania, and hence is more difficult to mitigate in a practical way. As mentioned above, most opinions expressed by community members (mainly through village chairmen or executive officers) in Tanzania were that communities would rather have reliable sources of high-fluoride water, than unreliable sources of low-fluoride water. Despite this, during the sampling in Tanzania it was apparent that fluorosis impacted people’s lives.

1. The teeth of many people were badly mottled, some appeared deformed.
2. Within the villages, there appeared embarrassment about dental colour. Before mentioning the reason for sampling, many children would hide their teeth and smile with their mouths closed. Adults who have spent their childhood in fluoride-affected areas and subsequently become educated and travel outside their home area are severely embarrassed by their poor teeth. This is likely to be an increasing problem as travel of individuals for economic or social reasons becomes more common.
3. Some middle-aged people complained of aching joints, although the cause is currently not known.
4. Very few consented to having a photograph taken of their teeth.

Within many communities, there is considerable diversity in the dental health of individuals, even given a common water source. Complicating factors are likely to include nutritional variations, migration and physiological susceptibility.

In one community in central Tanzania, the development of a new (high-fluoride) water supply had a considerable effect on the community. Prior to the borehole being constructed, water was taken from dugouts several kilometres way; most people had very good teeth. Mottled teeth were associated with people in Iramba to the north. A borehole was drilled closer to the village in 1990. Children are now developing the mottling characteristic of dental fluorosis. Since this had not been seen in this particular village before, the fidelity of women within the village is being called into question. Such misunderstandings are common and illustrate the importance of education of the communities involved.

8 In-project training

The field sampling in Ghana and Tanzania provided the opportunity for training local counterparts. A set of field equipment (pH and fluoride meter with electrodes, manual titrator for alkalinity measurement, hand-held GPS where necessary) were supplied to enable our partners to carry out basic water sampling. Partners trained included Dr K. Pelig-Ba (University of Tamale), Dr H. Nkotagu and Ms R. Ideva (MSc student, University of Dar es Salaam) and Mrs K. Mwambo (Tanzanian Bureau of Standards).

Training in the field included demonstration and operation of all the procedures that BGS routinely use on such field sampling campaigns including planning of the survey, sample labelling and tracking, sample preservation, use of GPS equipment, field measurement of labile parameters (pH, alkalinity, dissolved oxygen, etc.) and quality control.

Ms Radhia Ideva visited BGS (Wallingford) for training between November 17–December 13, 2002. She has previously carried out a separate water sampling exercise as part of her MSc project in Iramba District and has analysed the samples partially in Dar Es Salaam and partly in BGS laboratories. During her UK visit, she learnt how to analyse her data using various statistical and graph-plotting packages, spent time in the BGS laboratories and prepared an outline of her MSc thesis. She made extensive use of the BGS/CEH library at Wallingford, the BGS interlibrary loan system and the online Web-of-Science literature retrieval service. This enabled her to update her literature review.

An outline of Ms Ideva's MSc thesis plan is given in Appendix 1.

9 Conclusions and implications

9.1 WATER QUANTITY VERSUS WATER QUALITY

The fluoride problem in groundwaters is characteristic of arid areas, or more specifically, of low-recharge areas. Both northern Ghana and north-central Tanzania can be classed as such low-recharge areas. It is of course precisely in such areas that water resources are particularly stretched, not only in terms of quality but also quantity. These problems become particularly acute when, as in northern Ghana and central Tanzania, the rainfall is highly seasonal and often unreliable.

Water availability, of whatever kind, is a major issue in both of the communities studied. The lack of availability of clean water, especially during the dry season, has indirect effects on health and sanitation as well as being a major burden for the women of the villages. Investment in groundwater development over the last 30 years has eased this burden but has also produced new problems. High fluoride concentrations are one of these. Even traditional sources of water (dug wells, rivers and reservoirs) can also give high concentrations of fluoride but the problems are particularly prevalent in groundwater from boreholes and so the scale of the problem has probably increased in recent years. Nevertheless, it is important to remember that not all boreholes produce high-F waters. Water testing is therefore an important process for wells used for drinking water.

The choice between a short walk and poor-quality water and a longer walk to better-quality water is a difficult one to make. The communities are not always aware of dental fluorosis even when it exists in their community. They probably do not connect fluorosis with particular wells. In the dry season when water is extremely scarce, water quality becomes a secondary issue.

Nevertheless there are some indications as to how the situation could be improved:

1. monitor the fluoride concentration during the drilling of a well: abandon the well if high fluoride concentrations persist;
2. charco dams, as used quite widely in Tanzania, seem to give low-F water, probably because of their large recent rainwater component. A pond sand filter, as commonly used in Bangladesh and elsewhere, could be used to clean the output from these reservoirs;
3. encourage increased recharge by retarding runoff using small dams and then placing a shallow borehole nearby. This water should have low fluoride concentrations as a result of dilution by the increased proportion of newly infiltrated recharge.

9.2 ROLE OF GEOLOGY

There is clearly some geological control on groundwater fluoride concentrations from the investigations carried out. This control is strong in Ghana where the high concentrations can be related in large part to the occurrence of granite and granodiorite. Areas of metamorphic basement rocks tend to have much lower fluoride concentrations, in some cases insufficient for dental health. In Tanzania, the relationship between geology and fluoride concentration is less strong, although still some variations with lithology are apparent. Here also, granitic rocks appear particularly susceptible to developing groundwaters with high fluoride concentrations. Unfortunately, much of Africa is underlain by such granitic basement rocks. In Tanzania, the proximity to the East African Rift Valley and the faults that emanate from it, appears to be another factor. The role of geothermal inputs in the groundwaters of the study area in Tanzania are however, still unclear.

While it may be possible to predict the susceptibility of groundwaters to fluoride at a regional scale from the known geology of the area, this becomes much more difficult when extended to the local scale. This is the scale at which decisions have to be made about well siting. The difficulty may arise from deficiencies in our knowledge of the detailed geology of the area, local variations in rock type and faulting and from variations with depth.

The variation with well depth is particularly important as the driller has some control over this. It would seem reasonable to expect that fluoride concentrations will increase with depth of well since deeper waters have had more time to react with the rock. However, this is not clearly demonstrated by the existing data, perhaps because the only existing data are for different locations and different lithologies, potentially mixing several important factors. It is important that this is established for at least one given location. This is an important goal in Phase II.

9.3 PRELIMINARY GUIDELINES

The drawing up of generic guidelines for water providers (e.g. drillers, water engineers) is a defined objective of Phase II of the project and it is not the intention to define such guidelines at this interim stage. However, some initial observations and preliminary assessments have been made from the preliminary data collected so far. These are outlined below and will be the basis on which future guidelines in Phase II will be formulated.

1. Fluoride problems are dominantly a problem in arid (low-recharge) areas. Consideration of fluoride problems should be made especially when planning borehole installation programmes in such arid areas. High-recharge areas are less prone to high fluoride concentrations, unless at risk from other inputs of fluoride, notably geothermal water.
2. Well depth is a factor that could have major significance in terms of groundwater fluoride concentration. This work has shown that relationships between fluoride concentrations and well depth are as yet unclear. However, the uncertainty arises in many cases out of lack of knowledge of the well depths and in others out of lack of variation of well depths (as in the Ghana study area). It is logical that, all other things being equal, deeper groundwater should have higher fluoride concentrations than shallower groundwater. Potential complications arise through variations in geology, weathering, faulting and

groundwater flow. Dominance of fracture flow in crystalline aquifers makes the relationship between aquifer depth and groundwater residence time a complex one. The issue of fluoride concentration versus depth is important from a groundwater development viewpoint and requires more detailed study. This can be progressed by installing piezometers to known and variable depths and testing (and monitoring) the water quality.

3. Some of the groundwaters from this and other studies (e.g. Smedley et al., 2002) show relatively high fluoride concentrations at very shallow depths (e.g. dug wells and dugouts). This may be for a number of reasons, including evaporation near the ground surface and groundwater discharge in low-lying areas. These processes will likely increase the concentrations of other solutes besides fluoride and so will impact on the groundwater salinity to varying degrees. Very shallow water sources should also be avoided for reasons of vulnerability to bacterial contamination. In practice, very shallow groundwater sources are most likely to dry up in the dry season in any case and so for various reasons are unattractive. The uncertainties in fluoride concentrations with well depth highlight the importance of groundwater fluoride testing during well construction.

4. Probably the best form of testing of F in field situations or local laboratories is by ion-selective electrode. The method is relatively simple and inexpensive and the project has shown that results obtained can be very reliable provided staff are adequately trained in their use. Testing at regular stages during well drilling could be an effective means of optimising water quality with respect to fluoride concentrations.

5. There are clearly variations in fluoride concentrations in groundwater resulting directly from geology. From both the project results and published literature, groundwater from granitic rocks (including extrusive equivalents such as rhyolite, dacite) and alkaline igneous rocks (e.g. nephelinite, carbonatite) appear particularly vulnerable to high fluoride concentrations. The latter rock types are comparatively rare, being restricted to Rift zones such as the East African Rift, but granitic rocks are common throughout the basement complexes of Africa and elsewhere.

6. High-fluoride wells could be used for non-potable purposes, providing that the community is fully aware which wells have high fluoride concentrations and of the consequences for health of chronic fluoride ingestion.

7. Project results, as with other data, indicate that rainwater does not contain high fluoride concentrations. Where groundwater fluoride concentrations are high regionally, as in parts of Tanzania, rainwater harvesting is a potential option for potable supply, at least seasonally.

8. There is also a question of the threshold of acceptability of fluoride concentrations. In Tanzania, the interim national standard for fluoride in drinking water is 8 mg L^{-1}. Groundwater development organisations involved in new drilling programmes in Tanzania need to decide whether this is the cut-off above which a given well is unacceptable, or whether a lower value such as the WHO guideline value or something in between is a more acceptable target. Further discussion on how to respond to cases of groundwater fluoride excess will be included in the Phase II guidelines.

9.4 DECISION POINT ON PHASE II

One of the key objectives of Phase I of the project was to compile existing information on fluoride in groundwater and to carry out reconnaissance studies in new areas in order to assess the degree of predictability of fluoride concentrations in groundwater in a given aquifer or environment. This information provides the decision point on whether the results merit continuation of the investigations into Phase II.

The results outlined above give some clear pointers that, despite considerable regional variations, much of this variation is systematic and related to geology, structure (faulting), groundwater flow and residence time. These systematic variations provide a useful basis on which generic guidelines can be drawn up, but significant uncertainties arise from the results produced so far and require further investigation to clarify the processes involved in fluoride mobilisation. In particular, the lack of a distinct depth relationship makes it difficult at this stage to formulate clear recommendations on drilling depth. Information needs to be gathered on the variation of fluoride concentration at known and variable well depths, say in the top 50 m of the saturated zone. Installation and testing of piezometers (observation wells completed at discrete depths) would aid with this depth analysis. Monitoring of these piezometers would also allow assessments to be made of temporal variations in water quality over short time scales, of a few months. Further field testing of water from existing sources in selected areas, notably in granitic and heavily faulted terrains in Tanzania, would also help to characterise the nature of spatial variations in water quality.

Further work also needs to be carried out on groundwater flow in the different aquifers studied as an aid to understanding spatial fluoride variations. This can be achieved by further analysis of available hydrogeological data and more detailed assessment of the hydrogeochemical compositions of the groundwaters, together with an investigation of the stable-isotopic compositions of selected groundwater samples. It is believed that further study in Phase II of these aspects will help to clarify many of the uncertainties identified in this preliminary investigation.

By contrast, there are a number of consequences of not continuing into a second phase, the most important of which are outlined below.

1. Although the MSc student in Tanzania is continuing work on her thesis, no further BGS supervision will be possible. Supervision from Faculty staff at the University of Dar Es Salaam will continue, but the student will not benefit from further international collaboration and support that the project can provide.
2. Analysis of water samples collected from the current WaterAid drilling programme in Singida will not be possible. Feedback to WaterAid on the quality of water in newly drilled boreholes completed over the last few months would be a useful tool in directing the continued drilling programme in Singida area. It will also not be possible to feed back results to the World Bank in their proposed rural water supply programme in Tanzania.
3. Planned activities of project partners in Ghana and Tanzania will not be completed and momentum built up in the project to date will be lost.
4. Further dissemination of project results collected during Phase I will not be possible.

Together, these represent strong additional incentives for continuing with the second phase of the fluoride project.

9.5 PRINCIPAL OBJECTIVES AND ACTIVITIES OF PHASE II

Phase I produced significant information relevant to determining the main controls on fluoride mobilisation in groundwater in arid areas, but some notable areas remain unresolved. Principal among these are the relationships between dissolved fluoride concentration and abstraction depth, relationships to fractures and the precise sources of fluoride. Monitoring of groundwater fluoride concentrations with time has also not been tackled. As part of Phase II of the project, the main activities planned to address some of these uncertainties are outlined below.

1. Further water sampling will be carried out in selected study areas. This will principally involve field-testing of preliminary conclusions to assess their generic application. As the more widespread and extreme fluoride problems have been identified in Tanzania, efforts in Phase II will be preferentially concentrated in study areas there. Samples will be

collected in high-fluoride (granitic) and low-fluoride aquifers, with varying proximity to fault zones. There is also a need in Tanzania to clarify the role that Quaternary sediments have on dissolved fluoride concentrations. Further water sampling will ideally also be carried out in areas known to be prone to geothermal inputs.

2. Piezometers will be installed to discrete depths in selected areas to assess the fluoride-depth relationship. Since groundwater flow in the study areas investigated is fracture-dominated, piezometer depths will be defined from the configuration of local fractures and the relationships between fracture distribution and fluoride occurrence will be investigated. Although time in Phase II is short, attempts will be made to collect time-series data for fluoride concentrations in the completed piezometers, to assess seasonal variations in particular.

3. Groundwater flow and residence time could have an important impact on dissolved fluoride concentrations. More detailed investigations will be carried out on groundwater flow patterns in the selected study areas. These will make use of available (limited) hydrogeological information, together with a more detailed investigation of groundwater chemistry than was possible in the time allowed during Phase I, and stable-isotopic compositions ($\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C$) of selected groundwaters.

4. The geochemistry of selected rock and mineral samples will be investigated through chemical analysis (e.g. whole-rock, whole-mineral analysis and water-soluble fluoride concentrations).

5. Water samples collected by WaterAid during drilling and completion of new boreholes in Singida region will be analysed for fluoride and other solutes in the BGS, Wallingford laboratories. Results will be used to inform the project and will be relayed directly to WaterAid to provide guidance for the continuation of the WaterAid drilling programme in Tanzania.

6. Support will be provided for partners at the University for Development Studies in Tamale, Ghana for obtaining further groundwater samples from other areas of the country recognised from our preliminary results to be at risk from fluoride. The partners will be encouraged to make maximum use of equipment (specifically fluoride measuring equipment) provided during Phase I.

7. Further training and support will be given to the MSc student in Tanzania for the remaining duration of her MSc study. She is scheduled to complete the study in Summer 2003. Much of the remaining time will be spent completing her thesis, but it is envisaged that she will participate in further field-sampling campaigns in Tanzania during 2003.

8. Dissemination of project results will be by various media and at various technical levels. This will include end-of-project workshops in Ghana and Tanzania, involving partners, and local and regional water providers and policy makers. Research results will be published in various forms:

    - a manual outlining the best approaches for locating low-fluoride groundwater in vulnerable areas (optimal well siting and construction);
    - a publicity leaflet on fluoride in drinking water (sources, controls, distribution, health effects, testing, mitigation), prepared in consultation with a professional journalist;
    - a peer-reviewed review of the state of knowledge on fluoride in groundwaters in developing countries;
    - DFID Summary Report, other reports/scientific publications as appropriate;
    - results presented as appropriate at international conferences.

10 Reports and articles produced from the project

Smedley P. L. 2002. Minimising fluoride in drinking water in problem aquifers. Inception Report. British Geological Survey Commissioned Report CR/02/86C (confidential).

Edmunds W. M. and Smedley P. L. In press. Fluoride in natural waters: occurrence, controls and health impacts. In: *Medical Geology*. Ed: O. Selinus. Academic Press.

11 References

Apambire, B. 1996. Hydrogeological aspects of elevated fluoride levels in the Bolgatanga and Bongo Districts, Ghana. *Report for the GWSC/CIDA Community Water Project Upper Regions, Ghana*, COWAP Field Paper 13.

Apambire, W B, Boyle, D R, and Michel, F A. 1997. Geochemistry, genesis, and health implications of fluoriferous groundwaters in the upper regions of Ghana. *Environmental Geology*, Vol. 33, 13-24.

APHA. 1995. Standard Methods for the Examination of Water and Wastewater. *American Public Health Association, DC.*

Appelo, C A J, and Postma, D. 1994. *Geochemistry, Groundwater and Pollution*. (Rotterdam: A.A. Balkema.)

Ashley, P P, and Burley, M J. 1994. Controls on the occurrence of fluoride in groundwater in the Rift Valley of Ethiopia. 45-54 in *Groundwater Quality*. McCall, G J H (editor). (London: Chapman & Hall.)

Bardecki, C J. 1974. Fluoride probability in Tanzanian waters. 55 - 61 in *Maji Review Ministry of Water Development and Power. Volume 1.*

Bugaisa, S L. 1971. Significance of fluorine in Tanzania drinking water*of the Proceedings of a Conference on Rural Water Supply in East Africa*, Dar Es Salaam, 107-113.

Coe, K. 1953. Unpublished report of the Geological Survey of Ghana.

Coplen, T B, Herczeg, A L, and Barnes, C. 1999. Isotope engineering - using stable isotopes of the water molecule to solve practical problems. 79-109 in *Environmental Tracers in Subsurface Hydrology*. (Boston: Kluwer.)

Coster, F M. 1960. Undergroundwater in Tanganyika. *Dept of Water Development and Irrigation*.

Diaz-Barriga, F, Leyva, R, Quistian, J, Loyola-Rodriguez, J, A, P, and M, G. 1997. Endemic fluorosis in San Luis Potosi, Mexico. *Fluoride*, Vol. 30, 219-222.

Dincer, T. 1980. Fluoride content of the Kilimanjaro region water. in *The Use of Isotopes in Hydrology in Tanzania*. TA. Report No. 1722. (Vienna: International Atomic Energy Agency.)

Dissanayake, C B. 1991. The fluoride problem in the groundwater of Sri Lanka - environmental management and health. *International Journal of Environmental Studies*, Vol. 38, 137-156.

Edmunds, W M, and Smedley, P L. 1996. Groundwater geochemistry and health: an overview. 91-105 in *Environmental Geochemistry and Health*. McCall, G J H (editor). Geological Society Special Publication No. 113. (Geological Society of London.)

Fuhong, R, and Shuquin, J. 1988. Distribution and formation of high-fluorine groundwater in China. *Environmental Geology and Water Science*, Vol. 12, 3-10.

Gaciri, S J, and Davies, T C. 1993. The occurrence and geochemistry of fluoride in some natural waters of Kenya. *Journal of Hydrology*, Vol. 143, 395-412.

Gat, J R. 1981. Isotopic fractionation. 21 - 34 in *Stable Isotope Hydrology, Deuterium and Oxygen18 in the Water Cycle*. Technical Report Series 210. (Vienna: IAEA.)

Gat, J R, and Goanfiantini, R, (editors), 1981. *Stable isotope hydrology. Deuterium and oxygen-18 in the water cycle*. Technical Report Series 210. (Vienna: IAEA.)

Hamilton, M. 1992. Water fluoridation: a risk assessment perspective. *Journal of Environmental Health*, Vol. 54, 27-32.

Hem, J D. 1985. Study and interpretation of the chemical characteristics of natural water. USGS Water Supply Paper 2254. 2254.

Horatio-Larbie, G. 2000. Final report on COWAP (Community Water Project) 1999 borehole replacement programme. *Community Water and Sanitation Agency (CWSA/CIDA), Ghana*.

JICA. 1998. The Study on the Groundwater for Hanang, Singida Rural, Manyoni and Igunga Districts. Final Report (2).

Kilham, P, and Hecky, R E. 1973. Fluoride: geochemical and ecological significance in East African waters and sediments. *Limnology & Oceanography*, Vol. 18, 932-945.

Kloos, H, and Haimanot, R T. 1999. Distribution of fluoride and fluorosis in Ethiopia and prospects for control. *Tropical Medicine and International Health*, Vol. 4, 355-364.

Lahermo, P, Sandström, H, and Malisa, E. 1991. The occurrence and geochemistry of fluorides in natural waters in Finland and East Africa with reference to their geomedical implications. *Journal of Geochemical Exploration*, Vol. 41, 65-79.

Lahermo, P W, and Nanyaro, J T. 1981. Note on the occurrence of the fluorides in the natural waters in Tanzania with special reference to the Momella lake, Mount Meru area. in *A Report on Ground Water in Hard Rocks*. African Regional Seminar. (UNESCO.)

Mambali, S S. 1981. The necessary efforts made to map the occurrence of fluoride within the country mainland Tanzania*of the Report on the Workshop on the Domestic Water Health Standards with Special Emphasis on the Fluoride*, Arusha, Ministry of Water and Energy, 32-42.

Mambali, S S, and Kilham, P. 1982. A report on nature and distribution of fluorides in water resources in Arusha area*of the Report on the Workshop on Domestic Water Standards with Special Emphasis on Fluoride Tanzania*, Arusha, Tanzania, 45-48.

Marshall, E. 1990. The fluoride debate: one more time. *Science*, Vol. 247, 276-277.

Mjengera, H J, and Vilske, J. 1982. Efforts being made by the Ubungo Water Quality Laboratory in looking for ways of defluoridation to suit climatic economic conditions and natural resources of Tanzania*of the Report on the Workshop on Domestic Water Standards with Special Emphasis on Fluoride*, Arusha, Tanzania, 134-145.

Mjengera, J H, Mosha, H J, and Mtalo, F W. 1997. Excessive fluoride removal in potable water as a measure for fluorosis prevention in Tanzania. *Journal of Dental Research*, Vol. 76, 1152-1152.

Murray, R J. 1960. The Geology of the "Zuarungu" E Field Sheet. *Geol. Survey Ghana Bulletin No. 25*.

Nanyaro, J T, Aswathanarayana, U, and Mungure, J S. 1984. A geochemical model for the abnormal fluoride concentrations in waters in parts of northern Tanzania. *Journal of African Earth Sciences*, Vol. 2, 129-140.

Reeves, T G. 1986. Water Fluoridation. A Manual for Engineers and Technicians. *US Department of Health and Human Services Centres for Disease Control and Prevention*.

Reeves, T G. 1994. Water Fluoridation. A Manual for Water Plant Operators. *US Department of Health and Human Services Centres for Disease Control and Prevention*.

Slooff, W. 1988. Basis document fluoriden. *Bilthoven Netherlands National Institute of Public Health and Environmental Protection*, Report no. 758474005.

Smedley, P L. 2002. Minimising fluoride in drinking water in problem aquifers. *British Geological Survey*, CR/02/86C.

Smedley, P L, Edmunds, W M, West, J M, Gardner, S J, and Pelig-Ba, K B. 1995. Vulnerability of shallow groundwater quality due to natural geochemical environment. 2. Health problems related to groundwater in the Obuasi and Bolgatanga areas, Ghana. *British Geological Survey*, BGS Technical Report WC/95/43.

Smedley, P L, Nicolli, H B, Macdonald, D M J, Barros, A J, and Tullio, J O. 2002. Hydrogeochemistry of arsenic and other inorganic constituents in groundwaters from La Pampa, Argentina. *Applied Geochemistry*, Vol. 17, 259-284.

Tebbutt, T H Y. 1983. *Relationship Between Natural Water Quality and Health*. No. 47. (Paris: UNESCO.)

USEPA. 1985. Drinking water criteria document on fluoride. *USEPA Office of Drinking Water, US Environmental Protection Agency*, TR-832-51985.

WHO. 1993. *Guidelines for Drinking-Water Quality. Volume 1: Recommendations.* (Second edition). (Geneva: World Health Organisation.)

WRC. 2000. Water resources management problems identification, analysis and prioritization. *Water Research Institute, Water Resource Commission*.

Wuyi, W, Ribang L., Jian'an T., Kunli, L, Lisheng, Y, Hairong, L, and Yonghua, L. 2002. Adsorption and leaching of fluoride in soils of China. *Fluoride*, Vol. 35, 122-129.

Appendix 1 MSc student thesis plan

UNIVERSITY OF DAR ES SALAAM

1. **NAME OF CANDIDATE:** IDEVA, RADHIA J.
   B.Sc. GENERAL

2. **NAME OF SUPERVISOR:**
   1. DR. H. H. NKOTAGU (UNIVERSITY OF DAR ES SALAAM)
   2. DR. PAULINE SMEDLEY (BRITISH GEOLOGICAL SURVEY)

3. **DEPARTMENT:** GEOLOGY
   FACULTY: SCIENCE

4. **PROPOSED DEGREE:** M. Sc. ENVIRONMENTAL SCIENCE

5. **TITLE:** THE HYDROGEOCHEMISTRY OF HIGH FLUORIDE GROUNDWATER IN NORTHERN IRAMBA DISTRICT, SINGIDA REGION

1 Introduction

1.1 GENERAL INTRODUCTION

Fluoride in most groundwater occurs as the anion F^-. Sources of water with high fluoride contents are found mostly in calcium-deficient groundwater in many basement aquifers (Hem, 1985) such as granite and gneiss, in geothermal waters and in some sedimentary basins. In many developing countries high fluoride concentrations have been reported in association with rift zones, volcanic rocks and granitic (Ca-poor) basement rocks (Bugaisa, 1971; Kilham and Hecky, 1973; Nanyaro et al., 1984). High fluoride concentrations are noted in the Kenyan part of the rift valley (Gaciri and Davies, 1993) and in Uganda where incidences of dental fluorosis have been linked with concentrations of fluoride up to 3 mg L^{-1}.

Traces of fluoride are present in many water sources; higher concentrations are often associated with underground sources. In areas rich in fluoride-containing minerals, well-waters may contain up to about 10 mg L^{-1} of fluoride (Edmunds and Smedley, 1996). In groundwater, fluoride concentrations vary with the type of rock the water flows through but does not usually exceed 10 mg L^{-1} (USEPA, 1985). In some African countries where the soil is rich in fluoride-containing minerals, fluoride levels in drinking water are relatively high e.g. 8 mg L^{-1} in the United Republic of Tanzania (Mambali, 1981). The WHO guideline value for fluoride is 1.5 mg L^{-1} (WHO, 1993). Tanzania has adopted a temporary standard of 8.0 mg L^{-1} of fluoride in water to be used for domestic purposes in rural areas (Mjengera and Vilske, 1982). As defined by the final report of the Rural Water Supplies and Health Standards Committee (RWSHSC), the temporary standard will apply to rural water supplies with the exception of urban water supplies and large-scale rural water supplies. This include water supplies serving more than 5000 people, with the temporary standard of 8.0 mg L^{-1}, 95.5% of the water sources in Tanzania are acceptable for human consumption. The remaining 4.5% are unacceptable (Mjengera and Vilske, 1982).

The risk of toxic effect of fluoride rises with the concentration. Prevention of tooth decay and strengthening of skeleton occurs at fluoride concentrations of 0.8 – 1.2 mg L^{-1}. Concentrations of fluoride above 1.5 mg L^{-1} causes dental fluorosis (mottled enamel) and fluoride concentrations above about 10 mg L^{-1} results in crippling skeletal fluorosis (Mambali, 1981; Edmunds and Smedley, 1996).

According to Appelo and Postma (Appelo and Postma, 1994), the chemical composition of groundwater is the combined result of the water that enters the groundwater reservoir and the reaction with minerals present that may modify the water composition. They further noted that groundwater geochemistry has a potential of tracing the origins and the history of water.

1.2 STUDY AREA

The study will be conducted in the Northern Part of Iramba District. The District is bordered by Shinyanga and Maswa Districts to the West, Meatu District to the Northwest, Karatu to the North, Hanang District to the East and Singida Urban to the South. The reason of selecting the northern part of Iramba District is because the southern part of the District has already been surveyed by the DFID sponsored project aiming at minimising fluoride in drinking water in problem aquifers' being carried out currently as a collaboration between the British Geological Survey, University of Dar es Salaam and WaterAid. About 23 villages in the northern part of the Iramba District will be surveyed namely Iambi, Ilunda, Kinampundu, Ishenga, Kinyangiri, Singa, Nkungi, Mwanga, Kidarafa, Dominiki, Mwangeza, Nkinto, Isanzu (Matongo), Mkalama, Ibaga, Chemchem, Luono, Kidaru, Doromoni, Nsunsu, Kisana, Magula (New Kiomboi) and Lulumba (New Kiomboi) as shown in Figure A1 below.

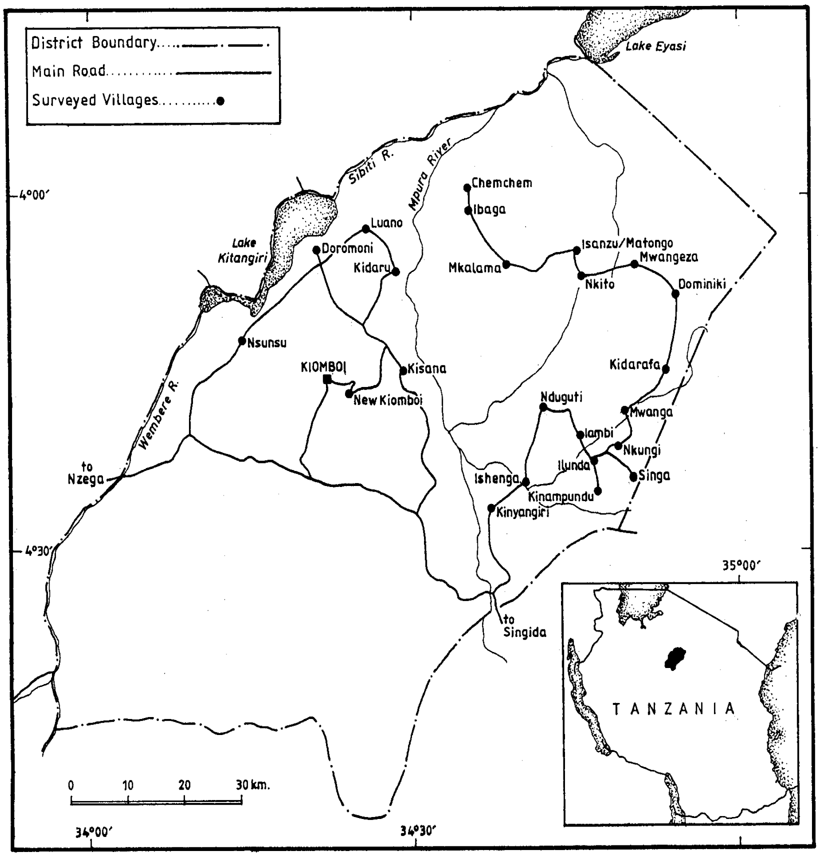

Figure A1 A map of Iramba District showing location of the villages to be surveyed (Kabuhu, 1996).

2 Statement of the research problem

Fluoride in water is common in groundwater sources as well as surface waters such as in Maji ya Chai River (Nanyaro et al., 1984). Minerals containing fluoride compounds slowly dissolve in groundwater which is then abstracted from wells. In Tanzania most of the research into fluoride concentrations in natural waters has focused in the northern part (Arusha and Kilimanjaro regions). It has been observed that the majority of the population in the northern part of Tanzania has dental fluorosis, the incidence associated with high fluoride concentration in the drinking water (Nanyaro et al., 1984). In Arusha and Kilimanjaro regions fluoride occurrence is associated with volcanic rocks. Most of the people living in Singida Region particularly Iramba District have dental fluorosis, although the rocks through which groundwater passes are different from those of northern Tanzania. Besides, there is no research or any documented information explaining the problem and the source of fluoride in the area. Therefore, this research intends to investigate the presence of fluoride and its origin in the groundwater in Iramba District, which have different geological and climatic nature from that of northern Tanzania. The research findings will shed light in efforts to solving this problem.

3 Objectives

The main objectives of the project are:

- to establish factors that bring about the chemical character of high fluoride groundwater in the study area;
- to explain the nature of groundwater flow system in the study area;
- to show how depth of boreholes is related to the fluoride concentrations in the groundwater in the study area.

4 Significance of the study

The research findings will contribute to:

- providing information about water quality and groundwater recharge mechanism of the northern Iramba District;
- providing information about the origin of fluoride in groundwater of Northern Iramba District;
- providing information to the water authorities about the distribution of fluoride, to enable them to locate the best sites for drilling wells and boreholes or look for a water treatment method.

5 Literature review

5.1 FLUORIDE IN GROUNDWATER

In many parts of the world, natural waters contain abnormal abundances of fluoride. Tropical and subtropical climates with seasonal rains favour weathering of rocks and soils releasing fluoride into waters, while high evaporation increases the F concentrations in solutions during dry seasons (Lahermo et al., 1991). It has been observed that natural waters in parts of northern Tanzania have abnormal high fluoride concentration with a marked enrichment taking place due to evaporation. A geochemical model proposed by Lahermo et al. (1991) supposes a steady influx of fluoride into the surface and groundwaters from sources such as leaching of the carbonitites and nephelinites (with F^- concentrations up to 0.49%). However, a report by JICA (1998) about studies conducted in the Igunga, Hanang and Singida Rural districts concluded that climate is a major factor in controlling the concentration of fluoride in groundwater. Numerous unpublished reports by Maji, the then Ministry of Water Energy and Minerals observed high concentrations of fluoride in various water sources throughout the country. The reports show that water sources from central and northern Tanzania can have high concentrations of fluoride which may exceed the WHO guideline value of 1.5 mg L^{-1}.

Fluoride concentrations in the groundwater of some villages in China are greater than 8 mg L^{-1} (Fuhong and Shuquin, 1988). In Canada, fluoride levels in drinking water of <0.05–0.2 mg L^{-1} (non-fluoridated) and 0.6–1.1 mg L^{-1} (fluoridated) have been reported in municipal waters; in drinking water prepared from well water, levels up to 3.3 mg L^{-1} have been reported. In the USA, 0.2% of the population is exposed to more than 2.0 mg L^{-1} of fluoride in drinking water (USEPA, 1985). In the Netherlands, annual averages for all drinking-water plants are below 0.2 mg L^{-1} (Slooff, 1988).

Nanyaro et al. (1984) reported that natural waters in parts of northern Tanzania are characterised by exceptionally high fluoride content in some rivers (12–36 mg L^{-1}), springs (15–63 mg L^{-1}) and alkaline ponds and lakes (60–690 mg L^{-1}). In lowland rivers, most of the fluoride is derived from weathering of F-rich nephelinitic and carbonatitic rocks and soils whereas in the rivers draining from mount Meru crater gaseous emanations through mineral springs may also contribute to the concentrations. According to Nanyaro et al. (1984) and Lahermo and Nanyaro (1981), the leaching of fluoride-rich sodium bicarbonate (trona, magadi) from the surface and top soil at the outset of the rainy season, affects the F concentrations in shallow groundwater and in surface water bodies as observed in the Momella lakes. Nanyaro et al. (1984) have observed that the solubility of villiaumite (NaF) which is known to occur in the vesicles in volcanic rocks is very high.

Also the volcanic rocks of the East African rift zones are known to be richer in fluoride than elsewhere (Nanyaro et al., 1984). According to Mambali (1981) and Bardecki (1974), the recommended water-quality standard for Tanzania of 8 mg L^{-1} far exceeds the recommended WHO value of 1.5 mg L^{-1}, and would render most water sources in Arusha, Kilimanjaro, Shinyanga, Singida and Mwanza unsuitable for human consumption. Fluorosis has been noted by many workers in northern Tanzania (e.g. Mjengera et al., 1997). However, Coster (1960) noted that the higher concentration of fluoride does not have harmful effects on human beings. The conclusion was drawn from an observation of an Old Dutch settlement in Oldonyo Sambu in the northern Arusha region, who used groundwater containing fluoride of 10–14 mg L^{-1} for several generations without any harmful consequences. Studies by Lahermo and Nanyaro (1981) have shown that fluoride-rich water draining the eastern and south-eastern slopes of mount Meru and flowing through the Maji ya Chai and Engare Nanyuki rivers are related to the volcanism that gave rise to the formation of Mount Meru.

5.2 FLUORIDE OCCURRENCE AND GEOCHEMISTRY

Fluorine is the lightest member of the halogen group and is one of the most reactive of all chemical elements (Lahermo et al., 1991). It is not therefore, found as fluorine in the environment. It is the most electronegative of all the elements (Hem, 1985), which means that it has a strong tendency to acquire a negative charge, and in solution forms F^- ions. Other oxidation states are not found in natural systems, although uncharged complexes may be. Fluoride ions have the same charge and nearly the same radius as hydroxide ions and may replace each other in mineral structures (Hem, 1985).

The average crustal abundance of fluoride is 300 mg kg^{-1} (Tebbutt, 1983). Fluoride is found at significant levels in a wide variety of minerals, including fluorite, rock phosphate, cryolite, apatite, mica, hornblende and others. Fluorite (CaF_2) is a relatively common mineral occurring in both igneous and sedimentary rocks. Fluoride is commonly associated with volcanic activity, fumarolic gases and thermal waters, especially those of high pH (Edmunds and Smedley, 1996). Cryolite and rock phosphates are of commercial importance. The fluoride salt cryolite is used for the production of aluminium and as a pesticide. Rock phosphates are converted into phosphate fertilisers by the removal of up to 4.2% fluoride; the removed fluoride (as fluorosilicates) is frequently used to fluoridate drinking water (Reeves, 1986, 1994). In rocks, fluorine occurs mainly in silicate and fluoride minerals. It is generally concentrated in late stages of crystallizing magmas and in the residual solutions and vapours. Fluorine occurs in several minerals (Bardecki, 1974) as indicated below:

Fluorite (CaF_2) contains fluorine as major component.

Apatite – $Ca_{10}(PO_4)_6$ – contains about 13,500–26,000 mg kg^{-1} of fluorine. Apatite is a raw material for phosphate fertilizer.

Topaz – $Al_2Fe_2SiO_4$, contains about a fluorine concentration of around 21%.

Some micas may reach a concentration level of 68,000 mg kg^{-1} fluorine.

In soils, fluoride depends on the initial concentration in the parent rock from which the soil is derived. Soils are formed as a consequence of rock weathering due to its interaction with air, water and organisms. Therefore, when rocks with minerals bearing fluoride weather, they could result in the production of highly fluoridic soils (Mambali, 1981).

In natural water, the fluoride content of both surface and groundwater depends on a variety of factors, including availability and solubility of the parent fluoride minerals with which the water interacts. Other factors include the porosity of the rocks or soils through which the water passes, their hydraulic conductivity (K), the temperature of interaction between rocks and water, the hydrogen ion concentration of the water i.e. pH and the concentration of calcium in the water (Mambali, 1981).

According to Appelo and Postma (1994), the chemical composition of groundwater is the combined result of the water that enters the groundwater reservoir and the reaction with minerals present that may modify the water composition. They further noted that investigating groundwater geochemistry has potential for tracing the origins and history of water. According to Mambali and Kilham, (Mambali and Kilham, 1982), the variation in the fluoride content of water among the region in northern Tanzania is attributable principally to the concentration and mode of occurrence of fluorine in rocks of the region with which, water has interacted, as well as to the flow pattern and residence time of water in the soil and aquifer.

6 Hydrogeochemistry of fluoride and stable isotopes

Bardecki (1974) pointed out that the evolution of fluoride-rich natural water results from leaching of chemically weathered fluoride-bearing minerals in rocks and soils. In general, the leachability of the elements in rocks depends on the strength of the bonding forces. The more the element is tied up in the silicate lattices, the less available it is for weathering. However, when associated with hydrothermal sulphides or when present in the intergranular films, it becomes more readily leachable. He also notes that the concentration of natural water depends on the residence time of the ion in that medium, which is mainly controlled by hydrogeology.

Dincer (1980) observed that the characteristic of groundwater has been the most successful areas of application of natural stable-isotope abundance and variations. This to a large extent, is due to the conservative nature of the stable isotope composition of water in an aquifer. As a result of which it is possible to characterise the origin of water unambiguously from the isotopic composition of groundwater over rather a long period, of the order of thousands of years, provided they are not exposed to temperatures above 60–80ºC (Gat and Goanfiantini, 1981). Change in isotopic composition is mainly the result of the recharge process. Possibilities for tracing the origin of groundwater depend on the distinctive composition of surface water (primarily lakes and reservoirs), which is enriched with heavy isotopes as a result of evaporation (Dincer, 1980). For any quantitative application of stable isotopes as a geohydrological tool, it is necessary to establish how well the isotopic composition of a groundwater source is defined in a supposedly homogeneous geographic setting. Both space and time are considered (Gat and Goanfiantini, 1981). Isotopic composition within aquifers varies not only from place to place but also as a function of depth, in a particular unconfined condition (Gat, 1981). The mean stable-isotope composition of samples from drilled wells was more depleted than that of shallower groundwater wells containing mixtures of river-groundwater and groundwater exhibit isotope concentrations that are on a mixing line for the two end members defined by river-groundwater and old groundwater (Gat and Goanfiantini, 1981). Stable isotope ratios of hydrogen and oxygen ($^{2}H/^{1}H$ and $^{18}O/^{16}O$) are used to address problems related to groundwater as a sustainable resource, and in particular to recharge, delineation of flow systems in groundwater (Coplen et al., 1999).

Hypotheses:

The study is founded on two main hypotheses. These are:

- that the chemical character of groundwater in the study area is naturally controlled, and;

- that fluoride and related trace ion concentrations in groundwater increase with depth in the study area.

7 Materials and methods

7.1 EXISTING DATA COMPILATION

The following data will be collected from the Ministry of Water and Livestock Development in Dodoma and Sustainable Environment Management Agency (SEMA) Offices in Singida, Maji Regional Office Singida, and Maji District offices in Iramba. Data will include those related to surface and groundwater quality, hydrogeological data for establishment of the sources of water, Iramba District map showing the villages, geological and topographical maps. Borehole data will also be used to obtain the depth of boreholes.

7.2 FIELD WORK

7.2.1 Sample collection

A random sampling technique will be adopted in this study. Water samples will be collected from both surface and subsurface reservoirs (including streams, borehole wells and dugouts). Six sub-samples will be collected in each sampling site. Two sub-samples will be collected in 30 ml polyethylene bottles and then acidified, one with HCl and another one with HNO_3. One sub-sample will be collected in 60 ml polyethylene bottles and remain unacidified. 40 ml glass bottles will be used for taking water samples for fluoride analysis. 20 ml glass bottles will be used for taking water samples for $^{18}O/^{2}H$ isotopes and another 60 ml glass bottle for taking a water sample for ^{13}C. Alkalinity, pH and electrical conductivity measurements will be taken in situ. Samples will be stored in a cool box during the fieldwork and after they will be stored in the refrigerator at the Department of Geology before sending them to the British Geological Survey, for laboratory analysis.

7.2.2 Laboratory methods

Chemical analyses of water will be conducted at the British Geological Survey laboratories , in the UK. Major ions and trace elements including Ca^{2+}, Na^{+}, K^{+}, Fe^{2+}, Mg^{2+}, SO_4^{2-}, Cu^{2+}, Mn^{2+} and Zn^{2+} will be determined by ICP-AES. Cl^{-}, I^{-} and NO_3^{-} will be determined by automated colorimetry, Br^{-} by ion chromatography and HCO_3^{-} ions by a titrimetric method (APHA, 1995). Preliminary analyses for fluoride will be conducted at the Department of Geology, University of Dar es Salaam using an Orion fluoride electrode supplied by the project.

Analyses for ^{18}O, ^{2}H, ^{13}C and will be performed at the British Geological Survey, UK and will be measured by mass spectrometry.

8 Data analysis and presentation

Standard statistical methods will be used, such as the sub-programs of the Statistical Package for Social Sciences (SPSS), version 10.0, to establish the factors/processes that influence the distribution and concentration levels of fluoride in the groundwater in the study area. Correlation, cluster, principal component, and factor analysis will be used during multivariate statistical analysis.

Hypothesis I: Multivariate statistical analysis will be used to test and explain the factors that control the occurrence and distribution of fluoride and related trace ions in groundwater in the study area. A regional fluoride map, hydrogeological information, stiff and piper diagrams along with the distribution of the stable-isotope data will be used to test the nature of high fluoride groundwater flow system in the Northern Iramba District.

Hypothesis II: Simple XY plots and correlations will be used to show how the fluoride and related trace-ion concentrations in groundwater vary with well depth.

9 Other relevant information

9.1 SPONSORSHIP

This study is sponsored by Deutscher Akademischer Austauschdienst e.V. (DAAD) and the research work is partially supported by the DFID sponsored project 'Minimising fluoride in drinking water in problem aquifers' being carried out currently as a collaboration between the British Geological Survey, University of Dar Es Salaam and WaterAid.

9.2 MSc TIMETABLE

	2002				**2003**							
Month	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**
Literature survey, proposal write-up and presentation												
Fieldwork												
Laboratory work												
Data analysis and dissertation writing												
Dissertation submission for examination												

Appendix 2 Water-quality data for samples from Bolgatanga area, northern Ghana

Number	Date	Village	Latitude deg N	Longitude deg W	Geology	Temp ºC	DO mg L^{-1}	SEC µS cm^{-1}	pH
Reservoir									
S02-00346	05-Feb-02	Vea Reservoir	10.8641	-0.8429	Granite	26.8	2.7	111	8.29
Boreholes									
S93-02947	18-Oct-93	Gowrie	10.8678	-0.8478	Granite	31.1	3.6	366	6.70
S93-02948	18-Oct-93	Yorogu Abagabisi	10.8564	-0.8303	Granite	29.2	0.1	257	6.78
S93-02949	18-Oct-93	Yorogu Abagabisi	10.8678	-0.8264	Granite	31.2	1.2	336	6.63
S93-02951	19-Oct-93	Sekoti	10.8103	-0.6408	Sekoti Granodiorite	31.1	0.6	356	6.88
S93-02954	19-Oct-93	Bolga Soe	10.8219	-0.8508	Granite	29.3	0.5	269	6.57
S93-02955	20-Oct-93	Yorogu	10.8369	-0.84	Granite	30.6	1.9	391	7.18
S93-02957	20-Oct-93	Bongo Nabisi	10.8986	-0.8222	Granite	30.9	1.3	343	6.70
S93-02958	20-Oct-93	Bongo Anabisi	10.9106	-0.8083	Granite	30.3	3.2	432	6.58
S93-02959	20-Oct-93	Bongo Centre	10.9181	-0.8133	Birimian granodior etc	30.8	0.9	666	6.59
S93-02960	20-Oct-93	Bongo Anafobisi	10.9217	-0.8106	Birimian granodior etc	29	2	390	6.95
S93-02961	20-Oct-93	Borogo	10.9031	-0.7911	Birimian Greenstone	30.6	3.8	385	6.66
S93-02962	20-Oct-93	Yichene	10.8897	-0.7992	Granite	30.3	2	315	6.45
S93-02963	21-Oct-93	Yorogo Abangabisi	10.8761	-0.8122	Granite	31.2	1.2	424	6.83
S93-02964	21-Oct-93	Yorogo Abangabisi	10.8597	-0.8261	Granite	31.2	-0.1	633	6.78
S93-02965	21-Oct-93	Amenteyoko	10.9181	-0.7942	Birimian Greenstone	31.4	1.5	1160	7.01
S93-02966	21-Oct-93	Apatanga	10.9172	-0.7667	Birimian Greenstone	31.3	-0.1	660	6.65
S93-02967	21-Oct-93	Adaboya	10.9075	-0.7333	Birimian granodior etc	30.1	0.1	661	6.55
S93-02968	21-Oct-93	Sapero	10.8811	-0.7403	Birimian granodior etc	30.5	2.7	726	6.71
S93-02969	21-Oct-93	Beo	10.8703	-0.7542	Birimian granodior etc	31.1	2.3	531	6.35
S93-02970	21-Oct-93	Kumbusgu	10.8664	-0.7386	Birimian granodior etc	31	3.4	448	6.55
S93-02971	22-Oct-93	Kumbusigo Angl. Sch	10.8008	-0.8131	Birimian granodior etc	31.3	1.3	502	6.88
S93-02972	22-Oct-93	Kumbusigo	10.8028	-0.8203	Birimian granodior etc	31.1	0.1	454	6.67
S93-02973	22-Oct-93	Kumbusigo	10.7997	-0.8222	Birimian granodior etc	30.8		543	6.87
S93-02974	22-Oct-93	Zuarungu Katanga	10.8194	-0.8022	Birimian granodior etc	30.7	2.5	625	6.59
S93-02975	22-Oct-93	Zuarungu	10.8094	-0.7881	Birimian granodior etc	31	-0.1	715	6.72
S93-02976	22-Oct-93	Zuarungu Benkote	10.8075	-0.7847	Birimian granodior etc	30.8	0.1	623	6.72
S93-02977	22-Oct-93	Asonge	10.8247	-0.7536	Birimian granodior etc	31.4	0.1	530	6.81
S93-02979	23-Oct-93	Zuarungu Moshie	10.8483	-0.7486	Birimian granodior etc	30.2	0.8	630	6.70
S93-02980	23-Oct-93	Kongo	10.8533	-0.7222	Birimian granodior etc	31.2	0.4	928	6.67
S93-02981	23-Oct-93	Kongo	10.8464	-0.7097	Birimian Greenstone	30.9	0.7	517	7.03
S93-02982	23-Oct-93	Zoa	10.8544	-0.6908	Birimian	30.9	-0.1	654	6.89

Number	Date	Village	Latitude deg N	Longitude deg W	Geology	Temp ºC	DO mg L^{-1}	SEC µS cm^{-1}	pH
					Greenstone				
S93-02983	23-Oct-93	Nangodi Yakoti	10.8444	-0.6867	Birimian Greenstone	30.7	0.4	948	6.90
S93-02984	23-Oct-93	Damulugu	10.8192	-0.7022	Birimian Greenstone	30.8	0.3	464	6.50
S93-02985	23-Oct-93	Pelungu	10.8075	-0.7	Birimian Greenstone	30.7	1.9	708	6.82
S93-02986	23-Oct-93	Zanlerigu	10.8042	-0.7317	Birimian Greenstone	31	0.9	692	6.88
S93-02987	23-Oct-93	Daliga Zanlerigu	10.8089	-0.7386	Birimian Greenstone	31.7	1.3	792	6.76
S93-02988	25-Oct-93	Nangodi Nakpaligo	10.8525	-0.6711	Birimian Greenstone	30.4	<0.1	861	6.98
S93-02989	25-Oct-93	Nangodi	10.8528	-0.6733	Birimian Greenstone	30.9	1	878	7.07
S93-02990	25-Oct-93	Nangodi Clinic	10.87	-0.67	Birimian Greenstone	30.9	1	921	7.16
S93-02991	25-Oct-93	Nangodi Nyobota	10.8319	-0.6378	Birimian Greenstone	30.5	0.8	886	7.02
S93-02992	25-Oct-93	Sekoti Kotentabiga	10.8236	-0.6556	Birimian Greenstone	31.4	0.9	644	6.57
S93-02993	25-Oct-93	Sekoti Kotendabiga	10.8225	-0.6544	Birimian Greenstone	31.2	0.7	771	6.99
S93-02994	25-Oct-93	Sekoti	10.8	-0.6231	Sekoti Granodiorite	30	4.1	546	7.11
S93-02995	25-Oct-93	Sekoti Clinic	10.7975	-0.6342	Sekoti Granodiorite	30.8	0.9	663	6.65
S93-02996	26-Oct-93	Sekoti	10.78	-0.6386	Sekoti Granodiorite	30.1	0.4	624	6.82
S93-02997	26-Oct-93	Nyua	10.7697	-0.6228	Sekoti Granodiorite	30.9	0.9	661	6.74
S93-02999	26-Oct-93	Datoko Kulpeliga	10.7517	-0.6419	Sekoti Granodiorite	30.8	2.8	555	6.69
S93-03000	26-Oct-93	Datoko Kulpeliga	10.7408	-0.6425	Sekoti Granodiorite	31	3.1	520	6.69
S93-03001	26-Oct-93	Datoko	10.7239	-0.6586	Birimian Greenstone	30.6	<0.1	942	7.25
S93-03002	26-Oct-93	Shiega	10.7322	-0.7247	Birimian Greenstone	30.7	0.5	575	6.85
S93-03003	26-Oct-93	Shiega Tindongo	10.7428	-0.7239	Birimian Greenstone	31.1	0.7	453	7.04
S93-03004	27-Oct-93	Nangodi Takoti	10.8411	-0.6842	Birimian Greenstone	31.5	0.3	929	6.82
S93-03005	27-Oct-93	Pelungu	10.7847	-0.6964	Birimian granodior etc	31.1	2.6	598	6.77
S93-03006	27-Oct-93	Dusi	10.7875	-0.7	Birimian granodior etc	31	2.4	517	6.64
S93-03007	27-Oct-93	Dusi Gari	10.7578	-0.7039	Birimian Greenstone	30.2	0.6	675	7.07
S93-03008	27-Oct-93	Gari	10.7625	-0.7139	Birimian Greenstone	30	0.7	614	7.08
S93-03009	27-Oct-93	Shiega Tindongo	10.7481	-0.7289	Birimian Greenstone	30.2	0.8	814	6.95
S93-03010	27-Oct-93	Yameriga	10.7214	-0.7681	Birimian Greenstone	30.5	0.1	677	6.93
S93-03011	27-Oct-93	Gbanbiega	10.7178	-0.7906	Birimian Greenstone	31	0.2	728	6.78
S93-03012	27-Oct-93	Tongo	10.7144	-0.8092	Birimian granodior etc	31.4	2.8	568	6.51
S93-03013	28-Oct-93	Zuarungu	10.7892	-0.7881	Birimian granodior etc	30.5	0.4	335	6.58

Number	Date	Village	Latitude deg N	Longitude deg W	Geology	Temp ºC	DO mg L^{-1}	SEC µS cm^{-1}	pH
S93-03014	28-Oct-93	Zuarungu Zono	10.7878	-0.7806	Birimian granodior etc	31	1.0	295	6.69
S93-03015	28-Oct-93	Yazore Sakwati	10.7769	-0.7686	Birimian Greenstone	31.7	1.5	379	6.74
S93-03016	28-Oct-93	Yazore Kpatia	10.7719	-0.7528	Birimian Greenstone	30.7	0.3	662	6.95
S93-03017	28-Oct-93	Zuarungu Kangoo	10.8067	-0.7794	Birimian granodior etc	30.2	3.3	209	6.17
S93-03018	28-Oct-93	Dulugu	10.7833	-0.8206	Birimian granodior etc	31.1	0.3	408	6.58
S93-03019	28-Oct-93	Dulugu	10.76	-0.8281	Birimian granodior etc	31.2	1.7	348	6.52
S93-03020	28-Oct-93	Gambibigo	10.7686	-0.8364	Birimian granodior etc	30.7	0.8	441	6.79
S93-03021	29-Oct-93	Gambibigo	10.7567	-0.8514	Birimian granodior etc	30	4.3	286	6.53
S93-03022	29-Oct-93	Gambibigo	10.7506	-0.8583	Birimian granodior etc	30.7	3.0	321	6.52
S93-03023	29-Oct-93	Dulugu	10.7897	-0.8236	Birimian granodior etc	31.2	0.2	476	6.7
S93-03024	29-Oct-93	Tongo Beo	10.7853	-0.8028	Birimian granodior etc	30.2	1.8	357	6.7
S93-03025	29-Oct-93	Zuarungu	10.7719	-0.7942	Birimian granodior etc	30.3	3.4	323	6.72
S93-03026	29-Oct-93	Beo	10.7733	-0.8011	Birimian granodior etc	30.7	0.6	355	6.85
S93-03027	29-Oct-93	Beo	10.7603	-0.8022	Birimian granodior etc	30.7	1.4	386	6.8
S93-03028	29-Oct-93	Baare	10.7447	-0.8042	Birimian granodior etc	30	0.8	371	6.73
S93-03029	29-Oct-93	Baare Tongo	10.7358	-0.8075	Birimian granodior etc	30.4	1.1	403	6.92
S93-03030	29-Oct-93	Baare	10.74	-0.8414	Birimian granodior etc	31.2	<0.1	341	6.83
S93-03031	30-Oct-93	Tongo Local Council	10.7225	-0.8003	Birimian granodior etc	30.5	1.2	0	6.86
S93-03032	30-Oct-93	Tongo	10.7261	-0.8114	Birimian granodior etc	30.5	1.1	264	6.47
S93-03033	30-Oct-93	Gorogu	10.71	-0.8406	Birimian granodior etc	30.1	1.3	341	6.96
S93-03034	30-Oct-93	Winkogo Alabisi	10.7194	-0.8592	Birimian granodior etc	30.3	1.9	394	6.55
S93-03035	30-Oct-93	Winkogo	10.7206	-0.8761	Birimian granodior etc	31.2	2.7	475	6.56
S93-03036	30-Oct-93	Awaradoni	10.7175	-0.8717	Birimian granodior etc	31.5	1.2	437	6.54
S93-03037	30-Oct-93	Abokrebisi	10.7342	-0.8567	Birimian granodior etc	30.9	2.4	422	6.75
S93-03038	30-Oct-93	Abokrebisi	10.7356	-0.8672	Birimian granodior etc	31.2	1.1	537	6.53
S93-03039	30-Oct-93	Gambibigo	10.7589	-0.8692	Birimian granodior etc	31.1	0.1	282	6.42
S93-03040	30-Oct-93	Tindonmulugu	10.7692	-0.8661	Birimian Greenstone	30.7	0.2	416	6.54
S93-03041	01-Nov-93	Bolgatanga	10.7769	-0.8614	Granite	30.9	3.4	482	6.55
S93-03042	01-Nov-93	Tindonmulugu	10.7889	-0.8756	Granite	31.2	1.6	263	6.69
S93-03043	01-Nov-93	Sokabisi	10.7942	-0.8919	Birimian granodior etc	31.2	5.2	153	6.08
S93-03044	01-Nov-93	Tanzui Sokabisi	10.8017	-0.8747	Granite	30.7	3.2	224	6.37
S93-03045	01-Nov-93	Yikene	10.8072	-0.8847	Birimian granodior etc	30.9	3.2	224	6.65

Number	Date	Village	Latitude deg N	Longitude deg W	Geology	Temp ºC	DO mg L^{-1}	SEC µS cm^{-1}	pH
S93-03046	01-Nov-93	Sokanisi	10.8031	-0.8739	Granite	31.1	3.5	519	6.43
S93-03047	01-Nov-93	Zaare	10.8278	-0.8733	Birimian granodior etc	30.9	2.8	469	6.82
S93-03049	02-Nov-93	Gowrie	10.8533	-0.8558	Granite	31.4	4.9	307	6.3
S93-03050	02-Nov-93	Veagunga	10.8867	-0.8789	Granite	30.3	4.7	360	6.6
S93-03051	02-Nov-93	Veaakubrebisi	10.8872	-0.8658	Granite	30.2	0.4	500	6.72
S93-03052	02-Nov-93	Bongo Kunkoa	10.7219	-0.8369	Birimian granodior etc	30.5	1.2	405	6.51
S93-03053	02-Nov-93	Bongo Kupelingo	10.9078	-0.8172	Granite	30.2	2.6	484	6.68
S93-03054	02-Nov-93	Dua	10.8942	-0.7842	Birimian Greenstone	30.1	<0.1	1080	6.64
S93-03055	02-Nov-93	Dua	10.8928	-0.7769	Birimian Greenstone	31	2.2	458	6.58
S93-03056	02-Nov-93	Akanaba	10.9125	-0.7564	Birimian granodior etc	31.1	1.6	1020	6.86
S93-03057	03-Nov-93	Zaare Ayoribisi	10.8222	-0.8708	Birimian granodior etc	29.9	2.0	434	6.7
S93-03058	03-Nov-93	Zaare Avombisi	10.8217	-0.8556	Granite	31	3.3	375	6.36
S93-03059	03-Nov-93	Yorogo Sorobisi	10.8389	-0.8522	Granite	30.9	3.8	313	6.47
S93-03060	03-Nov-93	Bolga Soe	10.8103	-0.8542	Granite	31	3.8	441	6.48
S93-03061	03-Nov-93	Bolga Soe	10.8042	-0.8447	Granite	31.2	1.3	1010	7.11
S93-03062	03-Nov-93	Yorogo	10.825	-0.8386	Granite	30.1	0.2	571	6.74
S93-03063	03-Nov-93	Yorogo	10.8389	-0.8258	Granite	30.5	<0.1	663	6.73
S93-03064	03-Nov-93	Yorogo Abangabisi	10.855	-0.8242	Granite	31	0.2	590	6.58
S02-00321	02-Feb-02	Pusu Namogo	10.6828	-0.8607	Birimian granodior etc	29.4	6.3	355	7.11
S02-00322	02-Feb-02	Pusu Namogo	10.673	-0.8668	Birimian granodior etc	31.9	1.4	310	6.7
S02-00323	02-Feb-02	Balungu Alangbisi	10.6429	-0.863	Birimian Greenstone	31.8	2.0	340	7.19
S02-00324	02-Feb-02	Balungu Abiembisi	10.6428	-0.8793	Birimian granodior etc	31.7	1.1	324	6.8
S02-00325	02-Feb-02	Shia	10.673	-0.8383	Birimian granodior etc	31.6	0.3	459	7.03
S02-00326	02-Feb-02	Sipare	10.6849	-0.8321	Birimian granodior etc	31.4		344	6.74
S02-00328	02-Feb-02	Gorogo	10.7066	-0.8329	Birimian granodior etc	31.2	1	388	6.75
S02-00329	03-Feb-02	Wakii	10.6957	-0.806	Birimian granodior etc	31	3.2	312	6.77
S02-00332	03-Feb-02	Tongo Zou	10.7106	-0.7877	Birimian Greenstone	31.1	0.5	441	6.7
S02-00335	03-Feb-02	Shega	10.7239	-0.7253	Birimian Greenstone	30.6	3.3	412	6.97
S02-00337	04-Feb-02	Tarongo	10.8983	-0.8842	Granite	31	1.4	338	6.5
S02-00338	04-Feb-02	Zokko Atiabisi	10.9096	-0.8862	Granite	31.6	3.5	303	6.4
S02-00340	04-Feb-02	Zokko Market	10.9074	-0.9014	Granite	31.7	2.7	407	6.85
S02-00341	05-Feb-02	Sambolgo	10.9592	-0.8589	Granite	30.6	4.6	155	5.93
S02-00342	05-Feb-02	Balungu Dune	10.9358	-0.8711	Granite	30.9	2.3	380	6.5
S02-00343	05-Feb-02	Zoko Kadare	10.9368	-0.8817	Granite	31.1	0.4	448	6.75
S02-00344	05-Feb-02	Zoko Kodorogo	10.9216	-0.9099	Granite	30.5	2.0	403	6.65
S02-00345	05-Feb-02	Zokko Kodorogo	10.9317	-0.9166	Birimian granodior etc	31.5		425	6.45
S02-00347	06-Feb-02	Sumbrungu Kolgo	10.8467	-0.9275	Birimian granodior etc	31.4	1.8	265	6.38
S02-00348	06-Feb-02	Ayone	10.8753	-0.8973	Birimian granodior etc	31.5	2.1	330	6.65
S02-00349	06-Feb-02	Sumbrungu Kulbia	10.8134	-0.8389	Granite	31.2	0.5	304	6.65
S02-00350	07-Feb-02	Bolga Sokabisi	10.7896	-0.8815	Granite	30.4	3.5	180	6.13
S02-00351	07-Feb-02	Sirigu Durungu	10.7733	-0.8899	Birimian Greenstone	31	2.1	247	6.56

Number	Date	Village	Latitude deg N	Longitude deg W	Geology	Temp ºC	DO mg L^{-1}	SEC µS cm^{-1}	pH
S02-00352	07-Feb-02	Sirigu Nayiri	10.7668	-0.9119	Birimian granodior etc	31	1.9	374	6.64
S02-00353	07-Feb-02	Bolga Tindamolgo	10.7798	-0.8706	Granite	31.6	0.7	270	6.68
S02-00354	07-Feb-02	Bolga Tindansologo	10.7649	-0.8721	Birimian Greenstone	31	1.1	523	6.9
S02-00355	07-Feb-02	Kalbeo	10.7566	-0.8823	Birimian Greenstone	30.9	0.3	541	6.94
S02-00356	08-Feb-02	Lungu	10.8897	-0.8419	Granite	28.8	3.6	420	6.97
S02-00357	08-Feb-02	Boko	10.9781	-0.838	Birimian granodior etc	30.9	3.3	527	6.84
S02-00358	08-Feb-02	Feo Nabisi	10.9887	-0.8186	Birimian granodior etc	31.1	1.5	315	6.67
S02-00359	08-Feb-02	Feo Abagbisi	10.9881	-0.8071	Birimian granodior etc	30	0.7	174	6.29
S02-00360	08-Feb-02	Feo Ayelbia	10.9921	-0.7594	Birimian granodior etc	31.4	2.8	204	6.36
S02-00362	08-Feb-02	Kanseringa	10.9462	-0.7501	Birimian granodior etc	31.6	1.0	651	7.02
S02-00363	11-Feb-02	Sapaligo	10.8424	-0.5282	Birimian granodior etc	30.8	3.5	134	6.29
S02-00364	11-Feb-02	Tilli	10.8824	-0.56	Birimian granodior etc	31	2.1	382	6.57
S02-00365	11-Feb-02	Widnaba	10.9696	-0.5678	Birimian Greenstone	31.3	3.5	360	6.78
S02-00366	12-Feb-02	Abenpengo Tankigi	10.8307	-0.9957	Birimian granodior etc	31.3	3.8	228	6.24
S02-00367	12-Feb-02	Azasi	10.879	-0.9872	Birimian granodior etc	32	1.0	580	6.85
S02-00368	12-Feb-02	Kandiga	10.9072	-0.9696	Birimian granodior etc	32.9	0.2	479	6.78
S02-00369	12-Feb-02	Serigu	10.9579	-0.9401	Birimian Greenstone	32.4	0.5	347	7.21
S02-00370	12-Feb-02	Mayoro	10.9819	-0.985	Birimian granodior etc	31.2	0.3	502	7.36
S02-00371	12-Feb-02	Navio	10.9648	-1.0492	Birimian granodior etc	31.2	3.0	485	6.81
S02-00372	12-Feb-02	Paga	10.9886	-1.1079	Birimian granodior etc	31.2	4.4	484	6.69
S02-00373	12-Feb-02	Paga Kakungu	10.9602	-1.0992	Birimian granodior etc	31.3	0.6	417	6.87
S02-00375	13-Feb-02	Saboro	10.9146	-1.0896	Birimian Greenstone	31.1	1.1	413	6.83
S02-00376	13-Feb-02	Navrongo	10.8655	-1.0762	Birimian Greenstone	31.1	1.0	524	6.79
S02-00378	13-Feb-02	Kologo Tindaango	10.7399	-1.0781	Birimian granodior etc	31.5	0.5	311	6.56
S02-00379	13-Feb-02	Naga Nayire	10.6015	-1.0272	Birimian granodior etc	31.5	3.3	340	6.71
S02-00380	13-Feb-02	Navrongo	10.868	-1.0743	Birimian Greenstone	32.2	1.9	453	7.22
S02-00381	13-Feb-02	Chuchuliga	10.8183	-1.1818	Birimian granodior etc	31.9	0.1	505	6.92
S02-00382	13-Feb-02	Sandema	10.7481	-1.2676	Birimian granodior etc	32		348	6.73
S02-00383	13-Feb-02	Chianna Kalivio	10.8423	-1.2442	Birimian granodior etc	30.9	0.2	575	7.1
S02-00384	14-Feb-02	Adaboya	10.8995	-0.7338	Birimian granodior etc	30.1		365	6.47
S02-00385	14-Feb-02	Adaboya	10.8942	-0.7233	Birimian granodior etc	31	1.7	204	6.06
S02-00386	14-Feb-02	Adaboya Nayire	10.8971	-0.7441	Birimian	30.6	2.0	490	6.59

Number	Date	Village	Latitude deg N	Longitude deg W	Geology	Temp ºC	DO mg L^{-1}	SEC µS cm^{-1}	pH
					Greenstone				
Dug wells and dugouts									
S93-02950	18-Oct-93	Yorogo Atiabisi	10.8442	-0.8378	Granite	29.4		124	6.01
S93-02952	19-Oct-93	Bolga Daporitindongo	10.7925	-0.8597	Granite	29.5		409	6.79
S93-02953	19-Oct-93	Bukere	10.8	-0.8572	Granite	29.7		431	6.61
S93-02956	20-Oct-93	Bongo Saro	10.8811	-0.8275	Granite	29.1		141	6.47
S93-02978	22-Oct-93	Asonge	10.8181	-0.77	Birimian granodior etc	30.4		306	7.22
S93-02998	26-Oct-93	Nyua	10.7622	-0.6403	Sekoti Granodiorite	29.3		590	7.32
S93-03048	02-Nov-93	Gowrie	10.8519	-0.8439	Granite	29.5		233	7.35
S02-00327	02-Feb-02	Sipare	10.6855	-0.8323	Birimian granodior etc	27.2	3.7	403	8.24
S02-00330	03-Feb-02	Tongzugu Nakienyire	10.6786	-0.8114	Granite	26.9	3.5	556	7.14
S02-00331	03-Feb-02	Tongzugu Bukieog	10.673	-0.8166	Granite	25.7	3.9	207	7.56
S02-00333	03-Feb-02	Sheaga Wong	10.723	-0.7221	Birimian Greenstone	30.6	0.8	315	7.23
S02-00334	03-Feb-02	Gban (mine shaft)	10.6888	-0.6687	Birimian Greenstone	25.6		736	7.76
S02-00336	04-Feb-02	Tarongo	10.8882	-0.8773	Granite	25.8	3.9	187	7.8
S02-00339	04-Feb-02	Zokko Atiabisi	10.9116	-0.886	Granite	26.6	2.1	540	7.57
S02-00361	08-Feb-02	Feo Ayelbia	10.9906	-0.7697	Birimian granodior etc	28.7	2.3	289	7.14
S02-00374	12-Feb-02	Saboro	10.9163	-1.089	Birimian Greenstone	28.6	3.8	320	7.47
S02-00377	13-Feb-02	Kologo Anyibisi	10.7569	-1.079	Birimian granodior etc	31.2	3.9	350	7.04
S02-00387	14-Feb-02	Adaboya Nayire	10.8986	-0.7467	Birimian Greenstone	24.1	1.9	287	6.96

Number	Na	K	Mg	Ca	Cl	TON	SO_4 mg L^{-1}	Alk	F	Fe	I	Mn	Si	As µg L^{-1}	U
Reservoir															
S02-00346	6.7	2.6	2.8	8.4	1.6	<0.2	0.8	57	0.22	0.039	0.004	0.004	8	1	0.1
Boreholes															
S93-02947	23.7	1.7	13.2	29.5	3.7	3.4	3	190	3.1	0.044	0.004	0.001	32	<0.4	2.5
S93-02948	16	2.3	8.5	18.8	3.2	4	1	116	3.2	0.26	0.003	0.005	34	<0.4	0.2
S93-02949	18.8	1.6	13.7	27.6	5.9	4.9	1.7	146	3.6	0.374	0.003	0.007	34	<0.4	1.3
S93-02951	22.4	1.6	7	35.3	4.2	6.1	5.2	160	1.6	0.266	0.003	0.003	37	<0.4	0.7
S93-02954	18.2	1.9	8.8	19.3	12.2	5.6	6.2	96	3.6	0.026	0.003	0.001	33	<0.4	0.1
S93-02955	33.5	2.1	19.9	14.9	4	2.5	1.5	226	2	0.001	0.006	0.002	16	2	6.2
S93-02957	19.3	1.1	11.1	18.3	4.9	7.1	2.9	114	3.8	0.314	0.003	0.005	33	<0.4	0.1
S93-02958	22.7	1.4	18.7	28.5	16.1	14.1	8.1	135	3.5	0.071	0.003	0.001	34	<0.4	1.0
S93-02959	20.3	1.7	19.7	37.3	30.3	19.1	10	117	2.8	0.001	0.003	0	38	<0.4	0.3
S93-02960	15.9	1.7	10.6	23.3	3.2	2.7	5.9	136	3.4	0.43	0.005	0.004	29	<0.4	0.4
S93-02961	17	1.7	9.8	18.6	8.5	6.1	3.2	102	2.5	0.1	0.003	0.001	30	<0.4	0.1
S93-02962	17.3	1.2	8.3	15.2	3.4	2.8	2.4	109	1.7	0.091	0.003	0.001	29	2	0.1
S93-02963	22.6	1.3	20.5	32.9	5.2	4.9	1.1	220	3.8	0.165	0.004	0.006	33	<0.4	1.0
S93-02964	27.1	3.1	17.2	33.1	<2	0.5	4.3	258	1.4	0.438	0.007	0.012	28	5	1.7
S93-02965	107.8	1.7	19.5	31.7	6.6	4.3	6.5	452	1.1	0.251	0.004	0.005	25	<0.4	1.7
S93-02966	36.1	3	20.2	34.8	<2	0.3	1	299	0.5	0.621	0.003	0.051	25	<0.4	0.3
S93-02967	30.7	2.5	13.8	38.9	2.3	2.9	2.2	259	0.6	0.153	0.003	0.002	28	<0.4	1.9
S93-02968	37.1	2.7	12.9	40.4	6.5	3.6	2	264	0.5	0.089	0.006	0.002	33	<0.4	2.0
S93-02969	26.1	1.6	7	28.6	12.3	6.2	1.6	145	0.4	0.152	0.004	0.002	36	<0.4	0.1
S93-02970	19.8	1.9	6.8	27	2	1.2	0.7	164	0.4	0.13	0.002	0.002	28	<0.4	0.2
S93-02971	38.8	4.2	11	58.2	9.8	6.1	5.1	288	0.7	0.504	0.009	0.004	29	<0.4	2.3
S93-02972	25.4	2.3	10.9	50.8	4.6	3.7	2.1	257	0.32	0.397	0.004	0.005	31	<0.4	1.2
S93-02973	26.5	2.4	10.8	51	6.4	4.7	3.9	247	0.41	0.391	0.005	0.004	32	<0.4	1.5

Number	Na	K	Mg	Ca	Cl	TON	SO_4 mg L^{-1}	Alk	F	Fe	I	Mn	Si	As µg L^{-1}	U
S93-02974	21.8	2.6	11.5	42.6	6.1	5.6	2.7	200	0.35	0.261	0.003	0.003	26	<0.4	0.8
S93-02975	27.0	3.9	12	41.9	12.2	3.9	7.8	216	0.55	0.951	0.008	0.01	24	<0.4	0.7
S93-02976	19.6	2.8	9.7	43.2	4.8	4.0	2.8	208	0.39	0.441	0.004	0.007	28	<0.4	1.5
S93-02977	11.4	0.7	14.4	32.4	<2	1.6	1.2	191	0.15	0.42	0.001	0.005	29	<0.4	0.1
S93-02979	20.5	3.3	9.5	38.1	2.4	3.5	1.6	201	0.36	0.275	0.003	0.008	28	<0.4	0.5
S93-02980	32.0	2.0	23.3	47.4	<2	0.2	0.3	338	0.31	0.808	0.003	0.011	24	<0.4	0.4
S93-02981	9.6	0.3	12.6	29.1	3.0	1.3	2.4	164	0.17	0.158	0.002	0.118	26	4	<0.05
S93-02982	11.3	0.3	16.8	38.2	<2	1.7	1.1	218	0.15	0.134	0.001	0.122	28	29	<0.05
S93-02983	37.6	0.4	19.6	44.5	2.6	0.2	0.8	332	0.41	0.133	0.009	0.011	21	2	0.3
S93-02984	21.2	0.2	11.1	19	3.1	1.7	3.2	155	0.44	0.368	0.004	0.007	29	<0.4	0.1
S93-02985	26.5	0.3	14.1	32.7	8.5	3.5	7.9	210	0.47	0.003	0.004	0.001	27	<0.4	0.2
S93-02986	14.6	0.2	17.6	37.6	3.4	<0.1	3.7	252	0.22	0.212	0.003	0.041	17	<0.4	0.1
S93-02987	25.7	0.3	15.7	34.6	9.4	3.1	1.9	240	0.41	0.257	0.003	0.018	27	<0.4	0.1
S93-02988	30.1	0.1	16.1	45.5	4.3	0.2	2.2	313	0.4	0.181	0.003	0.012	18	2	0.3
S93-02989	27.7	0.2	18.1	42.4	7.5	0.1	1.3	301	0.15	0.115	0.003	0.03	20	5	0.1
S93-02990	29.4	0.3	28.3	41	4.3	1	5.3	336	0.2	0.001	0.002	0.005	16	141	0.2
S93-02991	21.3	6.6	26.6	34.8	2.1	0.3	0.8	316	0.64	0.231	0.002	0.013	31	2	1.1
S93-02992	23.8	0.3	9.7	32.3	<2	0.1	1.1	227	0.44	1.013	0.003	0.017	29	<0.4	0.1
S93-02993	18.6	0.2	16.7	43.1	<2	0.4	0.4	288	0.14	0.098	0.002	0.002	28	5	0.1
S93-02994	17.1	1.0	6.5	35.2	3.7	1.6	8.9	160	3.2	0.07	0.002	0.008	25	<0.4	7.9
S93-02995	23.0	1.6	7.4	42.4	<2	1.3	6.1	215	1.02	0.002	0.002	<0.001	37	<0.4	2.1
S93-02996	22.8	1.4	8.3	34.8	<2	2.1	2.5	178	1.5	0.089	0.003	0.001	33	<0.4	1.1
S93-02997	24.2	0.8	10.4	36.3	<2	0.2	0.7	222	0.86	0.18	0.003	0.002	34	<0.4	1.4
S93-02999	19.1	0.9	5.5	32.1	<4	3.8	1.8	156	1.08	0.038	0.003	<0.001	36	<0.4	0.7
S93-03000	17.1	1.0	4.1	32.2	<4	3.8	4.2	138	1.9	0.084	0.003	<0.001	31	<0.4	1.0
S93-03001	31.2	1.1	22.4	53.2	5.6	2.6	3.7	332	0.43	0.064	0.008	0.08	20	<0.4	2.2
S93-03002	9.0	<0.04	13	32.4	13.7	7.3	8.5	118	0.14	<0.005	0.001	0.005	25	7	<0.05
S93-03003	8.9	<0.03	9.7	27.1	3.6	0.7	2.3	142	0.17	0.52	0.001	0.191	29	<0.4	<0.05
S93-03004	40.2	0.2	17	41.4	<2	<0.02	1.5	332	0.63	0.403	0.01	0.018	26	<0.4	0.4
S93-03005	22.4	0.3	11.6	22.5	6.3	5.2	4.7	143	0.75	0.043	0.005	0.002	37	<0.4	0.1
S93-03006	14.5	0.4	12.2	22.7	4.3	2.9	2.6	154	0.54	0.181	0.002	0.002	31	<0.4	<0.06
S93-03007	10.4	<0.03	14.8	44.2	2.9	1.0	6.6	140	0.2	0.107	0.001	0.406	26	<0.4	<0.06
S93-03008	10.0	0.1	9.3	38.9	6.0	0.9	2.0	181	0.18	0.072	0.003	0.06	21	<0.4	<0.06
S93-03009	11.2	0.1	16.7	52	13.7	8.0	11.6	200	0.19	0.099	<0.001	0.051	24	2.0	<0.06
S93-03010	9.8	0.1	14.3	45.8	3.2	1.8	1.7	226	0.18	0.245	0.001	0.087	19	7.0	0.1
S93-03011	11.8	0.7	15.6	44.2	6.4	1.6	7.0	226	0.22	0.216	<0.001	0.203	30	<0.4	0.1
S93-03012	15.3	2.0	10.7	21.1	14.8	6.8	6.2	116	0.34	0.058	0.003	0.001	32	<0.4	0.1
S93-03013	18.4	3.0	11	32.5	3.4	3.5	3.5	179	0.34	0.316	0.003	0.002	31	<0.4	0.3
S93-03014	17.5	2.6	8.4	29.3	3.2	2.8	2.1	165	0.45	0.143	0.003	0.005	26	<0.4	0.3
S93-03015	12.0	0.6	18.8	38	<2	1.4	1.7	241	0.19	0.299	<0.001	0.007	26	<0.4	<0.06
S93-03016	43.4	0.6	27.9	71.1	<2	0.1	5.7	451	0.16	0.803	0.005	0.03	23	3	0.9
S93-03017	14.7	1.6	3	14	<4	3.7	<4	87.1	0.2	0.117	0.002	0.001	31	<0.4	<0.06
S93-03018	23.7	1.9	10.5	31	4	1.4	2.5	199	0.4	0.614	0.005	0.007	27	<0.4	0.3
S93-03019	25.2	2.7	8.3	30.9	<2	1.4	1.3	200	0.37	0.598	0.004	0.006	32	<0.4	0.2
S93-03020	23.3	1.8	9.7	48	<8	4.2	2.2	218	0.51	0.112	0.003	0.003	25	<0.4	1.2
S93-03021	24.5	1.6	5.4	24.6	<8	4	2.6	158	0.41	0.176	0.003	0.001	32	<0.4	0.1
S93-03022	25.2	0.7	8.7	29	<8	5.1	3.8	155	0.44	0.07	0.002	0.001	35	<0.4	0.1
S93-03023	24.0	3.4	16.4	49.2	6.1	3.5	4.9	277	0.31	0.519	0.003	0.007	26	<0.4	1.5
S93-03024	29.4	3.6	8.3	27.3	9.8	4.5	12.9	156	0.56	0.227	0.006	0.002	26	<0.4	0.3
S93-03025	22.4	2.6	8.8	29.6	<8	3.7	2.3	164	0.59	0.144	0.005	0.003	28	<0.4	0.4
S93-03026	21.0	2.1	13.9	30.5	<4	2.4	10	194	0.56	0.308	0.005	0.004	29	<0.4	0.3
S93-03027	19.2	1.8	11.3	26.1	3.3	0.9	1.0	181	0.59	0.522	0.001	0.005	25	<0.4	0.1
S93-03028	23.1	3.2	8.5	24.9	<2	1.9	1.8	177	0.61	0.011	0.004	0.002	25	<0.4	0.2
S93-03029	20.7	3.7	7.9	30.7	8.8	3.6	2.3	163	0.46	0.202	0.003	0.002	24	<0.4	0.2
S93-03030	17.3	3.0	15.1	34	<2	0.7	1.5	227	0.4	0.113	0.002	0.005	24	<0.4	0.3
S93-03031	13.0	2.1	21	41.7	14.8	6.7	5.2	226	0.23	0.03	0.002	0.001	26	<0.4	0.2
S93-03032	15.6	2.7	8.4	18.2	6.6	6.6	3.7	105	0.46	0.223	0.004	0.029	34	<0.4	0.1
S93-03033	25.3	2.7	13	25	10.9	3.6	3.8	179	0.69	0.144	0.004	0.003	28	<0.4	0.2
S93-03034	27.8	2.7	6.3	21.3	<2	1.5	0.8	163	0.4	0.407	0.003	0.005	35	<0.4	0.1
S93-03035	26.4	2.5	8.9	29.9	5.7	5.6	3.6	163	0.37	0.001	0.004	<0.001	36	<0.4	0.2
S93-03036	24.3	1.5	7.2	26.8	2.2	2.8	1.0	178	0.4	2.442	0.004	0.014	39	<0.4	0.1
S93-03037	25.5	2.7	6.2	26.5	<2	3.6	1.8	168	0.34	0.051	0.002	0.003	30	<0.4	0.2

Number	Na	K	Mg	Ca	Cl	TON	SO_4	Alk	F	Fe	I	Mn	Si	As	U
							mg L^{-1}							µg L^{-1}	
S93-03038	30.5	2.7	8	35.5	3.4	3.9	2.9	215	0.38	0.26	0.003	0.006	33	<0.4	0.3
S93-03039	23.9	1.4	3.2	13.7	<2	0.6	0.6	118	0.3	0.23	0.004	0.004	39	<0.4	0.1
S93-03040	21.7	1.0	8.7	23.3	5.8	2.2	1.5	169	0.44	0.611	0.011	0.006	35	<0.4	0.4
S93-03041	30.4	13.2	9.6	39.8	30.5	1.4	22.9	188	0.3	<0.005	0.01	<0.001	12	<0.4	0.4
S93-03042	17.2	1.2	10.1	17.5	7.9	2	2.6	134	1.74	0.12	0.003	0.002	26	<0.4	0.3
S93-03043	12.7	2.6	4.7	8.4	3.6	5.5	0.3	57.9	0.8	0.015	0.004	<0.001	35	<0.4	<0.05
S93-03044	16.7	1.6	7.2	13.8	13.4	8.3	1.4	61	3.6	0.055	0.005	0.003	39	<0.4	0.1
S93-03045	14.5	2.0	7.7	14.7	2.4	3.4	0.9	101	2.8	0.011	0.005	0.002	37	<0.4	0.1
S93-03046	19.8	2.2	11.9	23.5	19.9	7.8	10.9	102	3	0.117	0.005	0.004	37	<0.4	0.2
S93-03047	18.1	1.7	10.6	21.3	3.6	3.1	12.2	132	3.6	0.002	0.004	<0.001	36	<0.4	0.4
S93-03049	18.8	2.4	3.9	12.7	<2	1.6	1.3	108	1.45	0.158	0.004	0.006	41	<0.4	0.1
S93-03050	24.5	0.9	6.7	11.2	2.3	2.8	0.9	113	3.8	0.06	0.004	0.001	36	<0.4	0.1
S93-03051	22	1.6	12.5	22.2	2.2	1.6	2.9	178	2.2	0.924	0.003	0.007	29	<0.4	1.7
S93-03052	16.7	1.5	8.4	21.2	2.6	3.6	8.3	106	2.75	0.048	0.002	0.003	35	<0.4	0.3
S93-03053	22.6	1.0	8.1	20.3	14.2	8.2	3.4	93	3.8	0.049	0.003	0.002	36	<0.4	0.2
S93-03054	43.8	3.0	19.4	71	9.7	0.8	13.9	396	2.75	0.456	0.061	0.098	24	<0.4	5.7
S93-03055	16.2	1.5	11.8	20.6	8.9	5.7	2.6	138	0.2	0.248	0.002	0.009	31	<0.4	0.1
S93-03056	43.7	2.4	23.5	57.4	5.3	1.9	4.1	385	0.31	2.061	0.002	0.034	24	<0.4	3.6
S93-03057	17.6	1.3	10.2	20.1	3.2	2.9	3.2	127	3.4	0.017	0.003	<0.001	31	<0.4	0.3
S93-03058	21.5	2.9	5.8	15.9	2.7	8.6	1.1	117	0.93	0.014	0.004	0.001	42	<0.4	0.1
S93-03059	20.3	1.7	6.8	15.3	<2	1.6	1.3	122	2.25	0.01	0.003	0.001	38	<0.4	0.2
S93-03060	20.8	2.2	8.8	17.3	15	7.8	1.7	87.8	2.9	0.114	0.004	0.001	37	<0.4	0.1
S93-03061	46.8	1.9	29.2	40.4	25.9	6.3	9	313	1.18	0.134	0.08	0.024	19	<0.4	13.2
S93-03062	23.1	1.4	14.9	26.6	6.8	2.6	2.4	191	1.65	0.605	0.005	0.008	29	3	0.7
S93-03063	27.9	2.3	15.9	35.6	7.7	1.2	2.7	237	0.64	0.286	0.007	0.004	29	<0.4	0.7
S93-03064	22.3	2.3	14.7	32.4	<2	0.1	0.8	227	0.35	0.42	0.005	0.006	30	<0.4	0.5
S02-00321	29	3.8	12.1	24.9	1.1	1.3	1.1	211	0.61	<0.005	0.004	<0.002	30	<1	0.4
S02-00322	24.1	3.0	10.5	21.8	0.9	1.8	1.1	180	0.42	<0.005	0.002	<0.002	36	<1	0.1
S02-00323	12.9	0.6	15.9	31.8	2.3	1	1	197	0.16	<0.005	0.002	0.02	31	<1	<0.1
S02-00324	23.5	2.5	12.9	22.6	3.8	1	1.4	183	0.41	<0.005	0.002	<0.002	31	<1	0.1
S02-00325	34.1	5.3	16.3	33.7	17.9	2.3	8.5	221	1.54	0.015	0.009	0.049	31	<1	6.1
S02-00326	27.9	1.6	11.3	23.4	10.7	7.1	5.5	140	1.7	<0.005	0.005	<0.002	39	<1	1.1
S02-00328	29.8	3.0	13.8	26.6	11	3.7	4.5	186	0.64	<0.005	0.005	<0.002	34	<1	0.2
S02-00329	24.6	0.8	9.3	20.6	13	33	6.1	98	2.42	<0.005	0.011	<0.002	41	<1	1.8
S02-00332	13.4	1.0	17.1	48.1	7.5	1.2	13	229	0.19	<0.005	0.001	0.245	36	3	0.1
S02-00335	9.9	<0.5	17.4	40.1	11.8	7.9	8.3	173	0.18	<0.005	0.002	0.006	24	1	<0.1
S02-00337	29.3	2.3	7.6	30.7	1.4	1.1	21.7	163	2.92	<0.005	0.005	<0.002	47	<1	2.8
S02-00338	28.3	2.0	6.5	23.3	18.1	12.8	6.3	74	2.02	<0.005	0.004	<0.002	47	1	0.2
S02-00340	18.2	3.2	17.7	28.8	19	7.2	3.7	149	1.87	<0.005	0.003	<0.002	38	<1	0.5
S02-00341	13.7	2.0	4.4	7.6	2.5	3.6	1	60	0.72	<0.005	0.004	<0.002	49	<1	<0.1
S02-00342	32.4	1.2	13	28.8	4.4	6.9	2.5	187	1.44	<0.005	0.004	<0.002	41	<1	6.8
S02-00343	40.4	1.8	13.2	38.5	1.1	0.6	7.9	261	3.59	<0.005	0.004	<0.002	32	<1	32.3
S02-00344	20.8	2.0	16.4	26.6	14	8.2	2.8	151	1.93	<0.005	0.003	<0.002	34	<1	0.7
S02-00345	24.9	3.2	22.8	33.6	5.7	1.4	3.2	257	0.9	<0.005	0.002	0.028	34	<1	1.8
S02-00347	18.5	2.9	8.7	17.8	1.9	2.8	1.1	137	0.32	<0.005	0.002	0.003	41	<1	<0.1
S02-00348	27.4	2.4	11.2	23.6	0.6	2.5	0.7	179	0.63	0.021	0.003	<0.002	43	<1	<0.1
S02-00349	22.8	3.0	11.1	20.3	2.5	1.8	1.9	159	0.6	<0.005	0.005	<0.002	30	<1	<0.1
S02-00350	13.1	3.0	5.5	9.8	3.7	5.8	0.4	59	0.62	<0.005	0.004	<0.002	44	1	<0.1
S02-00351	19.4	1.4	8.3	14.8	6	6.1	3.1	93	0.37	<0.005	0.002	<0.002	39	26	<0.1
S02-00352	37.6	2.4	14	23.6	3.9	1.2	2.1	212	0.32	<0.005	0.001	<0.002	31	<1	0.3
S02-00353	18.6	1.4	10.3	18	7.8	2.6	3.6	122	1.37	<0.005	0.003	<0.002	33	13	0.3
S02-00354	42	1.3	13.5	51.2	7.3	4.8	3.6	289	0.54	<0.005	0.007	<0.002	27	<1	3.8
S02-00355	40.2	1.7	17.5	55.2	4.1	0.8	4.5	327	0.64	<0.005	0.01	0.156	26	<1	10.4
S02-00356	38	3.3	11.6	34.2	5.1	5.3	3.4	212	1.51	0.008	0.005	0.002	42	<1	1.0
S02-00357	41.3	3.0	21.3	46.7	4.2	1.6	3.8	326	0.6	<0.005	0.038	0.054	39	<1	0.9
S02-00358	26.8	2.0	11.9	22.7	4.9	5.2	3	155	0.67	<0.005	0.005	<0.002	41	<1	<0.1
S02-00359	16.4	2.0	4.8	10.4	3.2	4.3	0.6	73	0.32	<0.005	0.003	<0.002	51	<1	<0.1
S02-00360	17.6	1.8	6.1	15.9	2.1	4.0	0.5	95	0.46	<0.005	0.003	<0.002	46	<1	<0.1
S02-00362	52.9	4.2	29.2	56.1	7.8	3.4	6.7	413	0.5	<0.005	0.002	0.017	31	<1	1.0
S02-00363	10.5	1.1	4.0	9.1	0.8	1.9	<0.2	72	0.26	<0.005	0.002	<0.002	46	<1	<0.1
S02-00364	25.9	1.2	16.5	30.1	12.4	6.4	5.9	180	0.33	<0.005	0.002	<0.002	29	<1	0.1
S02-00365	13.7	<0.5	18.8	38.7	0.6	1.5	2.6	231	0.26	<0.005	0.002	<0.002	40	2	0.1

Number	Na	K	Mg	Ca	Cl	TON	SO_4	Alk	F	Fe	I	Mn	Si	As	U
							mg L^{-1}							µg L^{-1}	
S02-00366	17.9	1.4	7.2	14.4	4.2	4.3	<0.2	99	0.28	<0.005	0.003	<0.002	48	<1	<0.1
S02-00367	27.5	3.3	27.9	53.2	5.4	3.5	2.7	347	0.29	<0.005	<0.001	<0.002	30	<1	1.4
S02-00368	24.1	3.5	20.8	46	2.0	0.6	5.3	295	0.39	<0.005	0.001	0.013	43	1	0.6
S02-00369	18.9	2.3	13.5	31.9	1.3	1.3	0.8	213	0.25	0.143	0.002	0.004	27	2	0.3
S02-00370	30.7	3.2	20	40.9	12.6	8.9	5	233	0.32	0.005	0.004	<0.002	23	1	0.8
S02-00371	38.1	3.8	14.3	37.8	18.7	10.4	11.6	194	0.58	<0.005	0.007	<0.002	41	1	1.6
S02-00372	35.6	2.9	16.4	36.8	22.4	10.6	8.3	188	0.64	<0.005	0.003	0.008	39	<1	2.2
S02-00373	25.5	3.6	20.9	27.8	5.3	2.5	6.7	227	0.52	<0.005	0.003	<0.002	32	<1	0.5
S02-00375	23.6	3.3	15.3	37.9	6.4	0.5	5.5	219	0.34	<0.005	0.006	0.044	39	1	0.6
S02-00376	26.7	1.8	27.7	40.7	10.6	4.7	6	292	0.35	<0.005	0.002	0.134	34	<1	0.9
S02-00378	18.6	2.2	11	21.9	11.3	6.4	2	124	0.4	<0.005	0.006	<0.002	43	<1	<0.1
S02-00379	22.9	1.4	6.5	26.5	13.1	11.9	6.5	90	0.67	<0.005	0.007	<0.002	45	1	0.2
S02-00380	25.5	3.2	23.8	35.8	0.9	<0.2	1.7	296	0.29	0.016	0.004	0.046	30	<1	0.9
S02-00381	28.9	2.7	25.5	39.6	10.1	5.4	4.9	279	0.46	<0.005	0.003	0.009	33	<1	1.0
S02-00382	25.9	2.5	15.4	26.9	0.7	0.6	0.8	221	0.49	<0.005	0.011	0.007	42	<1	0.5
S02-00383	41.1	5.5	18.9	50.9	19.7	12.2	9.7	249	1.91	<0.005	0.008	0.074	29	<1	7.7
S02-00384	25.6	4	9.4	31.8	3.6	2.4	2.7	190	0.5	<0.005	0.003	<0.002	30	1	0.6
S02-00385	15.1	2.3	6.1	15.3	<0.3	0.4	<0.2	119	0.17	<0.005	0.001	<0.002	51	1	0.1
S02-00386	28.1	3.4	14.6	40.8	29.2	12.4	7.1	158	3.6	<0.005	0.005	<0.002	36	1	0.8
Dug wells and dugouts															
S93-02950	7.8	7.7	1.5	4.9	10.8	4.9	3.1	14.9	0.09	0.456	0.001	0.006	11	<0.4	0.1
S93-02952	34.8	14.1	8.5	29.5	38.2	18.1	22.9	70.7	0.61	0.015	0.003	0.012	15	<0.4	0.1
S93-02953	24	8.0	7.8	34.9	35.3	16.8	15.5	67.7	0.3	0.002	0.002	0.011	13	<0.4	0.2
S93-02956	7.8	1.5	2.2	20.6	<2	0.1	1.7	81.7	0.37	2.51	<0.001	0.006	26	<0.4	0.3
S93-02978	12.4	3.3	3.4	15	6.5	3.1	2.4	70.7	0.34	0.161	0.004	0.055	24	<0.4	0.1
S93-02998	21.5	1.5	7.2	34.4	<2	0.6	3.6	191	1.3	0.019	0.002	0.01	32	<0.4	0.9
S93-03048	6.3	1.4	1.7	18.9	<2	3.6	1.5	68.3	0.16	0.036	0.002	0.015	20	<0.4	0.2
S02-00327	33.8	4.7	8.6	32.4	21.1	7.8	14.5	136	1.54	<0.005	0.003	<0.002	29	1	0.8
S02-00330	55.2	2.3	10.5	43.2	26	17.7	10.7	172	4.37	0.029	0.020	0.003	45	1	1.7
S02-00331	11.6	8.2	3.5	15.8	9.6	1.8	5.7	72	0.79	0.044	0.003	0.082	15	1	0.8
S02-00333	8.3	<0.5	10.6	33.4	10.9	4.5	12.6	119	0.17	<0.005	0.002	s0.009	30	3	<0.1
S02-00334	38	1.7	43.1	45.6	51.5	6	73.1	251	0.13	<0.005	0.003	0.017	29	434	1.7
S02-00336	12.3	1.0	5.2	15.2	2.1	2.3	2.2	87	1.2	0.226	0.002	0.008	35	1	0.3
S02-00339	30.3	15.8	8.1	53	39.7	23.1	13.4	115	0.2	<0.005	0.002	0.023	34	1	0.6
S02-00361	15.9	1.8	7.4	28.9	6.9	3.3	2	135	0.37	<0.005	0.002	0.009	29	1	<0.1
S02-00374	10.3	1.4	15	21.7	9.5	9.3	4.3	102	0.36	<0.005	0.003	0.005	25	<1	<0.1
S02-00377	24.9	2	9.1	26.9	8.5	12.2	4.7	115	0.4	<0.005	0.007	<0.002	45	1	<0.1
S02-00387	22	1.9	7.8	17.5	19.5	5.2	6.2	84	3.1	0.005	0.004	0.031	41	1	<0.1

TON: total oxidised nitrogen, alk: alkalinity (as HCO_3). All data as mg L^{-1} except for As, U (as µg L^{-1}).

Appendix 3 Water-quality data for samples from north-central Tanzania

Number	Village	Date sampled	Latitude	Longitude	Geology	Temp	DO	SEC	pH
			deg	deg			mg L^{-1}	µS cm^{-1}	
Springs, ponds and lakes									
S02-01277	Wembere spr.	10-Aug-02	-4.3059	34.2857	Greenstone	18.4	8.5	677	8.14
S02-00731	Imalanguzu	20-Mar-02	-4.1257	33.7928	Alluvium	31.4	17.7	205	10.13
S02-00733	Mwanzugi	20-Mar-02	-4.3698	33.8892	Lake sed.	25.9	4.7	178	8.13
S02-00764	Lake Singidan	25-Mar-02	-4.8034	34.7432	Granite	26	7.4	9950	8.72
S02-00767	Kindai Lake	25-Mar-02	-4.8318	34.7346	Granite	29.7	10.7	7920	8.72
S02-01263	Urughu pond	07-Aug-02	-4.6529	34.1907	Granite	20.5	<0.1	265	6.80
S02-01285	Matinge Dam	12-Aug-02	-4.0458	33.5047	Greenstone	26.8	7.3	279	7.82
Boreholes									
S02-00730	Imalanguzu	20-Mar-02	-4.1200	33.8012	Alluvium	27.7	3.5	1356	8.86

Number	Village	Date sampled	Latitude	Longitude	Geology	Temp	DO	SEC	pH
			deg	deg			mg L^{-1}	µS cm^{-1}	
S02-00732	Nguvumoja	20-Mar-02	-4.4209	33.8567	Greenstone	28.3	0.7	330	5.78
S02-00735	Ussongo	21-Mar-02	-4.3016	33.4877	Granite	27.2	2.5	804	7.35
S02-00736	Ussongo	21-Mar-02	-4.3007	33.4869	Granite	26.3	3.9	431	6.46
S02-00737	Moyofuke	21-Mar-02	-4.3350	33.5379	Granite	27.9	0.1	2310	7.23
S02-00739	Ziba	21-Mar-02	-4.2400	33.4069	Granite	26.2	1.0	205	6.17
S02-00745	Mgori	23-Mar-02	-4.8447	34.9761	Alluvium	25.4	2.2	767	7.19
S02-00748	Unyaghumpi	23-Mar-02	-4.9630	34.8602	Granite	23.5	6.4	365	6.84
S02-00749	Kimbwi	23-Mar-02	-5.0092	34.8423	Granite	25	4.9	303	6.09
S02-00750	Unyangongo	23-Mar-02	-4.9958	34.8391	Granite	24.5	5.6	402	6.32
S02-00751	Midaani	23-Mar-02	-5.0493	35.0263	Alluvium	27.9	<0.1	1542	7.44
S02-00752	Ilongero	24-Mar-02	-4.6817	34.8688	Granite	24.1	<0.1	995	7.1
S02-00753	Ilongero	24-Mar-02	-4.6579	34.8743	Granite	23.7	3.2	404	6.33
S02-00754	Kijota Asili	24-Mar-02	-4.5907	34.8686	Granite	23.3	2.2	436	5.72
S02-00756	Laghanida	24-Mar-02	-4.5639	34.7357	Granite	25.8	3.7	1450	6.76
S02-00757	Amani	24-Mar-02	-4.5600	34.7413	Granite	25.5	7.1	1163	6.9
S02-00758	Senenemfuru	24-Mar-02	-4.5709	34.6836	Granite	26	0.6	2400	6.59
S02-00759	Kijota	24-Mar-02	-4.5697	34.8582	Granite	25.8		1540	7.5
S02-01245	Puma mission	03-Aug-02	-4.9985	34.7573	Granite	23	2.1	293	6.24
S02-01248	Ikungi	03-Aug-02	-5.1399	34.7647	Granite	24.3	1.6	709	6.66
S02-01249	Dungunyi deep	03-Aug-02	-5.1399	34.7647	Granite	23	1.9	771	7.29
S02-01250	Dungunyi shallow	03-Aug-02	-5.0779	34.803	Granite	22.3	1.4	327	6.46
S02-01251	Kisuluda	05-Aug-02	-4.6782	34.5826	Granite	25.6	<0.1	1324	6.04
S02-01252	Mughongo	05-Aug-02	-4.6729	34.578	Granite	26.1	0.9	2790	6.59
S02-01254	Ilala	05-Aug-02	-4.5963	34.6328	Granite	27.2	1.2	1265	6.74
S02-01258	Mkuyuni	07-Aug-02	-4.3685	34.2599	Alluvium	28.4	1.4	1607	6.84
S02-01259	Shelui	07-Aug-02	-4.3564	34.1948	Lake sed.	26.3	6.1	804	7.94
S02-01260	Masagi	07-Aug-02	-4.4112	34.2598	Granite	27.2	0.1	787	7.25
S02-01261	Mtekente	07-Aug-02	-4.5510	34.2266	Alluvium	27.9	<0.1	1545	6.92
S02-01262	Urughu	07-Aug-02	-4.6546	34.1885	Granite	28.2	0.9	787	6.77
S02-01264	Ulemo	08-Aug-02	-4.4036	34.4104	Granite	25.1	<0.1	1009	6.63
S02-01265	Usure	08-Aug-02	-4.6556	34.3735	Granite	26	0.3	1341	6.68
S02-01266	Kaselya	08-Aug-02	-4.6927	34.5073	Granite	26.3	7.0	372	5.74
S02-01267	Madukani	08-Aug-02	-4.6137	34.4634	Granite	25.3	<0.1	1583	6.68
S02-01268	Nduwa	08-Aug-02	-4.4215	34.4787	Granite	24.7	0.3	1520	6.94
S02-01269	Tumuli	08-Aug-02	-4.5542	34.5465	Granite	22.6	2.6	447	6.32
S02-01270	Mgundu	09-Aug-02	-4.4039	34.4483	Granite	24.1	1.2	520	7.02
S02-01271	Itinku Bh	09-Aug-02	-4.3814	34.4944	Granite	25.1	<0.1	1402	7.02
S02-01273	Mwambao	09-Aug-02	-4.3966	34.5257	Granite	25.1	<0.1	1311	6.97
S02-01274	Mkusi	09-Aug-02	-4.3410	34.5513	Alluvium	27.9	0.4	2150	7.43
S02-01275	Madukani	09-Aug-02	-4.2309	34.5513	Granite	25.2	0.2	808	6.91
S02-01276	Kitima	09-Aug-02	-4.3053	34.7052	Granite	24.6	<0.1	1036	6.95
S02-01278	Mampanda	10-Aug-02	-4.3368	34.3391	Greenstone	25.2	0.6	742	6.92
S02-01279	Salala	10-Aug-02	-4.2963	34.3621	Greenstone	23.9	3.9	657	7.56
S02-01281	Salala	10-Aug-02	-4.2847	34.3655	Granite	26	2.5	959	7.1
S02-01282	Old Kiomboi	10-Aug-02	-4.2527	34.3759	Granite	23.8	3.6	1128	7.62
S02-01283	Kisiriri	10-Aug-02	-4.1920	34.4387	Granite	23.9	0.4	782	6.88
S02-01286	Chibiso	12-Aug-02	-3.9633	33.3463	Lake sed.	27.7	7.1	1080	7.45
S02-01289	Makomelo	13-Aug-02	-4.3022	33.9829	Lake sed.	28.1	4.6	708	7.1
S02-01293	Isakamaliwa	13-Aug-02	-4.0731	34.043	Lake sed.	29.6	1.3	19480	8.65
Dug well or dugout									
S02-00734	Ussongo	21-Mar-02	-4.2956	33.486	Granite	27.9	0.4	1051	7.05
S02-00738	Moyofuke	21-Mar-02	-4.3387	33.5341	Granite	26.8	3.3	1685	6.29
S02-00744	Mgori	23-Mar-02	-4.8456	34.988	Alluvium	24.5	1.4	790	7.22
S02-00746	Mnkhola	23-Mar-02	-4.8349	34.9688	Alluvium	32.4		262	
S02-00747	Mnkhola	23-Mar-02	-4.8349	34.9688	Alluvium	30.4		410	
S02-00755	Elimu	24-Mar-02	-4.6380	34.7541	Granite	26.4	4.1	1176	6.77
S02-00762	Kititimo	25-Mar-02	-4.8288	34.7807	Granite	27.3	0.7	912	6.99
S02-00763	Utemini	25-Mar-02	-4.8143	34.7455	Granite	27.3	6.1	1437	6.22

Number	Village	Date sampled	Latitude	Longitude	Geology	Temp	DO	SEC	pH
			deg	deg			mg L^{-1}	µS cm^{-1}	
S02-00765	Njuki	25-Mar-02	-4.7881	34.7346	Granite	26.1	6.8	602	7.16
S02-00766	Uhasibu	25-Mar-02	-4.8012	34.7339	Granite	26.4	4.4	569	6.72
S02-01246	Puma dispensary	03-Aug-02	-5.0030	34.754	Granite	22.8	0.9	379	6.71
S02-01247	Puma stones	03-Aug-02	-4.9884	34.7611	Granite	22.5	1.0	282	6.72
S02-01253	Itigi	05-Aug-02	-4.6951	34.5939	Granite	22.6	1.7	316	5.67
S02-01255	Msumbiji	05-Aug-02	-4.5916	34.6166	Granite	25	1.3	1840	7.51
S02-01256	Iguguno Parish	05-Aug-02	-4.5766	34.6318	Granite	25.5	7.2	1466	7.59
S02-01257	Mukwajuni	07-Aug-02	-4.3613	34.2576	Alluvium	24.8	<0.1	1477	7.06
S02-01272	Itinku Dugout	09-Aug-02	-4.3814	34.4930	Granite	18.7	4.0	181	7.08
S02-01280	Kinginga	10-Aug-02	-4.2963	34.3621	Greenstone	26.4	0.2	578	7.31
S02-01284	Ngulu	12-Aug-02	-4.1732	33.4599	Granite	26.8	5.2	753	6.78
S02-01287	Kinungu	12-Aug-02	-3.9690	33.5505	Lake sed.	26.1	2.4	910	7.96
S02-01288	Igurubi	12-Aug-02	-3.9908	33.7043	Granite	24.7	2.4	581	7.84
S02-01290	Makomelo	13-Aug-02	-4.3025	33.9832	Lake sed.	21.4	3.3	627	7.1
S02-01291	Mbutu	13-Aug-02	-4.2508	33.8888	Lake sed.	20.3	4.4	869	7.98
S02-01292	Isakamaliwa	13-Aug-02	-4.0746	34.0396	Lake sed.	23.5	1.2	1215	7.62

Number	Na	K	Mg	Ca	Cl	TON	SO_4	Alk	F	Fe	I	Mn	Si	As	U
							mg L^{-1}								µg L^{-1}
Springs															
S02-01277	53	0.4	38.7	44.2	3.6	1.3	7	462	0.9	0.1		0.032	21	<1	1
S02-00731	33	2	0.8	4.8	1.6	<0.1	1.2	94	0.8	0.03	0.042	0.029	9	1	0
S02-00733	13	3.7	3.3	18.7	3.5	<0.1	2.5	98	0.65	0.08	0.044	0.008	8	13	1
S02-00764	1736	25.8	105	44.1	3485	<0.1	344	362	4.46	<0.01	0.47	0.002	3	5	38
S02-00767	1298	34	107	74.3	2858	0.5	45.5	201	2.61	<0.01	0.05	0.005	4	4	10
S02-01263	37	8.6	4.6	12.7	40.4	<0.1	5.9	85	0.49	0.19		0.09	41	1	0
S02-01285	40	4.6	3.7	13.2	8.2	0.9	4.6	133	1.1	0.43		0.059	5	2	1
Boreholes															
S02-00730	332	2.1	1.4	17.6	13.6	7.8	20.8	845	17.45	0.02	0.116	0.003	54	25	10
S02-00732	36	1.8	7.2	22.3	38.1	8.4	5.5	77	0.67	<0.01	0.012	0.005	47	<1	0
S02-00735	104	1.9	11.5	54.6	42.7	2.4	8	393	3.21	<0.01	0.194	0.002	55	1	7
S02-00736	40	3.3	5.7	32	49	2.6	10.9	115	0.82	<0.01	0.041	0.007	54	<1	1
S02-00737	448	2.6	40.6	46.6	256	5.1	21.4	1008	5.26	<0.01	0.718	0.003	47	16	149
S02-00739	32	4.2	1.1	5.7	12.8	2.1	3.9	62	0.98	0.99	0.013	0.012	50	1	1
S02-00745	100	2.8	11.8	49.4	22.2	3	39.8	371	2.63	<0.01	0.023	0.014	22	1	68
S02-00748	39	5	6	16.3	16.7	15.8	19.3	57	0.32	<0.01	0.014	0.003	49	<1	1
S02-00749	22	7.8	5.6	16.9	16.9	15	10.6	30	0.16	<0.01	0.007	0.001	45	<1	1
S02-00750	32	9.8	7.8	20.7	23.5	16.2	23.7	50	0.25	<0.01	0.011	0.001	45	<1	0
S02-00751	277	6.8	8.3	40.3	268	<0.1	123	244	3.97	0.11	0.081	0.029	22	<1	2
S02-00752	133	5.8	19.5	52.7	99.4	14.2	42	314	3.52	<0.01	0.077	0.007	25	<1	25
S02-00753	60	5.8	6.7	10.3	30.4	6.8	18.3	98	1.46	0.66	0.029	0.007	39	<1	0
S02-00754	67	11.1	2.9	3.5	46.5	20.1	14.6	107	0.52	<0.01	0.01	0.014	36	<1	1
S02-00756	147	13.2	21.7	118.5	155	44.1	13.1	374	3.33	<0.01	0.407	0	41	<1	8
S02-00757	114	14	16.3	90.8	109	29.9	9.2	331	3.95	<0.01	0.348	0	45	<1	3
S02-00758	219	4.9	75.1	178.9	347	31.7	159	538	3.18	<0.01	0.27	0.042	24	1	28
S02-00759	280	2.3	19	28.2	129	18.2	90.5	526	8.16	<0.01	0.408	0.022	30	<1	37
S02-01245	24	10.5	6.7	17.1	18.6	7.3	21.1	70	0.85	0.02		<0.005	46	<1	1
S02-01248	59	6.2	17.3	52.7	92.6	10.9	12.4	164	0.6	0.58		0.084	50	1	5
S02-01249	93	1.9	22.4	51	43.6	0.6	38.5	380	2.57	0.05		0.009	36	1	40
S02-01250	17	12	5.5	29.8	12.2	3.7	14.7	125	0.67	0.07		0.042	55	1	1
S02-01251	97	6.2	44.7	103.9	228	30.7	64.4	183	2.75	0.12		0.031	32	2	8
S02-01252	155	11.4	145	289.8	443	14.1	451	545	1.41	0.6		0.039	26	3	135
S02-01254	92	9.6	35	93.7	181	15.7	7.1	316	1.55	0.13		0	44	1	15
S02-01258	181	0.1	80.7	74.3	124	11.9	111	646	0.78	0.11		0.001	28	3	2
S02-01259	162	4.2	20	16.4	14	<0.1	20.9	504	1.05	0.08		0.009	21	4	0
S02-01260	137	0.5	15.8	34.4	11.9	1.2	73.7	383	4.02	0.06		<0.005	33	1	2
S02-01261	138	8.5	100	97.8	66.9	1.2	350	560	1.35	0.15		0.115	35	20	9

Number	Na	K	Mg	Ca	Cl	TON	SO_4	Alk	F	Fe	I	Mn	Si	As	U
							mg L^{-1}								µg L^{-1}
S02-01262	73	4.1	37	49.3	49.3	5.3	7.7	398	3.1	0.08		<0.005	42	1	33
S02-01264	100	4.3	45.1	75.5	58.2	<0.1	126	449	1.16	3.58		0.106	22	1	3
S02-01265	82	1.7	52.9	99.5		66.1	11.7	215	0.81	0.18		<0.005	46	1	7
S02-01266	57	8.2	2.8	6.4	34.2	24.6	1.8	29	0.47	0.03		0.01	49	<1	0
S02-01267	111	9	68	140.3	209	13.2	128	444	0.71	0.22		0.023	21	2	10
S02-01268	148	6	43.7	123	135	13.7	172	441	3.74	0.18		0.068	24	1	12
S02-01269	53	8.4	4.7	7.5	40.4	16.8	12.6	33	0.37	0.14		0.115	13	<1	0
S02-01270	59	4	18	24.4	4	8.7	41.3	212	1.98	0.06		<0.005	23	5	1
S02-01271	226	4	40.2	68	49	2.8	137	680	5.54	0.11		0.031	22	1	60
S02-01273	179	2.3	44.7	85.2	56.4	0.8	137	630	3.13	0.18		0.013	26	1	27
S02-01274	483	1.2	22.2	19.4	178	1.1	46.6	1077	9.67	0.04		<0.005	53	2	131
S02-01275	73	4.2	16.1	92.2	22	2.9	9.9	478		0.17		0.005	24	<1	22
S02-01276	115	6.7	28.4	69.3	70.6	18.4	15	440	3.2	0.12		0.048	27	1	21
S02-01278	47	1.1	33.9	70.5	4.7	5.3	10.7	458	0.7	0.15		0.016	32	<1	1
S02-01279	73	0.9	16.2	41.4	0.5	<0.1	9.3	385	1	0.1		0.009	26	<1	0
S02-01281	115	1.7	29.2	68.7	53.5	1.5	38.1	484	2.7	0.16		0.011	26	<1	31
S02-01282	177	0.9	29.5	55	35.3	0.2	66.8	588	6	0.14		0.019	30	<1	22
S02-01283	95	0.7	18.6	44.7	42.9	7.5	24.2	321	2	0.06		<0.005	34	<1	6
S02-01286	154	5.5	13.9	47.1	49.2	<0.1	126	379	1.4	0.2		5.836	18	28	5
S02-01289	86	4.7	4.5	70.3	23.4	0.8	11.7	379	0.8	0.15		0.089	32	8	3
S02-01293	6450	13.6	1	1		<0.1	967		111	0.32		0.022	12	123	647
Dug well or dugout															
S02-00734	193	2.3	16.8	41.5	37.2	5.3	19.8	544	4.04	<0.01	0.169	0.001	49	2	21
S02-00738	24	2.6	3	7.2	5.6	4.5	9.3	38	0.57	1.36	0.009	0.024	29	<1	2
S02-00744	94	3.8	11.4	64.6	20.1	2.6	28.1	415	2.39	<0.01	0.053	0.003	14	<1	75
S02-00746	16	7.1	5.7	19.7	2.5	<0.1	2.1		0.55	<0.01	0.056	0.004	10	<1	1
S02-00747	38	10.8	8.7	30.5	8.6	<0.1	6.4		0.77	<0.01	0.118	0.004	15	1	6
S02-00755	130	14.2	20.3	63	191	22.8	17.9	204	2.51	<0.01	0.078	0	38	<1	6
S02-00762	114	4	12.1	56.1	79.2	13.6	52.7	265	3.33	0.03	0.06	0.001	28	<1	57
S02-00763	113	19.1	28.6	93.3	168	62.3	65.7	172	1.15	<0.01	0.073	0.12	42	<1	44
S02-00765	83	4.9	9.4	25.4	30.9	22.1	25.7	143	2.49	0.76	0.034	0.001	50	<1	5
S02-00766	56	5.7	10.5	30.9	24.1	31.3	19.8	93	1.66	<0.01	0.019	0	45	<1	2
S02-01246	38	14.9	6.8	24	31	<0.1	18.3	149	0.72	0.49		0.676	40	<1	0
S02-01247	13	8.5	7.3	24.5	17.1	7.8	17.2	60	0.59	0.03		0.012	42	<1	0
S02-01253	33	20.8	1	0.7	20.5	6.1	26.3	26	0.51	3.64		0.109	32	<1	2
S02-01255	254	8.5	50.8	44.7	194	10.8	55.8	597	3.47	0.05		0.001	50	3	12
S02-01256	160	6.8	48.4	73.6	232	<0.1	20.6	460	4.28	0.12		0.044	38	2	12
S02-01257	191	1.1	55.7	76.1	91.9	19.3	80.7	646	1.83	0.13		0.632	25	3	6
S02-01272	14	8.4	4.9	6.2	9.2	0.6	10.2	27	0.93	11.17		0.055	37	<1	2
S02-01280	75	0.7	16.7	42.3	0.4	<0.1	9.2	379	1.0	0.09		0.004	26	<1	0
S02-01284	117	1.3	9	37.6	42.8	11.6	13.5	302	2.3	0.07		<0.005	61	2	3
S02-01287	158	3.9	2.6	30.3	130	0.9	28.9	226	0.9	0.1		0.104	20	5	6
S02-01288	99	5.2	2.1	29.1	20.2	0.6	12.3	306	1.3	0.09		0.329	24	4	6
S02-01290	73	8.4	7.8	64.3	17.3	<0.1	6.6	379	0.8	0.17		0.28	23	5	3
S02-01291	149	3	5.9	45.8	30.8	0.9	29.2	469	2.7	0.11		0.705	20	4	16
S02-01292	252	8.3	10.1	37.3	22.5	0.8	35.4	689	10.5	0.18		0.305	59	4	3

TON: total oxidised nitrogen, alk: alkalinity (as HCO_3). All data as mg L^{-1} except for As, U (as µg L^{-1}).