Fluoride in Groundwater: Investigating the cause, scale, effect and treatment of fluoride in drinking water in Northern Tanzania

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Declaration

The content of this thesis is solely my responsibility and the original work herein is my own, except where specified otherwise in the text. Neither the thesis nor any of the original work comprising it has been submitted to this or any other institution for consideration for a higher degree.

Signed:

Date: ……22/9/10……

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Abstract:

High fluoride in drinking water sources is a problem throughout the East African Rift Valley and can lead to dental fluorosis and skeletal fluorosis in exposed local populations. One such area is the Hai District of Northern Tanzania. The study began by mapping the concentrations of fluoride in drinking water across the Hai district. Measured at 152 locations, fluoride concentrations varied from <0.1 mg/L to 33.2 mg/L, with a mean value of 1.6 mg/L. 12.5% of samples had fluoride above the World Health Organization recommended water quality standard (1.5 mg/L). Along with mapping the levels of fluoride, rock samples were also taken in an attempt to identify the source of the fluoride. Rock samples taken from areas with high levels of fluoride in the drinking water contained fluorite that shows textural evidence of dissolution. Other geological evidence from studies in a neighbouring district suggest that a geological system only present in part of the Hai district is responsible for the high levels of fluoride in the drinking water.

Two villages where fluoride was identified as a problem from the mapping were investigated. The prevalence of dental fluorosis and deformities due to skeletal fluorosis were assessed in children attending school in the two villages. Over 25% of children in each village had skeletal deformities, though one village had much higher levels of fluoride in the drinking water, a mean of 23.5 mg/l compared to 5.4 mg/l) in the other village. Over 99% of children in both villages had dental fluorosis. Deformities relating to skeletal fluorosis are common, but the reasons for individual susceptibility remain unclear and may include low calcium diets, ingestion of magadi (local salt) with high fluoride, or genetic factors.

The study concluded by considering possible treatment options and installed a bone char treatment plant in the village of Tindigani. Throughout the study, the communities were educated about the issue of fluoride in the drinking water. The village of Tindigani responded by mobilizing to provide piped water for themselves, removing the need for the bone char treatment plant.

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Chapter 1: Introduction

1.1 Introduction

Millions of the world's population still lack access to safe drinking water. The 2008 Millennium Development Goals (MDG) report indicates that while progress is being made, the progress in Sub-Saharan Africa is extremely slow (UN, 2006). In Sub-Saharan Africa 42% of people still lack access to an improved water source (WHO and UNICEF, 2008) with the most at risk communities being in rural areas. In Tanzania, less than 50% of the rural population have access to an improved water source (WHO and UNICEF, 2008). The World Health Organisation (WHO) and United Nations Children's Fund (UNICEF) joint monitoring program has measured whether or not the Millennium Development Goals (MDG) for sanitation and drinking water are being met based on whether or not the drinking water source is unimproved, improved or piped water (WHO and UNICEF, 2008). An "improved" source includes public taps, standpipes, tube wells, boreholes, protected wells, protected springs and rainwater collection. Studies have shown that improvements to a drinking water source or increased provision of water can reduce the amount of disease-causing pathogens ingested by a community (Esrey et al., 1985). This however may not give a completely accurate picture of the problems of accessing safe drinking water in the developing world. Firstly, protecting water sources does not protect against contamination of drinking water in the home (Moyo et al., 2004) and it does not protect against contamination already in the water such as chemical contamination.

Chemical contamination of a water source can either occur naturally or be caused by pollution, generally from industry. While man-made contamination can hopefully be identified and stopped it is the natural chemical contamination of water sources that puts communities in developing countries at risk. Natural chemical contamination[1] generally occurs during the water cycle as the water infiltrates through the surrounding ground and picks up natural contaminants. One of the most well documented naturally occurring contaminants is arsenic which affects drinking water supplies in a number of countries (Mandal and Suzuki, 2002). Another reasonably well-documented contaminant and one on which this study will focus is fluoride. A WHO publication (Fawell et al., 2006, J. Fawell, 2006) along with a paper by Ayoob *et al*. (2006) show that more than 25 countries across both the developed and the developing world have high concentrations of fluoride within drinking water sources, which are having serious health consequences for the consumers. Tanzania is one of these countries and has been described as being one of the worst affected countries in the world (Ayoob and Gupta, 2006).

Consuming high concentrations of fluoride puts communities at risk of developing dental and skeletal fluorosis. Dental fluorosis occurs if there is exposure to high levels of fluoride while the adult teeth are forming in childhood (DenBesten and Thariani, 1992). It is observed in the enamel of the permanent teeth as a mottling and brownish discolouration of the teeth. In severe cases the tooth surface may be pitted and the edges of the teeth may become chipped (DenBesten and Thariani, 1992). Skeletal fluorosis occurs as a result of ingesting or inhaling excessive amounts of fluoride (Fawell et al., 2006). It causes deformities of the skeleton, which can be crippling. Most commonly, the condition is chronic[2], caused by prolonged ingestion of high concentrations of fluoride, although acutely high levels of fluoride may cause death

[1] Natural chemical contamination, where the levels of chemicals in the water put human health at risk and the source of the chemical is naturally present rather than manmade.

[2] A chronic condition is one that lasts longer than 3 months or more. This is compared to acute which is often used in reference to an illness with a rapid onset and in need of urgent assistance.

via intoxication. The main pathway of fluoride ingestion for communities is via their drinking water (Weinstein and Davison, 2004). In regards to a level of fluoride consumption at which skeletal fluorosis occurs, the WHO guidelines (Fawell et al., 2006) suggest that "*crippling skeletal fluorosis can ensue when fluoride levels exceed 10mg/l*" in regards to drinking water. The WHO guideline for fluoride in drinking water is a maximum concentration of 1.5mg/l.

This study concentrates on a small district in the north of Tanzania where there have been reports of high concentrations of fluoride (8 - 25mg/l) leading to fluoride-related health problems in a number of communities (see section 1.2).

1.2 Background to Study Location

This study is based in the Hai district, found in the Kilimanjaro region in northern Tanzania (Figure 1.1). The Hai district comprises of around 50 villages and is situated between the major towns of Arusha and Moshi. The population is predominantly rural with the largest town being Boman'gombe, situated on the main road that runs through the centre of the Hai district. The majority of the population in the district lives in the northern part of Hai on the forested mountain slopes of Kilimanjaro. The communities here mainly obtain drinking water from streams and natural springs. The majority of the villages also have access to a standpipe, operated by the Hai District Water Authority with a small charge of $0.20 per 20 litres[3]. In southern Hai the population is spread out over a large area and the environment is generally arid and dry for most of the year. The main source of drinking water is groundwater from

[3] Price reported by community leader June 2008

hand-dug wells and, in a few cases, boreholes that have been provided by NGOs or charities. The majority of villages in southern Hai do not have access to a standpipe.

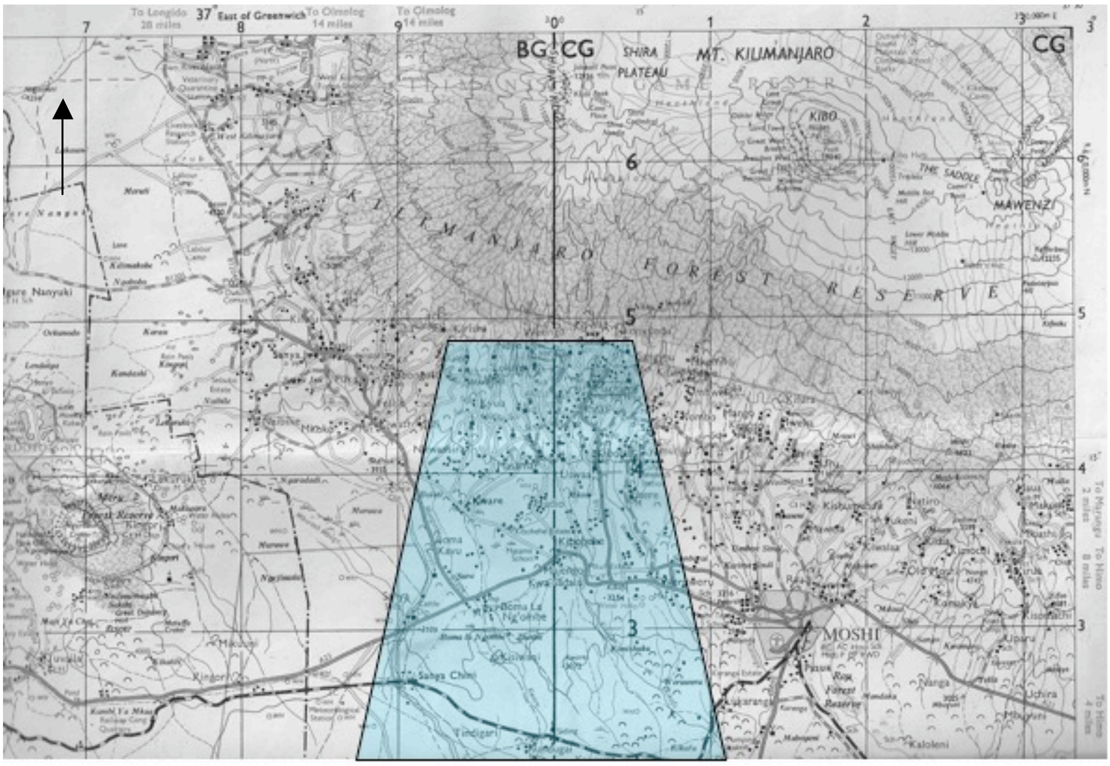


Figure 1.1: Map of area around Kilimanjaro, northern Tanzania (Tanzanian Ministry of Lands, 1967). Study area is highlighted. Each box is 10km.

A study that began in 1995 in the Hai district found a problem with skeletal fluorosis concentrated within one village, Rundugai (unpublished study)[4]. The water wells that the community was using had fluoride concentrations varying from 8 to 25mg/l. The World Health Organisation recommends a maximum concentration of 1.5mg/l. The wells in this village were closed and the community advised to collect water from a different source known to have acceptable levels of fluoride. Further to this water was piped to Rundugai and a number of standpipes were opened in the village. No new cases of fluoride related deformities have been reported. In 1998 further wells were

[4] Unpublished study carried out by Richard W. Walker. Department of Medicine, North Tyneside General Hospital, North Shields, UK

dug in an adjacent village, Tindigani, as part of an overseas aid project and by 2000, children in the village started to show similar deformities. A 2004 survey identified that the water sources had high concentrations of fluoride. Unfortunately, there were no water sources within the village with a fluoride level below 1.5mg/l. The problem of high fluoride concentrations in the village of Tindigani became the starting point for this study.

Chapter 2: Aims and Objectives

2.1 Aims, Objectives and Scope

This study is multi-disciplinary and touches upon the disciplines of medicine, dentistry, engineering, geology and nutrition. Having such a wide number of disciplines involved was important. So often in developing country based studies there is a distinct crossover between water treatment and health. Often an engineer will have to take more things into account then just an engineering solution.

The scope of the problem, the impacts on the community and the viability of a solution all have to be considered. Excessive fluoride exposure can create a wide range of health problems and it is important that these are understood fully before work is done on providing an acceptable solution. Although there has been previous work done on studying the sources of fluoride in drinking water, the impact of fluoride on consumers and the treatment of fluoride, this study aimed to tackle the problem from a more holistic view following the process of identifying the problem through to suggesting a solution.

The aim of the study is as follows:

To investigate the causes, scale, impacts and treatment of fluoride in the drinking water of the Hai district of Tanzania.

The aim was broken down into the following objectives:

- To identify the causes and scale
    - Sample and monitor fluoride concentrations in villages across the Hai district
    - Map the levels of fluoride within drinking water across the Hai district
    - Acquire rock samples and analyse for potential fluoride sources

  - Compare geological data and water quality data and identify the main source of fluoride
- To investigate the impact
  - Identify those villages at risk from high concentrations of fluoride
  - Conduct a survey to assess the prevalence of dental and skeletal fluorosis within the villages
  - Assess contributing factors such as diet and its impact upon prevalence of fluorosis
- To identify appropriate treatment
  - Design a viable and suitable treatment system within an identified village
  - Analyse the performance of the chosen treatment system in terms of fluoride removal, sustainability and acceptability within the village

By meeting these aims and objectives, this work and its results are intended to add to the scientific world's understanding of the problem of fluoride in drinking water and the viability and need for treatment in such areas. At the same time it was hoped that this work would provide education and relief to the affected communities within Tanzania covered during this study, empowering them to make their own decisions over their drinking water.

2.2 Thesis Layout

As previously mentioned this study took a holistic view of fluoride in drinking water in the Hai district of Tanzania. A basic structure of the thesis is shown in Figure 2.1. Each chapter covered a part of the aim and the associated objectives identified in the previous section. Each chapter contained a literature review specific to the area in question, methodology, results and discussion and a summary. The final chapters will be an overall discussion and conclusion of the study which will draw together the various points that have arisen in the previous chapters and analyse how well the overall aims and objectives were met, limitations in the study and opportunities for further work.

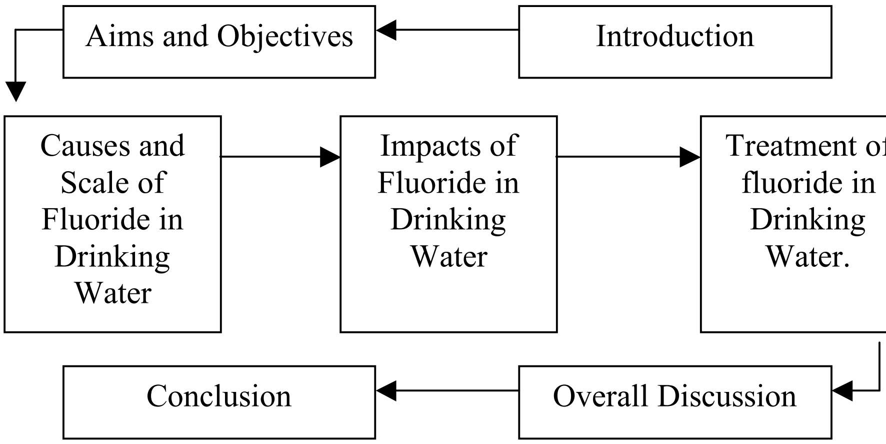


Figure 2.1: Thesis layout

Chapter 3: Causes & Scale of Fluoride in Drinking Water

This chapter will concentrate on the aim of identifying the causes and scale of fluoride in drinking water within the Hai district by covering the following objectives

- Sample and monitor fluoride concentrations in villages across the Hai district
- Map the levels of fluoride within drinking water across the Hai district
- Acquire rock samples and analyse to determine potential fluoride sources
- Compare geological data and water quality data and identify the main source of fluoride

3.1 Literature Review

The following literature review will cover the chemical background of fluoride, the origin of fluoride, fluoride in rocks and soil, and fluoride in groundwater.

3.1.1 Fluoride

Fluoride is the ionic form of fluorine, an extremely reactive element due to its atomic structure. Fluorine on its own is a yellow-brown poisonous gas that does not occur naturally and has to be isolated via experimental methods. In its many forms fluorine is used in modern day products and industries and can be found naturally in rock, water and food products. Over the course of the last 200 years it has been at the centre of controversial weapons manufacture and for some people a very controversial public health initiative.

Fluorine in the form of the calcium fluoride mineral fluorite was first mentioned in writings dating from the 1500s where it was used in metallurgy to assist working molten metals (Meiers, 2008). In the 1600s, scientists of the time found that adding acid to fluorite would etch glass, leading to the discovery of hydrofluoric acid. It wasn't until 1886 that fluorine was isolated – and in the process, it claimed several scientists' sight and lives (Meiers, 2008).

3.1.2 Sources of Fluoride in the Environment

Ozsvath (2009) described three main sources of fluoride in the environment; these are atmospheric, mineral and geothermal sources.

Natural atmospheric sources of fluoride include marine aerosols, volcanic gas emissions and air-borne soil or dust (Ozsvath, 2009). Weinstein and Davison (2004) suggest that it is active volcanoes that contribute to the majority of natural atmospheric fluoride, though emissions from industry can also add to the fluoride in the atmosphere. Weinstein and Davison (2004) identify 8 main industrial sources which add to atmospheric fluoride. These are: aluminium smelting, petroleum refining, iron and steel production, phosphate fertilizer production, glass production and brick, ceramics and cement manufacture. The emission of fluoride from such industries can be in either gaseous or particulate form. The effect on rainfall is minimal, but in some cases the rain can contain concentrations of fluoride exceeding 1mg/l (Weinstein and Davison, 2004). There are limited studies on the affect of atmospheric fluoride concentrations on human health. A study in the UK showed cattle affected by emissions from a nearby brickworks, and there are also reports from Iceland of livestock being affected by ash from a volcanic eruption containing high levels of fluoride (Weinstein and Davison, 2004). Perhaps one of the best examples of how airborne fluoride can affect human health is a series of studies carried out in China. Chaoke et al. (1997) showed how burning coal in the house was responsible for endemic dental fluorosis. The burning of high fluoride coal has not been reported in Tanzania. The area in which this study is based has no industry, and although in northern Tanzania there is active volcanicity, it seems to be unlikely, based on Weinstein and Davison (2004) that gaseous emissions from this would enough to be detrimental to human health.

Minerals are the main source of fluoride in the environment, and fluoride is an abundant and widely occurring trace element within the Earth's crust (Tavener and Clark, 2006, Edmunds and Smedley, 2005). Ozsvath (2009) lists the most common fluoride bearing minerals as fluorite (CaF_2), fluoroapatite ($Ca_5(PO_4)_3F$), micas and amphiboles, cryolite (Na_3AlF_6), villiaumite (NaF), and topaz ($Al_2(SiO_4)F_2$) along with certain clays, which Ozsvath (2009) goes on to indicate are mostly found in igneous and metamorphic rocks, and sedimentary deposits derived from such rocks (Edmunds and Smedley, 2005). The concentration of fluoride held in each rock varies with type, and the type and amount of mineral contained within (Edmunds and Smedley, 2005).

Geothermal sources are responsible for some of the highest levels of dissolved fluoride measured on the Earth's surface (Ozsvath, 2009). As previously mentioned, volcanic activity, and the related volcanic material, is closely related to fluoride production, thus magmas and their associated hydrothermal solutions can contain high levels of fluoride (Ozsvath, 2009). As surface or ground water comes into contact with these magmas or associated volcanic solutions it can obtain levels of fluoride up to the limit imposed by fluorite solubility (Ozsvath, 2009). Thus, depending on the rock type, the dissolved concentration of fluoride can exceed 1000mg/l (Edmunds and Smedley, 2005).

3.1.3 Fluoride in Groundwater

As mentioned in the previous section, one source of high fluoride bearing groundwater, is groundwater from an active geothermal system which can have dissolved fluoride concentrations exceeding 1000mg/l (Ozsvath, 2009, Edmunds and Smedley, 2005). However, the most common type that Edmunds and Smedley (2005) report, is the high fluoride bearing groundwater that occurs in areas of active geothermic activity (including the East African Rift Valley), is alkali-chloride solutions with neutral pHs and fluoride concentrations of between 1-10mg/l. The other cause of high fluoride bearing groundwater is the geological system in which it occurs. In this case the concentration of fluoride in groundwater will be limited by the source mineral, the contact time in the system and temperature of the solution (Ozsvath, 2009). Ozsvath (2009) also points out that pH, hardness and ionic strength can also play a part in terms of its influence on a mineral's solubility. Fluorite is one of the most common fluoride bearing minerals, and while usually stable, fluorite's solubility can be affected by the calcium concentrations in the water where the absence of calcium encourages dissolution of fluorite and so allows higher concentrations of fluoride (Edmunds and Smedley, 2005). These conditions are typical in volcanic regions, where the geology is mostly alkaline (in the geological sense of the word) volcanic rocks, which is the system that covers most of northern Tanzania (Kilham and Hecky, 1973). The solubility of fluorite also increases with an increase in temperature, so in arid areas with low rainfall, high concentrations of fluoride are more likely (Edmunds and Smedley, 2005). Edmunds and Smedley (2005) also report that arid regions decrease the flow rate of groundwater thus allowing more contact time with the rocks and, in turn, allow more chemical transfer to take place. There was a high possibility that the area in which this study is took place could have high fluoride bearing groundwater, for either of these reasons and both needed to be investigated as possibilities.

3.1.4 Fluoride in Drinking Water Across the World

The East African Rift is a huge geological fault system that stretches from Ethiopia through to Mozambique. Along the Rift Valley there are many incidences of high natural concentrations of fluoride occurring in groundwater. Studies in Ethiopia (Bjorvatn et al., 2000, Reimann et al., 2003, Tekle-Haimanot et al., 2006), Kenya (Zevenbergen et al., 1996) and Malawi (Msonda et al., 2007), all demonstrate how widespread the issue of high fluoride bearing groundwater is, as well as the impact this natural occurrence has on the communities that rely on such sources for drinking water. The problem though is much more widespread than just East Africa. The WHO (2006) lists a long list of countries at risk, including China, Mexico and India. The majority of the countries affected are in areas of active or once-active volcanicity, which, as mentioned in the previous section, is one of the main causes of natural high concentrations of fluoride.

Tanzania is one of the countries where the high concentrations of fluoride are a documented problem. A study conducted as early as the 1940s, in the region of Arusha, noted the high incidence of dental fluorosis (MacQuillian, 1944). Despite the issue of high fluoride concentrations in Tanzania being known (WaterAid and BGS, 2006), still little is being done to combat the problem of fluoride. As with many developing countries with hot arid climates water is a vital need yet limited resource. Thus many communities are forced to drink groundwater sources high in fluoride even in full knowledge of the health affects.

With increasing population and increasing water demand, communities in the developing world are migrating to new areas or accessing new water sources. This along with increased communication and travel has meant that over the last 50 years we have seen an increase in the number of communities across the world affected by drinking water with high levels of fluoride.

3.2 Materials and Methods

The first stage of the study was to identify those communities within the Hai District that were accessing high fluoride drinking water sources. The Hai district is in the Kilimanjaro region in northern Tanzania. The Hai district disease surveillance site (DSS) comprises 52 communities (INDEPTH, 2002). The population is predominantly rural with the largest community being Boman'gombe, which is situated on the main road that runs through the centre of the Hai district. The majority of the population live in the northern part of Hai on the forested mountain slopes of Kilimanjaro. The communities here mainly obtain drinking water from streams and natural springs. The majority of the villages also have access to a standpipe provided and operated by the Hai District Water Authority, with a small charge of $0.20 USD per 20 litres[5]. In comparison, the population in the southern part of the Hai district is spread out over a large area of plains, and the environment is generally arid and dry for most of the year. The main source of drinking water is groundwater from hand-dug wells and, in a few cases, boreholes that have been provided by NGOs or charities.

[5] Price reported by community leader June 2008

Local community leaders in each of the 52 communities were asked to identify drinking water sources accessed by the community in each village; these sources were then measured for fluoride using a fluoride ion selective electrode (ISE) in the field. The selective electrode was a fluoride half cell ISE from EDT direct-ion (www.edt.co.uk), and was calibrated in the field with laboratory prepared standards. The standards were prepared using deionised water, obtained from a local Tanzanian laboratory, and analytical grade sodium fluoride (NaF). The fluoride ISE was calibrated each day before field-testing began. No significant instrumental drift was observed, and reproducibility was estimated to be better than ±0.1 mg/l, on the basis of triplicate analysis of each sample. At each sampling site, a 50ml-sampling container was used to collect a water sample. A new container was used for each sample site. Each sample was then tested 3 times using the fluoride ISE, a pH meter and conductivity meter. If the sample returned a fluoride concentration above or within 0.5mg/l of 1.5mg/l, a larger 250ml sample was collected and shipped back to the laboratory at the Newcastle University. Other 250ml samples were taken from other testing sites, where the fluoride concentration was less than 1.5mg/l, to provide an overall picture of the water chemistry across the sampling area (Fig 3.1).

Figure 3.1: Sampling taking place in the Hai Region, Tanzania (June 2007).

The sample containers were made from polyethylene which, was chosen as Pehrssona *et al*. (2006) demonstrated that transport in such containers does not affect the fluoride concentration of the sample. Measurements of pH (Jenway 3310) and conductivity (VWR EC300) were also taken in the field and calibrated daily with laboratory prepared standards. Triplicate analysis in the field indicated reproducibility of 0.01 pH unit and 1 μS/cm respectively. A photographic record along with other details such as type of well and depth were also recorded. Well depth was measured using a piece of string with a weight; this string would be lowered until it touched the water and then measured (to the nearest cm) to indicate the depth. Where the well was a borehole the depth was recorded by the builders on the wellhead. The co-ordinates of each source were also mapped using a Garmin eTrex HCx handheld GPS device (www.garmin.com).

As previously mentioned drinking water sources identified as having a fluoride concentration above or close to 1.5mg/l, the guideline level suggested by WHO, were sampled for further analysis by technical staff in the School of Civil Engineering and Geosciences, Newcastle University. A selection of additional samples was taken from other sources measured as low in fluoride as a comparison and to add to the overall understanding of the water chemistry. In the Newcastle laboratories cations were determined by inductively couple plasma – optical emission spectroscopy (ICP-OES) and anions determined by ion chromatography (IC), to identify the chemistry of the water as well as to confirm the field fluoride readings. The ion chromatography was carried out using a Dionex ICS-1000 with a AS40 auto sampler, and an Ionpac AS14A, 4x250mm analytical column. The flow rate is 1ml/min, and the eluent is a 8.0mM Na_2CO_3/1.0mM $NaHCO_3$ solution. The injection loop is 25μl and the instrument detects the sample via a conductivity cell that measures the electrical conductance of the sample ions. Calibration standards were prepared using analytical grade reagents. Accuracy is reported to be ±10% and precision ±5%. ICP analysis was carried out using a Varian Vista MPX axial ICP-OES. Samples were filtered through a 0.45 micron filter and then acidified using concentrated nitric acid (HNO_3 69%). Calibration standards were prepared using analytical grade reagents, and were run every 10 samples to correct for instrumental drift. Accuracy and precision are reported to be ±5% and ±2% respectively. Overall accuracy of the water analysis was checked by calculation of the charge balance for the analysed samples. The average charge balance was -2.8%, which is well within the widely used ±5% acceptance criteria (Appelo and Postma, 1993). 9 of the 18 samples had charge balances below 5%, and 2 between 5 and 10%. Those samples with high charge balances should be disregarded, as the source of the imbalance is uncertain.

Eleven rock samples were collected for further analysis from six sites from across the study area. Three sites were chosen due to their proximity to areas that had water samples with fluoride concentrations exceeding 1.5mg/l. The other three sample sites were selected to provide an overview of the areas with low concentrations of fluoride in the sampled water. Ten of the rock samples were taken from the surface and they were selected based on the frequency of that rock type in the surrounding area. One rock sample was taken from the bottom of a well that was in the process of being excavated at a depth of 10m. Polished thin sections of these samples were prepared, and mineralogical analysis was carried out on an SEM, at the University of New Mexico. The SEM used was a FEI Quanta 3D FEGSEM/FIB (field emission gun scanning electron microscope / focus ion beam). The instrument was equipped with an EDAX Genesis EDS X-ray analysis system using an Apollo 40 SDD (silicon drift detector). All EDAX data presented in this thesis are semi-quantitative.

All compositional data for rock an water samples collected between May and July 2007 are presented in Appendices B,C, and D.

3.3 Results & Discussion

3.3.1 Water sources

In total 153 water sources across the Hai district were tested for fluoride concentrations, as summarised in Table 3.1.

Type of Source	Number of Sources	% of Total
Borehole	4	2.6
Protected Spring	6	3.9
River	10	6.5
Spring	41	26.8
Standpipe	8	5.2
Stream	62	40.5
Hand dug well	20	13.1
Shallow Open Well	2	1.3
Total	**153**	**100**

Table 3.1: Types and number of drinking water sources for 52 communities in the Hai District

There were 4 boreholes, all of which, according to the community leaders, were provided by NGOs or charities that had carried out short-term improvement projects in the villages. The protected springs were covered or a spring box had been built surrounding the spring. There are a number of rivers that run through the Hai region and numerous streams. Due to the lack of published mapping it was difficult to know if in some cases whether the stream or river passed through multiple villages and this may have led to some surface waters being tested twice, but as a stream can change composition along its length this is not necessarily a problem. Most of the springs in the area were in the northern part of the Hai district but a number of the springs were found in the southern part of the Hai district. These springs were sometimes referred to as “Maji Moto” which is Swahili for “Hot Water”, which suggested geothermal activity in the area. The majority of the wells were in the southern part of the Hai region where water was scarcer. The Hai District Water authority maintained the standpipes, and the water supply came from a number of small reservoirs outside of the Hai district within the Kilimanjaro national park boundary. A member of each village was usually in charge of maintaining the standpipe and collecting a small charge, 20TSH ($0.20) per 20 litres. Although this project’s focus was on fluoride in drinking water, it is worth noting from the photographic evidence that many of these communities went at risk of other water borne diseases, as most of the sources were unprotected and were also shared with livestock. Animal waste was often found around the wells, springs and streams (see Fig. 3.2 as an example).

Figure 3.2: Photograph taken of a community water source, Mbatakero, Hai district, Tanzania (June 2007).

3.3.2 Fluoride Levels

The fluoride levels in each of the 152 sources were measured using a fluoride electrode probe (Appendix B). Table 3.2 shows the type of source, the fluoride range, and fluoride mean.

Type of Source	Fluoride Range (mg/l)	F Mean (mg/l)	F Median (mg/l)
Borehole	0.8-1.9	1.2	0.9
Protected Spring	0.2-0.4	0.2	0.2
River	0.2-2.1	0.4	0.3
Spring	<0.1-33.2	1.1	0.1
Standpipe	0.1-0.4	0.2	0.2
Stream	<0.1-21.2	0.7	0.2
Hand dug well	0.5-26.0	7.4	4.9
Shallow Open Well	0.5-0.7	0.6	0.6

Table 3.2: Fluoride concentrations of water sources measured using a fluoride selective electrode

The majority of the drinking water sources that contained high levels of fluoride were from the hand dug wells, and these were anywhere from 5-15 metres in depth. In terms of the other sources there were a couple of outlying results. For the river samples, there was one sample that returned a fluoride level of 2.1mg/l, which was high compared to the other river samples tested. There was also one high result of 33.2mg/l measured in a spring situated on the outskirts of Boman'gombe. The stream sample that recorded a fluoride level of 21.2mg/l was a stream that the Boman'gombe spring fed into further upstream, which is the reason behind the high level of fluoride.

3.3.3 Distribution of high fluoride

GPS data was collected for each water source and community centre. The GPS data was plotted on a map using ArcMap, part of the ArcGIS software package (www.esri.com). The measured concentrations of fluoride were used to create contour lines on the map to visually indicate the concentrations of fluoride across the district. Figure 3.3 is a map of the Hai region showing the distribution of high fluoride levels. This map excludes fluoride levels in standpipes and rivers, but includes levels taken from springs, streams and wells.

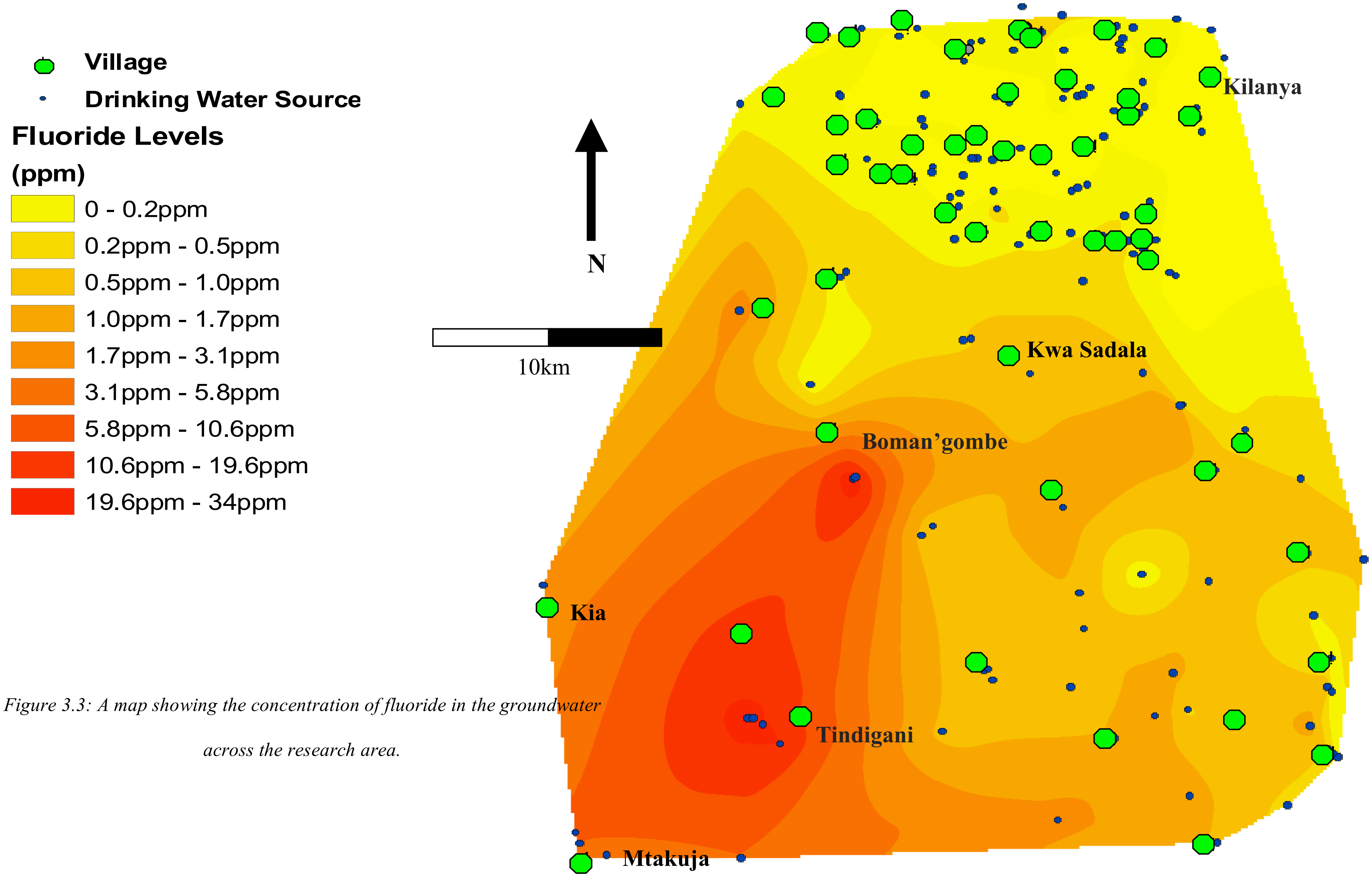


Figure 3.3: A map showing the concentration of fluoride in the groundwater across the research area.

Figure 3.3 clearly shows that the highest concentration of fluoride is in the south west of the district. This highly affected area is bordered by the town of Boman'gombe and the river Njoro (to the east of Tindigani). North and east of Boman'gombe and the river Njoro the levels of fluoride are, for the most part, within the WHO recommended fluoride concentrations for drinking water of 1.5mg/l.

3.3.4 Chemical Analysis of Water

It was possible to ship back 18 water samples from Tanzania; these samples were from across the district and with various field measured fluoride concentrations ranging from 0.5-33.2mg/l. As mentioned in the literature review, one of the controlling factors on the concentration of fluoride is the amount of calcium present in the water.

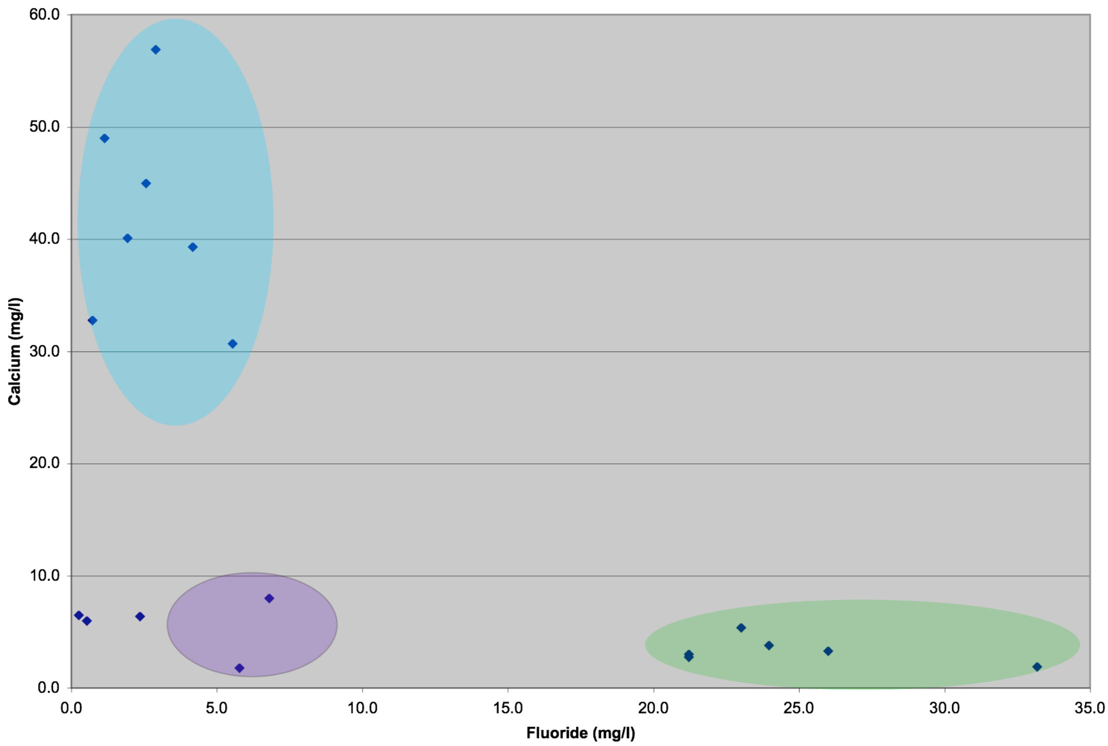


Figure 3.4: Fluoride and calcium concentrations (mg/l) of 18 drinking water samples, from the Hai District of Tanzania. Fluoride determined in the field using a fluoride ISE and calcium determined by ICP-OES in the Newcastle University laboratories. 3 Distinct groups of fluoride and calcium concentrations are highlighted as different colour regions.

Figure 3.4 shows a plot of fluoride concentration against calcium for drinking water samples returned to the UK. There does seems to be three distinct groups. Group 1 has some fluoride levels of up to 5mg/l but in general the calcium levels seem to be relatively high (up to 60 mg/l). However Group 2, which contains all the sources with fluoride values over 20mg/l, has relatively low calcium (below 10 mg/l). Edmunds and Smedley (2005) suggest that if fluorite is present in the host formation, and the calcium is low within the groundwater, this can mean that the levels of fluoride can be high. This may also account for the samples marked Group 3, and the lower fluoride levels could be due to less fluorite present in the host formation.

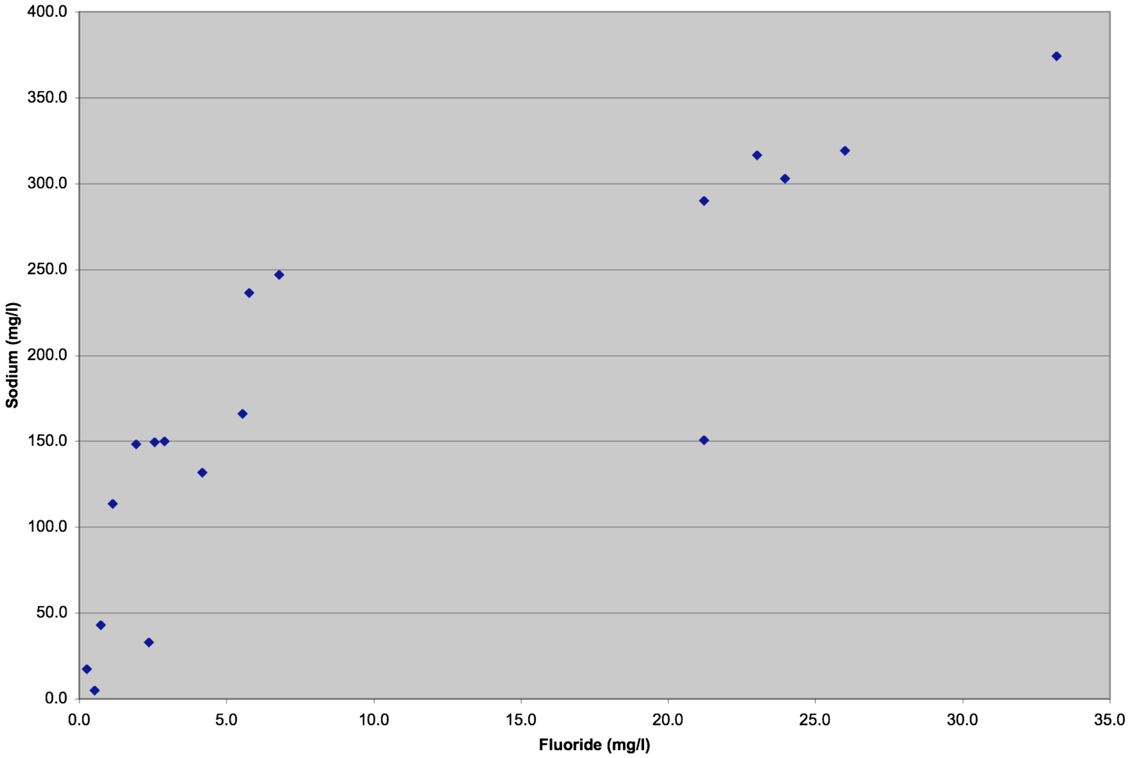


Figure 3.5: Fluoride and sodium concentrations (mg/l) of 18 drinking water samples, from the Hai District of Tanzania. Fluoride determined in the field using a fluoride ISE and sodium determined by ICP-OES in the Newcastle University laboratories.

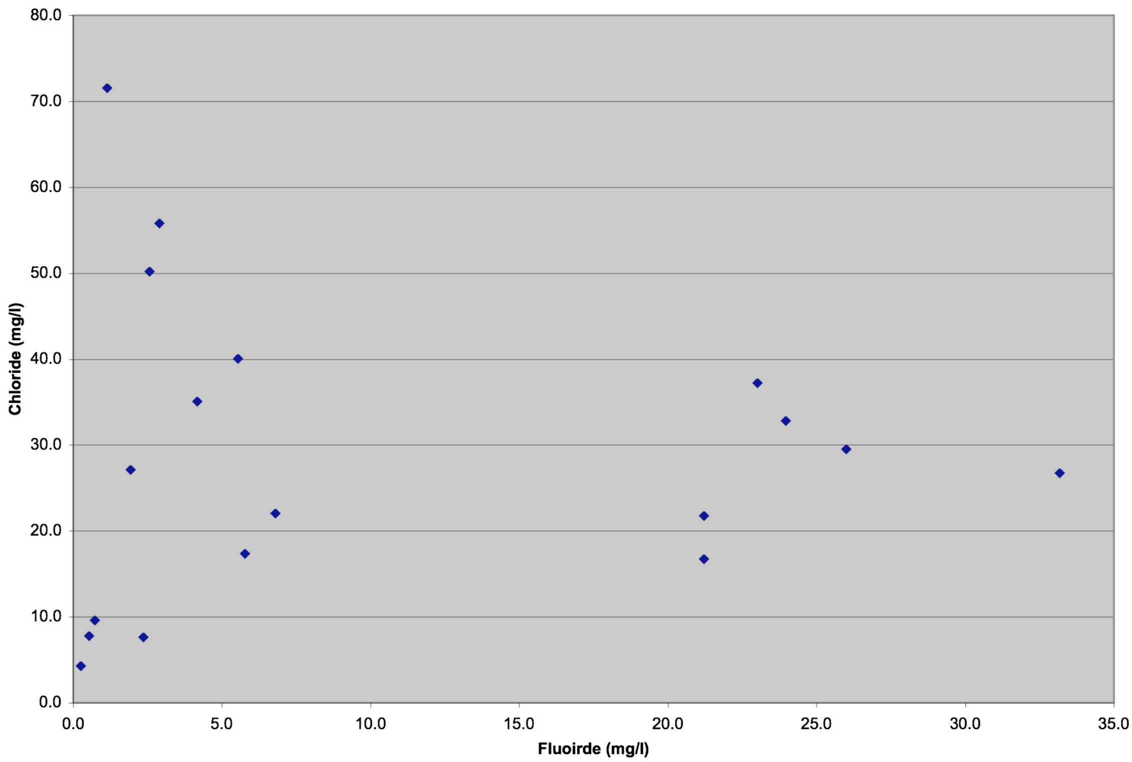


Figure 3.6: Fluoride and Chloride concentrations (mg/l) of 18 drinking water samples, from the Hai District of Tanzania. Fluoride determined in the field using a fluoride ISE and sodium determined by ion chromatography in the Newcastle University laboratories..

Figures 3.5 and 3.6 show the comparison of concentrations of fluoride to sodium and fluoride to chloride. Killam and Hecky (1973), who did extensive work in Northern Tanzania, identified the high fluoride bearing waters in this area as being sodium bicarbonate waters with low chloride. Kilham and Hecky's (1973) work was carried out around Meru, which is very close to the study area. Again in the chloride/fluoride plot, there seems to be two different groups present, which perhaps suggest, two differing geological systems in the research area. Further evidence of two different water types present is that in Figure 3.6 there seems to be two straight line segments. For full water analysis results see Appendix D.

3.3.5 Geological Analysis

A map of the area around Kilimanjaro that included the survey area was consulted (Downie and Wilkinson, 1972, Downie et al., 1964). While most of the study area is part of a geological system related to Kilimanjaro, in the south west of the study area, the area found to have high incidences of naturally occurring fluoride, the map suggests that a different geological system is in place (fig 3.7). Downie et al. (1964) identifies the affected area is being part of an old lahar flow created by Mount Meru. This is particularly interesting as the area around Meru has been well-documented as having groundwater high in fluoride (Kilham and Hecky, 1973).

In total 11 rock samples from 6 sites were returned to the UK for analysis, which were collected from a number of different sites across the study area (Figure 3.8). Thin sections were made of all the rock samples which were then viewed through a petrographic microscope. A few these images are shown below (Figure 3.9), along with a brief description of each rock type (Table 3.3).

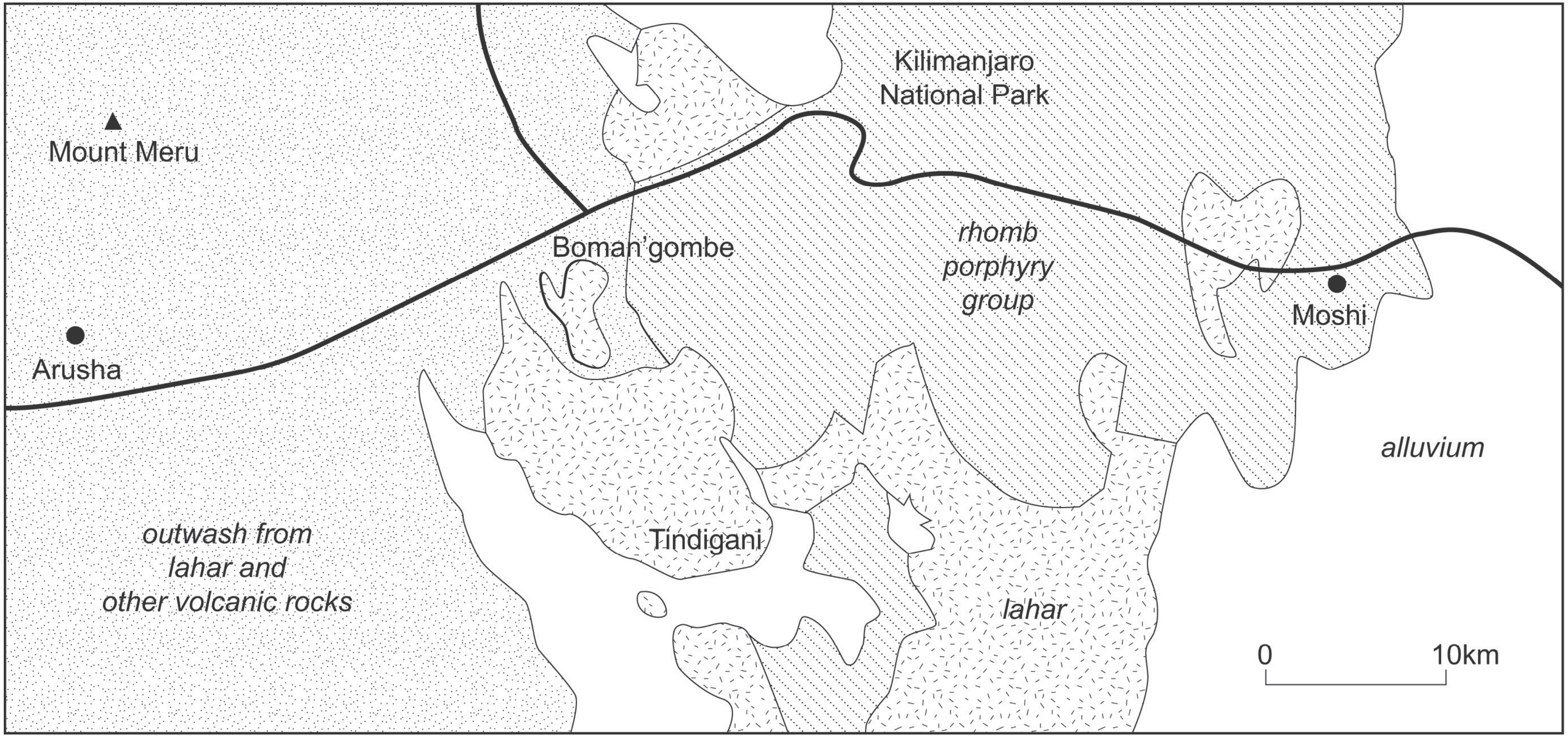


Figure 3.7: Section of a geological map of the Kilimanjaro region, Tanzania. Villages and rock types are labelled. Geological map part of the Tanganyika geological survey (Downie et al., 1964). See Downie and Wilkinson (1972) for detailed description of rock types.

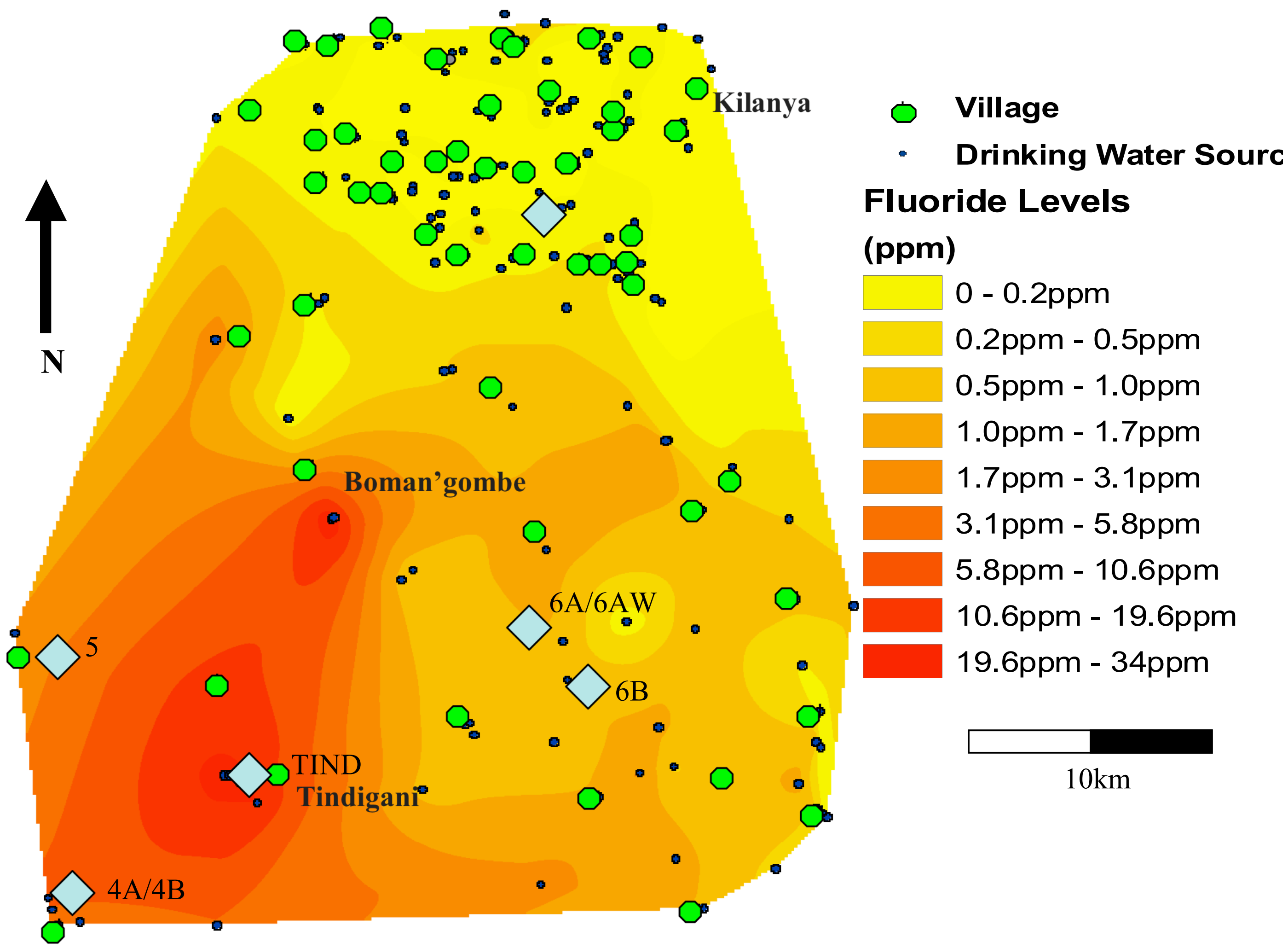


Figure 3.8: Location of rock samples (◊) and matching I.D. codes.

Sample I.D.	Location	Brief description (thin section)
1A	Shiri Njoro, Tanzania, surface.	Coarse, deeply weathered feldspars
1B	Shiri Njoro, Tanzania, surface	Highly altered, feldspar-bearing, very corroded crystals
2A	Shiri Njoro, Tanzania, surface	Very fine grained groundmass, vesicular, sparsely crystalline
2B	Shiri Njoro, Tanzania, surface	Fine grained, holocrystalline, dominated by feldspars, almost trachytic texture
4A	Mtakuja, Tanzania, surface.	Glassy in part, holocystalline in part; fractured phenocrysts
4B	Mtakuja, Tanzania, surface.	Similar to 4A; crosscut by veins with interesting devitrification texture
5	KIA, Tanzania, surface.	Very fresh, holocrystalline, almost trachytic texture
6A	Between Kwa Sadala and Kikavu Chini, Tanzania, surface.	Coarse rounded feldspar phenocrysts in fine grained groundmass
6B	Between Kwa Sadala and Kikavu Chini, Tanzania, surface.	Almost trachytic groundmass with irregular vesicles.
TIND	Tindigani, TZ, taken from a depth of 10m	Fine grained with glassy matrix, abundant olivine
6AW	Weathered Crust of 6A	Weathered Crust of 6A

Table 3.3: Description of rock samples returned to the UK for analysis, including the location of the samples and a description of the thin sections.

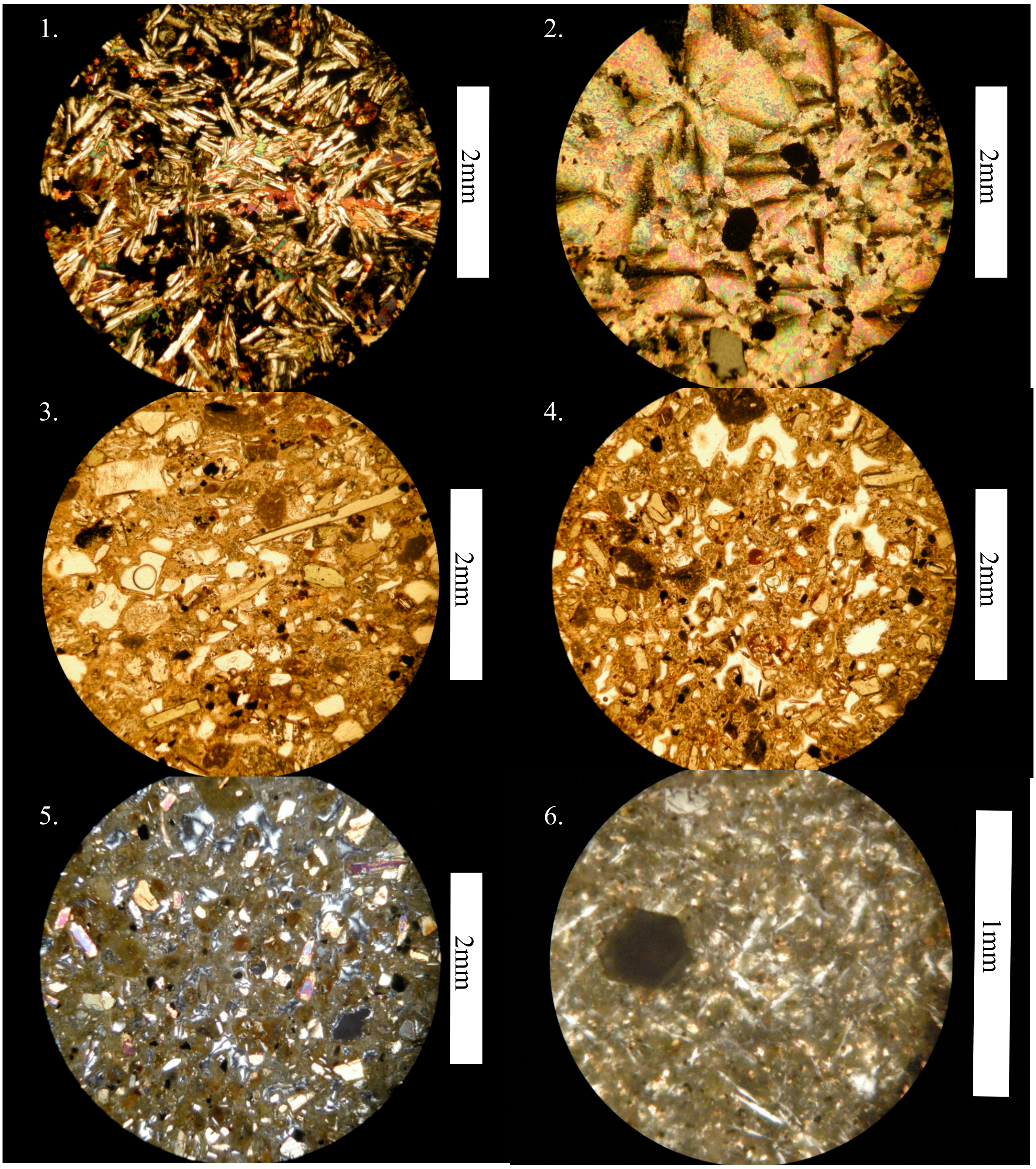


Figure 3.9: Optical images of thin sections. 1, sample 5 cross-polars 2, sample 4B cross-polars 3, sample 4B 4, Sample Tind 5, Sample Tind 6, Sample 2A

6 of the 11 samples were selected for X-ray fluorescence (XRF) analysis, which was carried out by the Department of Geology at the University of Leicester. Of particular interest were the samples TIND, 6A and 6B as all three of these samples were taken

from locations that had been identified as having high naturally occurring concentrations of fluoride. Major element data are reported in Table 3.4 for full results of major and trace element data see Appendix C.

Sample I.D.	SiO_2 (wt%)	TiO_2 (wt%)	Al_2O_3 (wt%)	Fe_2O_3 (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)
JS07/5	48.82	3.21	14.50	13.75	0.17	4.52	8.06
JS07/6B	48.26	3.07	15.44	16.05	0.26	2.11	6.01
JS07/TIND	47.12	1.97	16.14	8.33	0.19	2.34	5.66
JS07/1B	55.43	1.14	21.80	5.60	0.19	0.73	1.78
JS07/2B	56.15	0.94	18.81	6.32	0.19	0.77	1.93
JS07/6A	56.19	1.01	19.62	5.06	0.19	0.93	2.43
Sample I.D.	**Na_2O** (wt%)	**K_2O** (wt%)	**P_2O_5** (wt%)	**SO_3** (wt%)	**LOI**[6] (wt%)	**Total** (wt%)	
JS07/5	3.73	1.72	0.44	0.06	0.58	99.56	
JS07/6B	3.59	2.14	1.05	0.02	1.20	99.19	
JS07/TIND	5.71	4.46	0.58	0.02	6.88	99.40	
JS07/1B	4.32	4.59	0.32	0.01	3.48	99.38	
JS07/2B	7.62	5.74	0.25	0.01	0.36	99.08	
JS07/6A	7.71	4.85	0.49	0.04	0.51	99.02	

Table 3.4. XRF analysis of rock samples.

[6] Loss on ignition

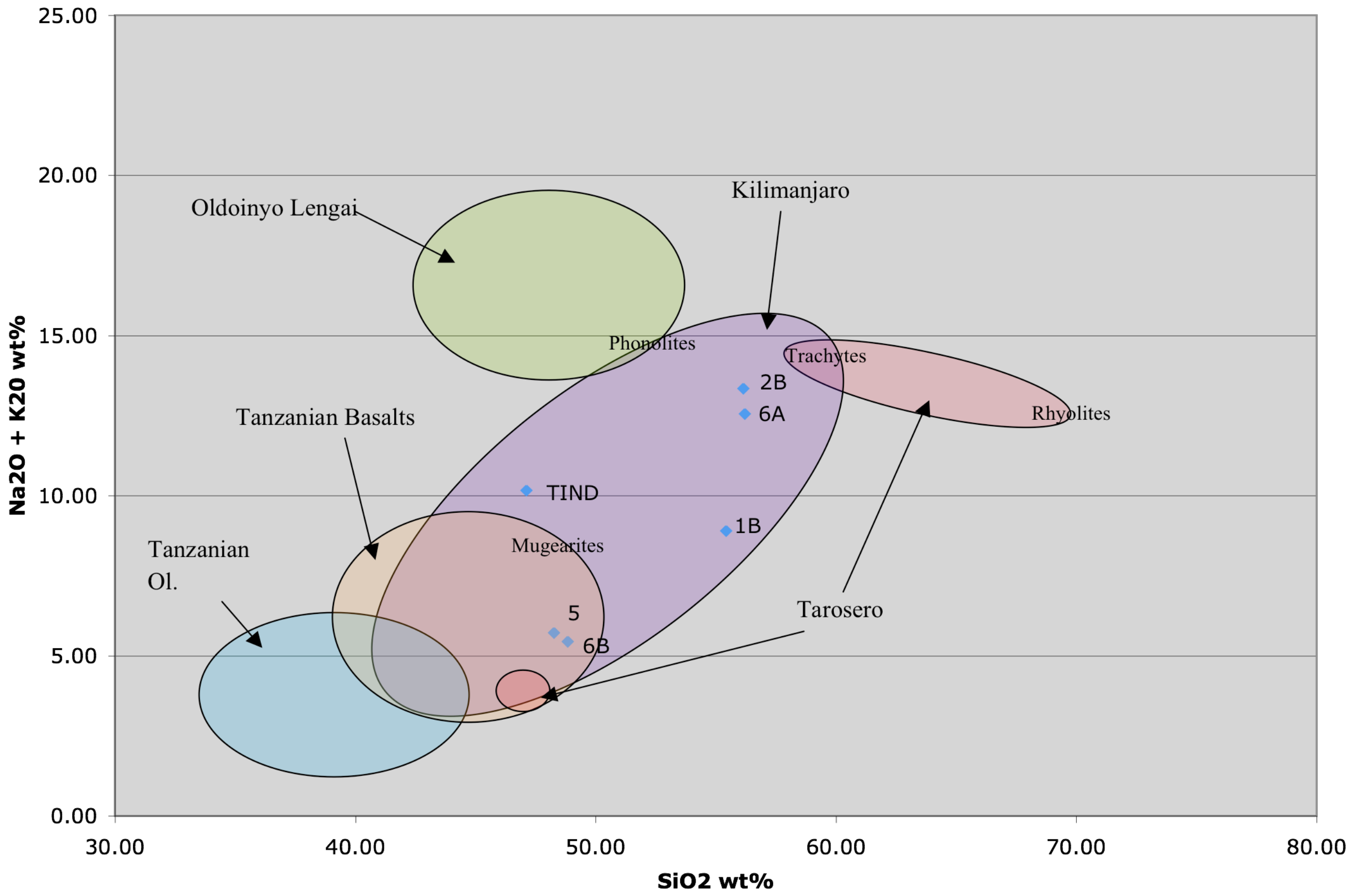


Figure 3.10: Alkali-silica diagram of lavas from Northern Tanzania (Dawson, 2008). Data obtained by XRF at Leicester University, of rock samples from Tanzania, are labelled on the diagram.

From the XRF data (Table 3.4) it was possible, using descriptions given by Dawson (2008), to identify at least the rock groupings of the rocks that were analyzed (Figure 3.10). It seems that there were 4 distinct groups, 2B and 6A, 5 and 6B, 1B and TIND, all lying within the Kilimanjaro field identified by Dawson (2008), and extending from mugearite (samples 5 and 6B) to trachytic (samples 2B and 6A) compositions. As previously mentioned, the geological map for the Kilimanjaro and Meru area was consulted, and it would seem that 2B, 6A, 1B, 5 and 6B all sit within the geological system created by Kilimanjaro (Downie and Wilkinson, 1972). The TIND sample, however, seems to lie within a different geological feature, created by a lahar[7] flow from Meru (Downie and Wilkinson, 1972). This observation would also match up with the results for fluoride levels in the ground and surface water. The waters around Kilimanjaro had relatively low levels of fluoride, however the southwest area, the area that is part of the Meru geological system, contained the highest levels of fluoride in the water. Further evidence would be that it is a well-documented fact that the area around Meru has some extremely high levels of fluoride recorded in the ground and surface water (Kaseva, 2006a, Mjengera and Mkongo, 2003).

In light of these observations, it was decided to further investigate the TIND sample using an electron microprobe to see if fluoride bearing minerals were present which could possibly be the source of the high levels of fluoride within this area. A number of suspected occurrences of fluorite were found in the TIND sample, and 4 were chosen to analyze further for confirmation. Finding fluorite was expected after analyzing the chemical concentrations in the water samples from this area.

[7] The deposits formed by a pyroclastic flow from a volcano

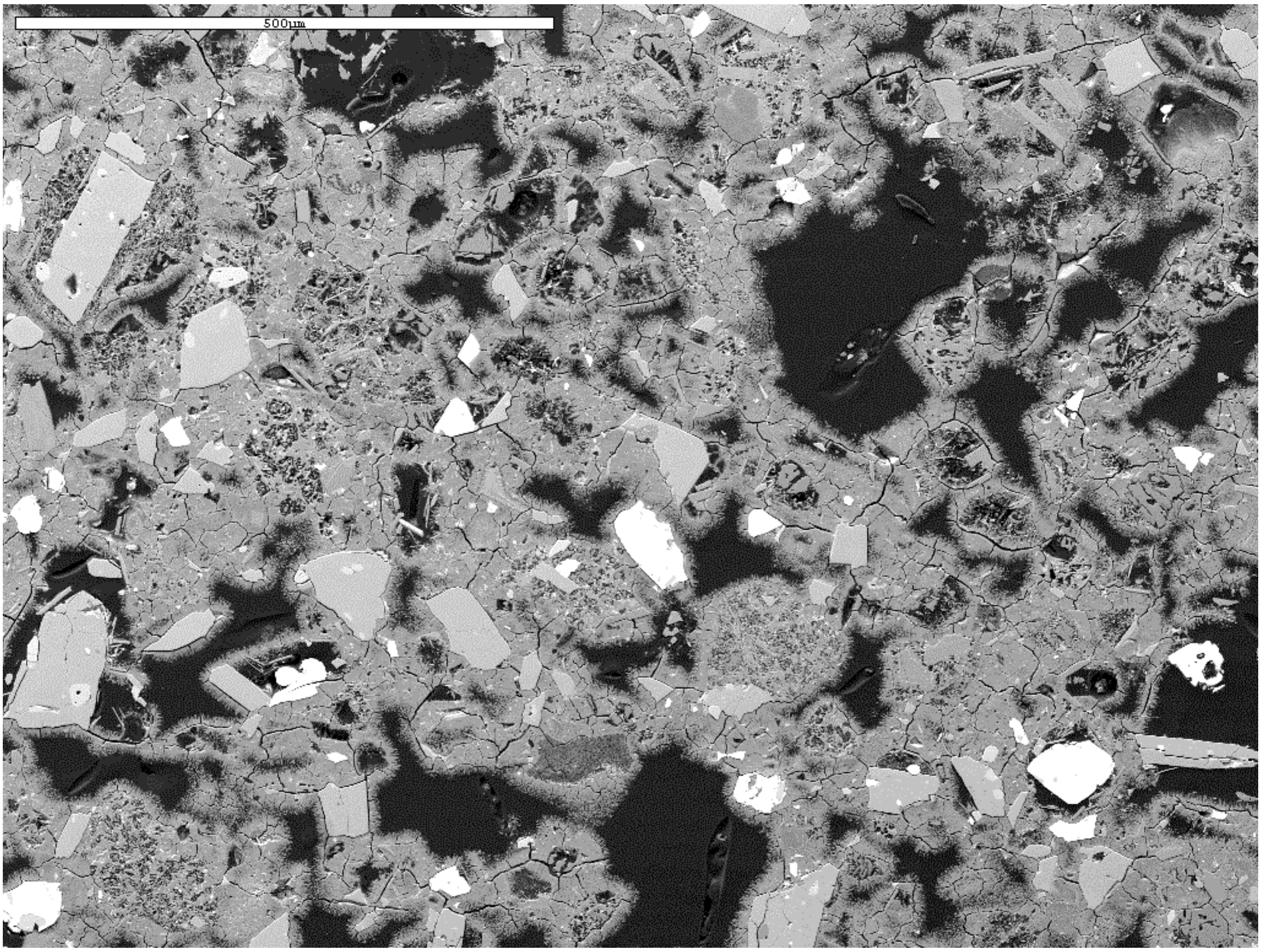


Figure 3.11: Back-scattered electron (BSE) image of sample TIND. Darkest grey is void space, surrounded by the lighter grey of glass. The 'brightness' of an individual mineral grain reflects the proportion of high atomic mass elements; iron-titanium oxides appear white.

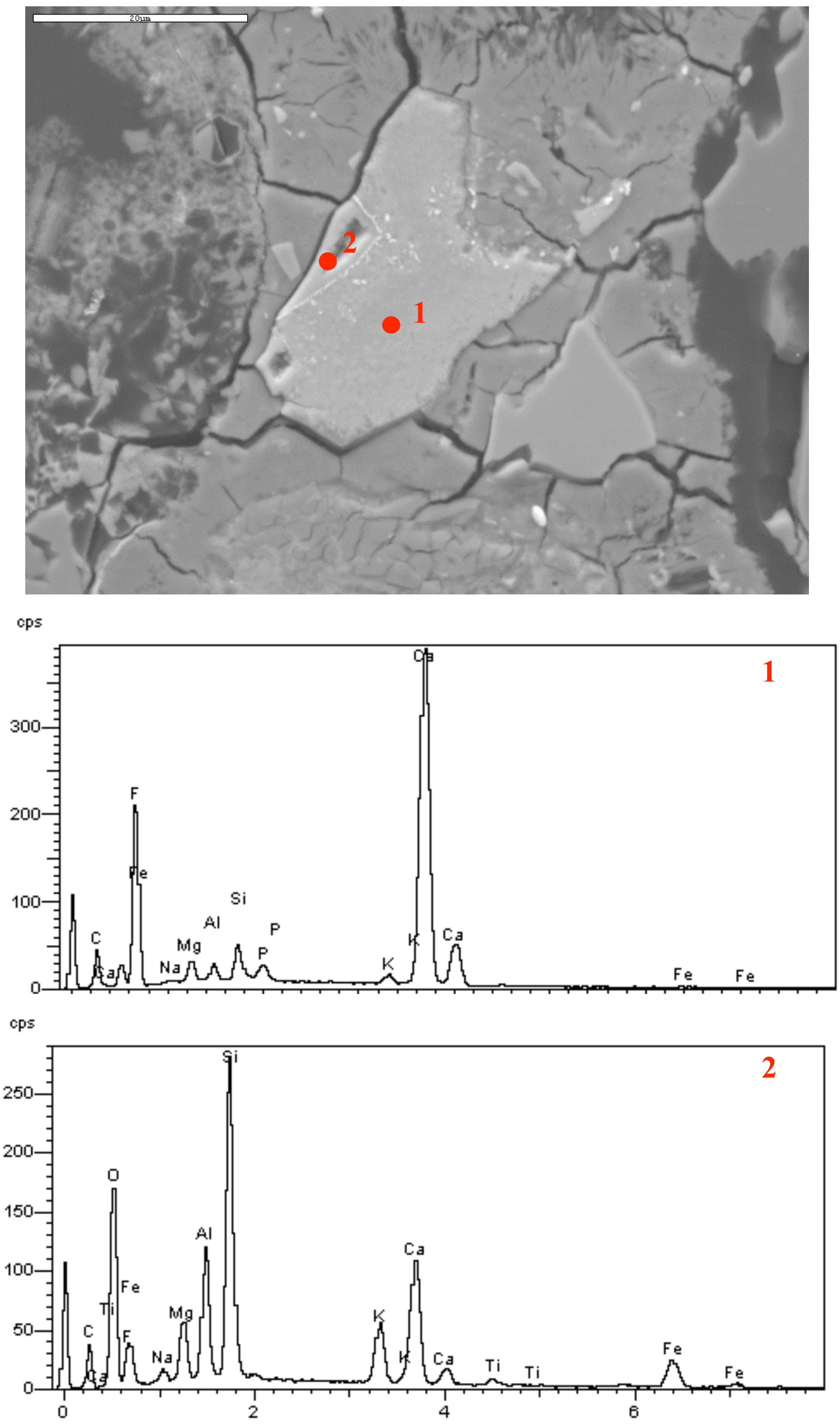


Figure 3.12: BSE image of fluorite in sample TIND 1-1 and X-ray spectra from spot analysis. Point 1 appears to be pure fluorite; Point 2 shows evidence of replacement by or overlap with silicates at the edge of the grain.

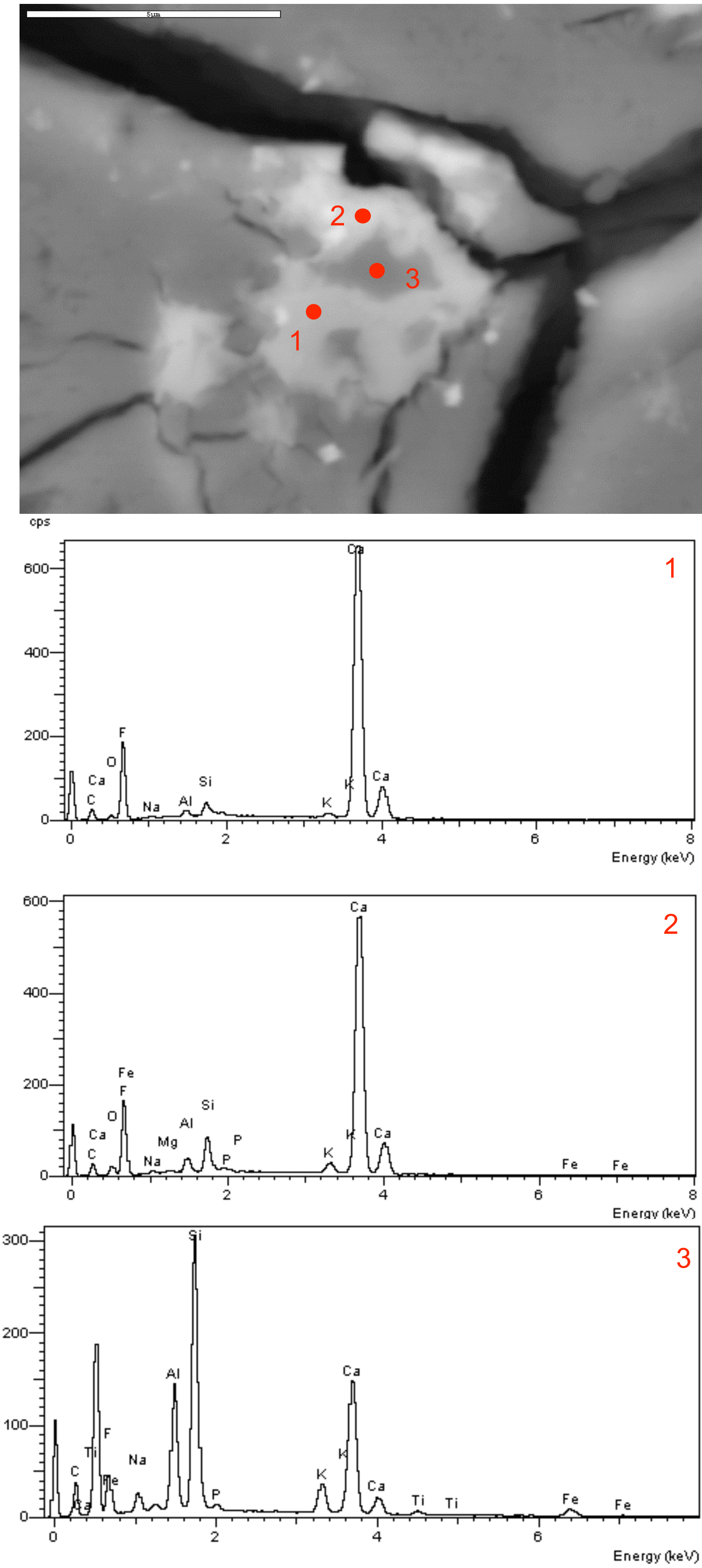


Figure 3.13: BSE image of fluorite in sample TIND 1-2 and X-ray spectra from spot analysis. Points 2 and 3 show a low F content, evidence of possible replacement.

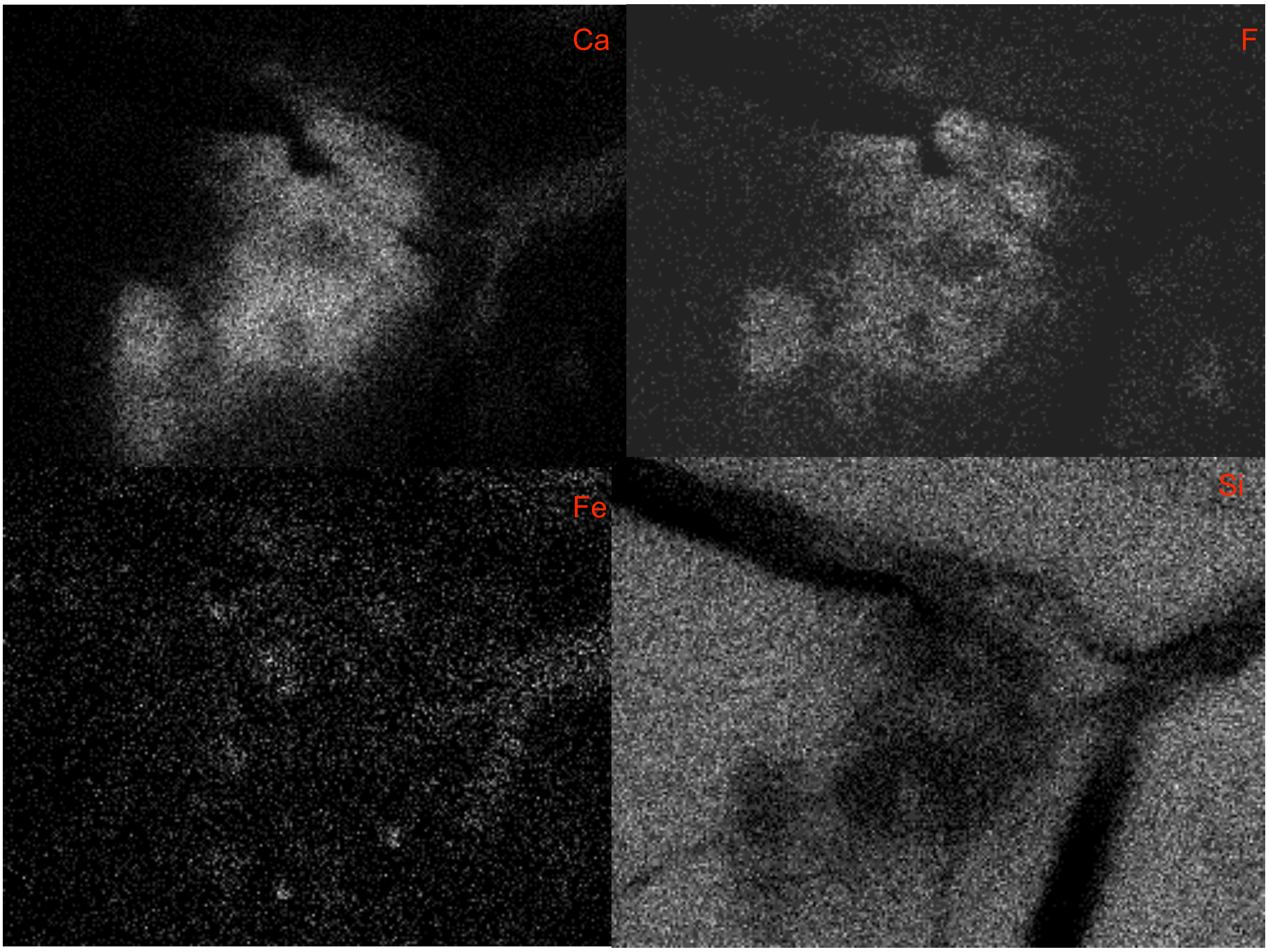
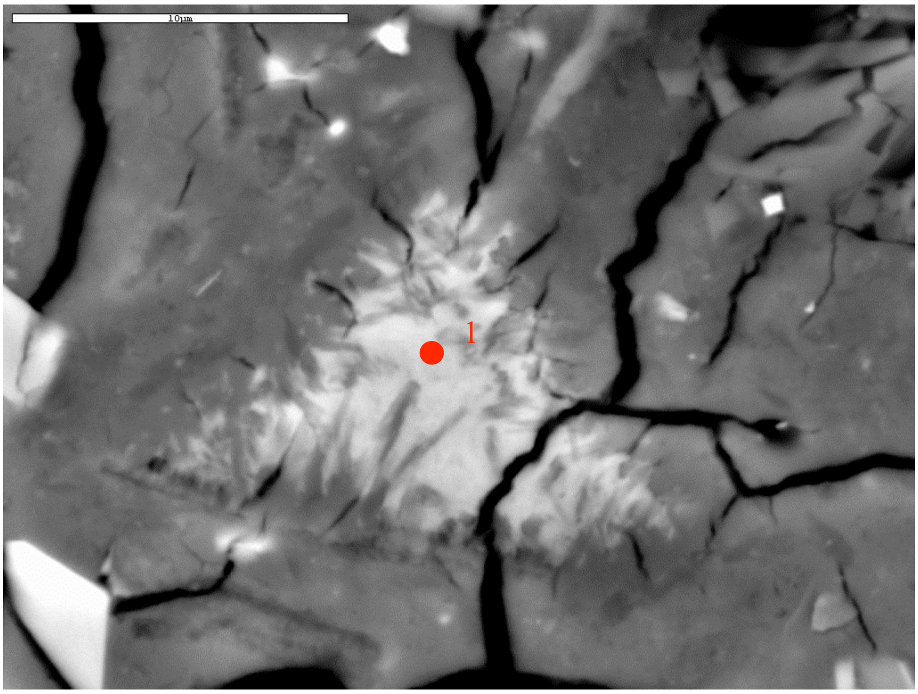


Figure 3.14: X-ray maps of Fluorite in sample TIND 1-2.



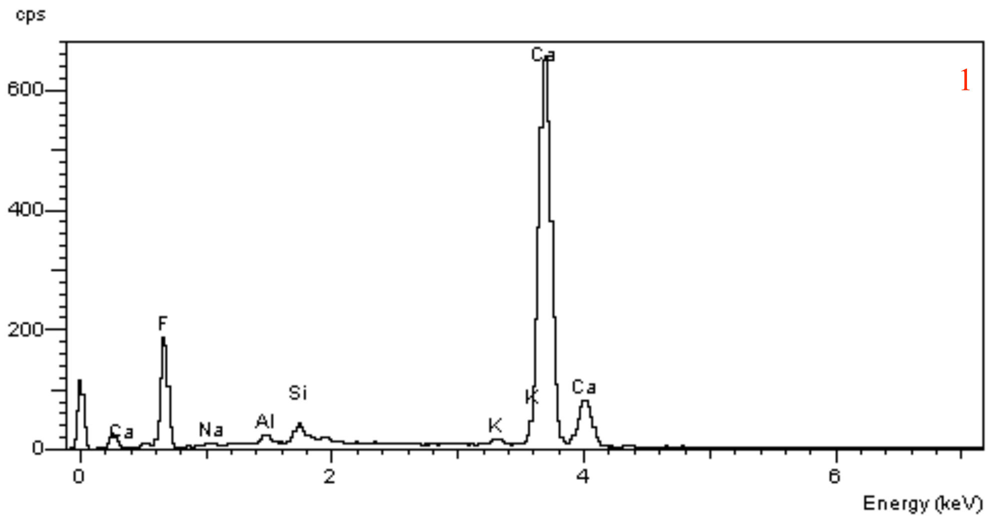


Figure 3.15: BSE image of fluorite in sample TIND 1-3 and X-ray spectra from spot analysis.

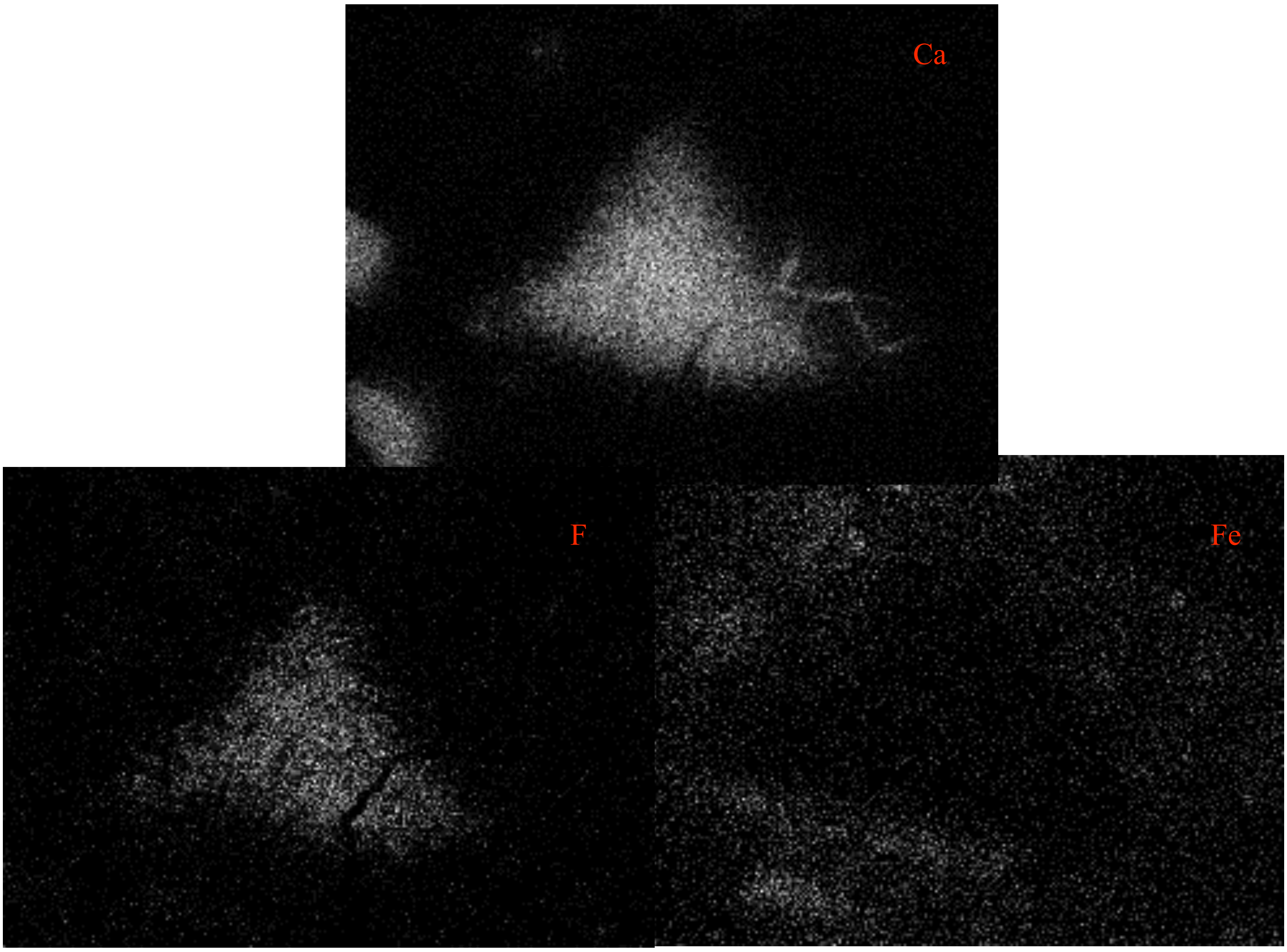


Figure 3.16: X-ray maps of fluorite TIND 1-3.

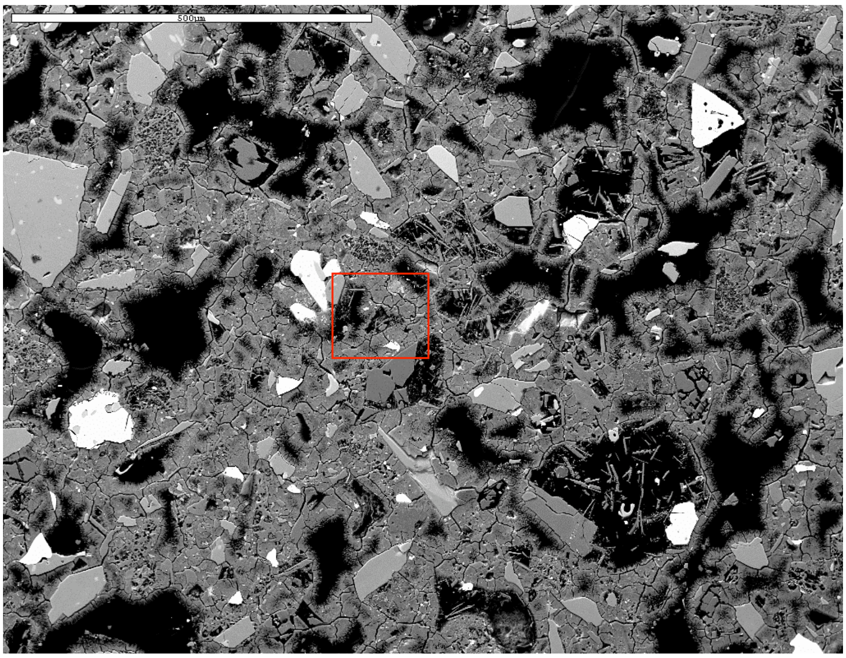


Figure 3.17: Overall view of sample TIND 1-4 (BSE image).

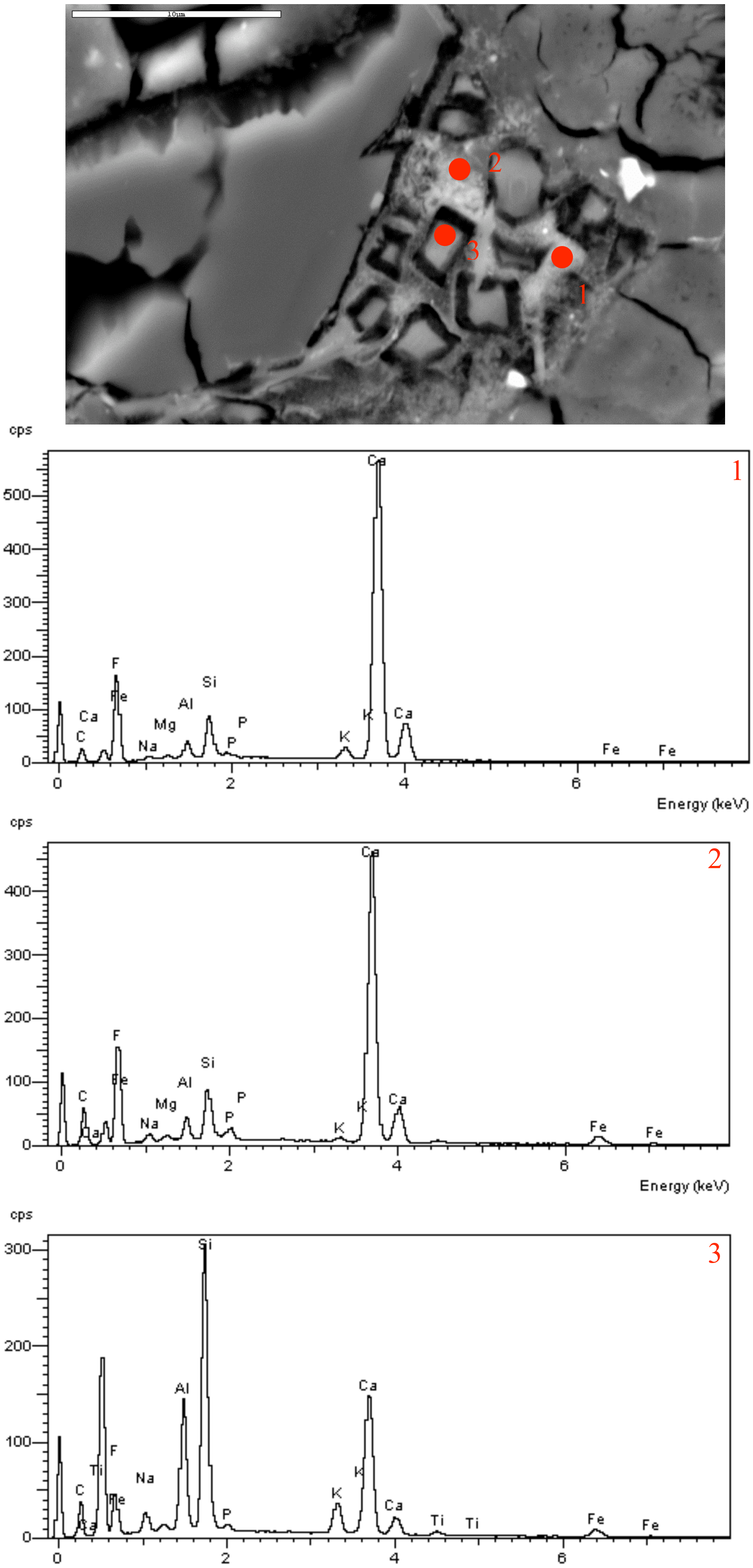


Figure 3.18: BSE image of fluorite in sample TIND 1-4 and X-ray spectra from spot analysis. Point 3 taken where alteration of the fluorite is taking place

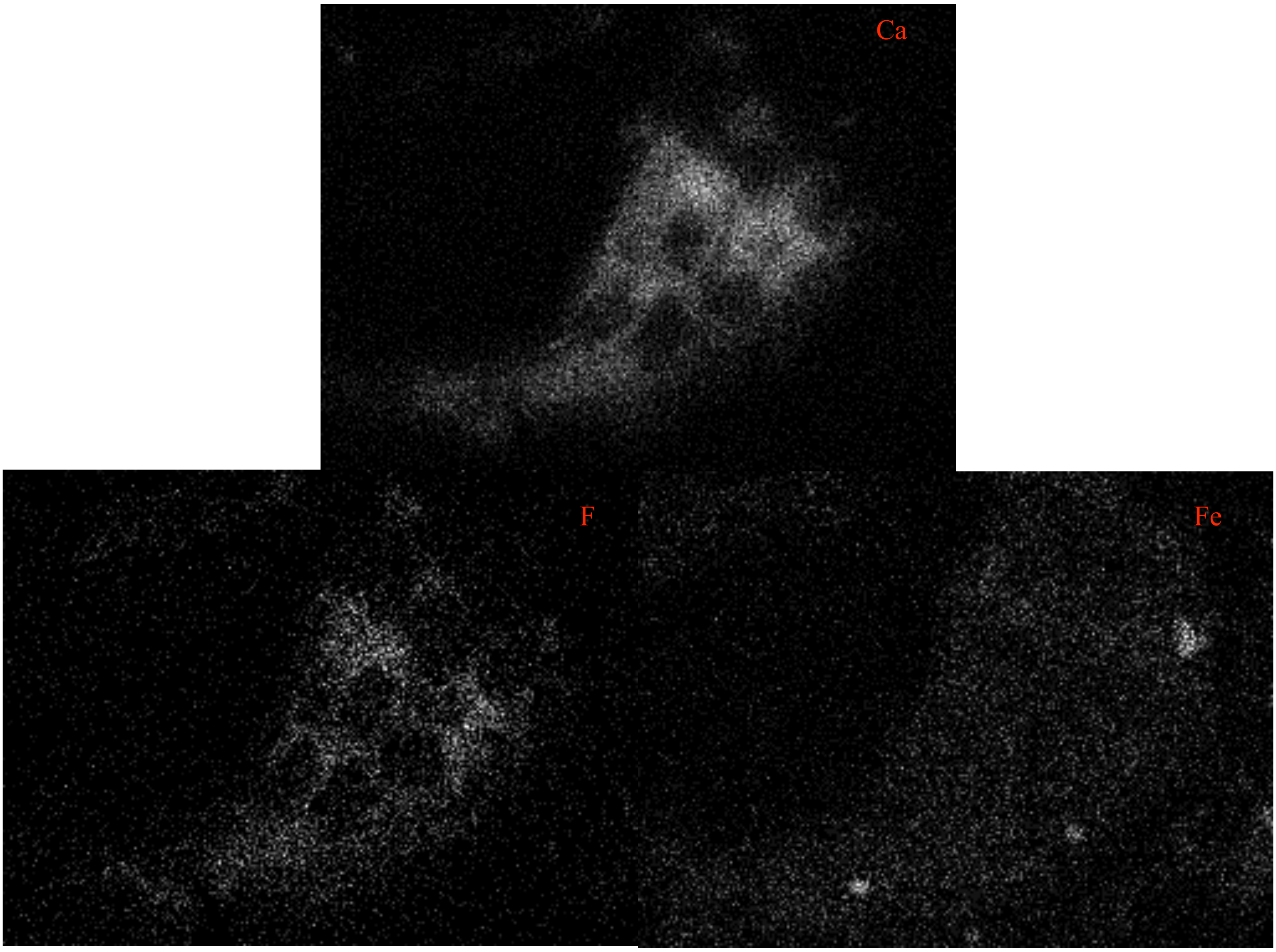


Figure 3.19: X-ray maps of TIND 1-4 Ca, F and Fe

In all of the 4 examples of fluorite found within the TIND sample chosen for analysis there seems to be evidence that the fluorite is dissolving or being replaced. One of the most dramatic visual examples is Figure 3.18, where the fluorite seems to be in the process of being replaced. Other evidence of replacement is from the TIND 1-2 site. Table 3.5 shows a comparison of the spot analysis at points 1 and 3 (Figure 3.13).

TIND 2-1 Point 1			TIND 2-1 Point 3		
Element	**Element %**	**Atomic %**	**Element**	**Element %**	**Atomic %**
F	41.8	59	**F**	15.4	24.0
Na	0.3	0.4	**Na**	2.7	3.4
Mg	1.9	2.1	**Mg**	0.5	0.6
Al	1.1	1.1	**Al**	11.2	12.3
Si	2.4	2.3	**Si**	26.9	28.5
P	1.8	1.6	**P**	1.2	1.2
K	1.1	0.8	**K**	5.4	4.1
Ca	47.1	31.6	**Ca**	29.9	22.1
Ti	0.4	0.3	**Ti**	1.3	0.8
Mn	0.3	0.2	**Mn**	0.1	0.1
Fe	1.7	0.8	**Fe**	5.4	2.9
Total	100.0	100.0	**Total**	100.0	100.0

Table 3.5: Comparison of spot analysis for TIND 2-1 (determined by semi-quantitative EDAX analysis and expressed on an oxygen-free basis).

At point 1 the amount of fluorine and calcium demonstrate that this mineral is fluorite (there is minor deviation from the ideal, as the atomic % of F and Ca should be in the ratio of 2:1). At point 3 however the amount of calcium and fluoride almost halves, and the relative proportion of Ca:F almost doubles, providing evidence that the fluorite at this point is being replaced with the loss of F greater than the loss of Ca. Similar results are also found in TIND 1-1 between points 1 and 2 (Figure 3.12).

There are two possible origins for the fluorite within the sample; either the fluorite is of magmatic origin, formed during the crystallisation of the magma, or it has formed by devitrification of a fluorine-bearing volcanic glass by reaction with groundwater at the Earth's surface. It was not possible as part of this study to determine the fluoride content of the volcanic glass. There is some evidence that devitrification is taking place; the needle like crystal growths in Figure 3.15 are evidence of this. Figure 3.15 would suggest that the fluorite has formed very late, as the crystal seems to be soaking into the glass. However the more likely explanation is that the fluorite is tied into discrete magmatic grains that have dissolved.

Although there appears to be evidence of fluorite dissolution, this does not definitively mean that the fluorite in this particular area is solely responsible for the high levels of fluoride, as the groundwater in this area may have come into contact with other geological conditions outside of the research area. In this area there is also some evidence of geothermal activity, close to the TIND site there is a series of warm springs. However when tested for fluoride within these springs it only returned a level of <1mg/l, suggesting that the geothermal system in this case is not related to the high levels of fluoride found in the TIND area.

3.4 Conclusion

While the source of the fluoride concentration within the groundwater cannot be determined with any certainty, the presence of fluorite found within the sample at Tindigani, and the textural evidence of its dissolution, would suggest that it quite possibly could be the source. What is clear from the water samples collected, however, is that the highest levels of fluoride in the groundwater and surface water are found in the south western part of the research area. Geologically this would match up with the high levels of fluoride being related to a different geological environment created by Meru, rather than the rest of the geology that is dominated by Kilimanjaro. The area surrounding Meru is already documented as having groundwater and surface waters with high natural levels of fluoride, so this would support the idea that it is the source of the high fluoride. In this area identified as having groundwater high in fluoride, the villages of Mtakuja and Tindigani were identified as being the most at risk due to the high levels of F (greater than the WHO recommended level) and the lack of alternative water sources.

Chapter 4: Impacts of Fluoride in Drinking Water on Human Health

This chapter will concentrate on the aim of investigating the impact of fluoride in drinking water by covering the following objectives.

- Identify those villages at risk from high concentrations of fluoride
- Conduct a survey to assess the prevalence of dental and skeletal fluorosis within the villages
- Assess contributing factors such as diet and its impact upon prevalence of fluorosis

4.1 Literature Review

This literature review will cover the literature related to the impact of fluoride in drinking water on human health, firstly reviewing the historical study of fluoride in drinking water and then considering current policy on drinking water standards and water fluoridation. Following this will be a more detailed look at fluoride intake and its relation to health.

4.1.1 History of Fluoride and Drinking Water

While fluoride has always been interacting with the humans who consume it, it was not until the early 1900s that scientists made the connection between the signs of fluorosis and the ingestion of high levels of fluoride. While many scientists contributed to the discovery and investigation it is perhaps McKay and Dean that provide us with most of the published data from this time. In 1916, McKay and Black identified a community in Colorado Springs that had mottled enamel but unusually the teeth also showed a resistance to dental caries[8] (McKay and Black, 1916, Black and McKay, 1916). Over the next 15 years scientists began to investigate the link between fluoride and mottled enamel. In 1931, the Science News journal published an article in which Dr. Margaret Cammack Smith claimed to have definitively proved the relationship between mottled teeth and fluoride in drinking water, speculating that poor nutrition could also exacerbate the condition (Smith, 1931). It was probably before 1931 that a connection was identified, at least linking drinking water with mottled enamel (McKay, 1930). This connection was also demonstrated in a study published in 1938 which had monitored a community in Arkansas for 10 years following a change in the water supply, from a supply containing high fluoride to one containing a low level of fluoride (Dean and McKay, 1938). Dean and McKay (1938) showed that this action was successful in halting the occurrence of severe dental fluorosis. McKay also showed, in his 1930 study, that reports of mottled enamel similar to those that he and Dean had investigated, were being reported in many other parts of the world; South America, Mexico and North Africa were all cited (McKay, 1930) which are all places known today to have water supplies affected with high levels of fluoride. McKay's 1930 paper also identified that the majority of the water sources identified with high levels of fluoride in the USA were from shallow or deep wells (McKay, 1930). What was of great interest to these pioneers was the ability of fluoride in drinking water to reduce the prevalence of dental caries. This led to the idea that there could possibly be a level of fluoride in drinking water at which prevalence of caries could be reduced without the side of effect of dental fluorosis (Dean and Elvove, 1937). This work in turn led to the public health initiative of fluoridating public water supplies which began in the 1940s (Burgstahler, 1965).

[8] Cavities

The damaging effects of fluorine (see 4.1.4.1) on bone from industrial exposure were observed in the 1930s (Roholm, 1937) and work began in the late 30's on studying the effect of fluoride on bone, which later became known as skeletal fluorosis (Burgstahler, 1965). A case study from China in 1946 identified bone deformities in a population drinking water high in fluoride, and although at this time it was not given the name skeletal fluorosis, it is clear from the descriptions that this was the case (Lyth, 1946). A later 1971 study based in India describes endemic skeletal fluorosis and refers to a series of studies throughout the 1940s and 1950s (Teotia et al., 1971). As for Tanzania, where the current project was based, probably the first extensive study took place in 1944 (MacQuillian, 1944) and is quoted in Latham's 1967 study (Lathman and Grech, 1967), as a study of chronic fluoride poisoning in the Arusha district, very close to the chosen area of study.

Although there have been numerous studies over the last 80 years looking at fluoride in drinking water and its impact upon the consumer, there are still some areas not fully researched. The fluoridation of public drinking water still remains a controversial issue.

4.1.2 Fluoridation of Public Water Supplies

While fluoridation of public water supplies mainly occurs in developed countries, and is not of relevance to Tanzanian communities affected by naturally occurring high levels of fluoride, the controversies and disagreements that surround safe fluoridation levels have a direct impact upon the standards set and adopted by water authorities and governments.

"One of the 10 great public health achievements of the 20^{th} century," so claimed the U.S. Centre for Disease Control and Prevention, when talking about the fluoridation of public water supply (CDC, 2008). If this statement is true then it is sad to see that in 2007 it was believed that only 5.7% of the world's population drank fluoridated water (Cheng et al., 2007). Fluoride is added to the water due to its perceived dental health benefits. As previously discussed, studies that began in the 1930s found that drinking water with a fluoride concentration of between 1-1.5mg/l can reduce the incidence of dental caries by around 50-60% without the "*aesthetically objectionable*" side effects of dental fluorosis (Dean and Elvove, 1937, Dean, 1938, Dean, 1952).

Even before the beginning of fluoridation of public water supplies doubts were raised over its safety. One of the early investigators of dental fluorosis in the USA, Dr. Margaret Cammack Smith, in 1940, warned that "*The range between toxic and non-toxic levels of fluorine ingestion are very small. Any procedure for increasing fluoride consumption to the so-called upper limit of non-toxicity would be hazardous. This would especially be true in the case of addition of fluoride to public food or water supplies where uncontrollable individual fluctuations in intake would be encountered" (Smith and Smith, 1940)*. In the same paper Smith and Smith (1940) suggest that the benefits of reduced dental caries may in fact be negated by the reduction of the integrity of the tooth structure. These feelings were also held by Burgstahler (1965), who mentions that the lack of data on the effects of ingested fluoride and suggests that perhaps that controlling dietary factors would be a better and safer control of dental caries than the use of fluoride. Today opposition to fluoridation of public water supplies still remains, with some people calling for a cessation of fluoridation, such as Ananian *et al.* (2006) and Connett (2007) who claim to be backed up by a wealth of scientific evidence and respected members of the scientific community. On the other side of the argument there is a wealth of studies showing the benefits of fluoride (Crall, 2007, Stephen et al., 2002, Featherstone, 2000) and a number of prominent proponents such as the World Health Organization (WHO), American Dental Association (ADA) and the US Center for Disease Control (CDC). A recent article produced by the ADA is just part of an almost propaganda war, to try to educate the public in regards to the safety and benefits of fluoride (ADA, 2009). However it seems unlikely that the opposition to water fluoridation will end at any time soon, with many articles sometimes citing the same reports as proponents do in support. The opposition also seems to be spread across a spectrum of views from the scientific to the ridiculous, and it is difficult to distinguish real scientific study from wild speculation. On the scientific side, the most compelling arguments are the ones levelled at the lack of data on long-term consumption of fluoride and its affect on health; the longest any water source has been artificially fluoridated is around 60 years. On the ridiculous side, such theories exist that water fluoridation was a communist plot or a method of government control, to undermine the intelligence and health of the American people (Johnston, 2004). A valid point worth noting though is that presently fluoridated drinking water is not the only source of fluoride for many people. Fluoride is also present in most dental products, such as mouthwash and toothpaste and is present in some processed food and drink due to the manufacturing process where fluoridated water or certain processes are used (Clarkson and McLoughlin, 2000). Clarkson and McLoughlin (2000) would support the inclusion of fluoride in dental products and food as they perceive the dental benefits to outweigh the risk of fluorosis. However other studies, even those in support of the use of fluoride, would say that when fluoridated water was first introduced, fluoride was not obtained from these other sources, which means that it is likely that people drinking fluoridated water and using such products are getting too much fluoride, which could increase the prevalence of fluorosis (Griffin et al., 2002, Burt, 1992). In light of this, though, the main source of fluoride intake will, in most cases, be from drinking water, especially when the level of fluoride is above recommended level of 1.5mg/l (WHO, 2004).

What is true from the data available is that there are still knowledge gaps in terms of the long term effects of fluoride and its interaction with the human body (Cheng et al., 2007). It is worth noting that most of this discussion over water fluoridation concerns the effect of long term consumption of drinking water containing 1.5mg/l. For many communities, such as those investigated in Tanzania, drinking water contains well in excess of 1.5mg/l (Ayoob and Gupta, 2006), and no one from the scientific community would argue that regularly drinking water over 1.5mg/l could not lead to dental fluorosis and with increased concentration, skeletal fluorosis.

4.1.3 Fluoride Drinking Water Standards

The drinking water standards for fluoride are built on work done in the 1930s. McKay and Black found that communities exhibiting dental fluorosis also had a lower incidence of dental caries (McKay and Black, 1916, Black and McKay, 1916). This led to the hypothesis that a minimum concentration of fluoride in drinking water could be established which would mean that dental caries could be reduced without the side effect of dental fluorosis. Dean and Elvove conducted a number of studies in the 1930s to investigate what an acceptable level of fluoride would be (Dean and Elvove, 1937). Their 1937 study compared 10 cities with drinking water fluoride levels ranging from 0.6 to 4.4mg/l, and one of their conclusions was that the evidence pointed towards the fact that "*amounts of fluoride (F) not exceeding 1 part per million are of no public health significance*" (Dean and Elvove, 1937) . It was on the basis of these preliminary studies that in 1984 WHO adopted 1.5mg/l as the standard for fluoride in drinking water (Fawell et al., 2006).

Fawell *et al.* (2006) state that in their investigation of an acceptable fluoride concentration it is found that levels above 1.5mg/l can be associated with dental fluorosis and levels exceeding 10mg/l can be associated with crippling skeletal fluorosis. The reference to crippling skeletal fluorosis occurring at 10mg/l however is contradicted in another WHO publication (WHO, 2002) which cites data from Chaoke *et al.* (1997), Choubisa *et al.* (1997) and Xu *et al.* (1997), that shows that skeletal fluorosis can occur at water fluoride concentrations as low as 4mg/l, 1.4mg/l and 0.65mg/l respectively. Choubisa *et al.* (1997) indicated that cases of crippling skeletal fluorosis occurred at levels of 3mg/l. Fawell *et al*. (2006) does make clear that factors such as temperature, consumption and altitude are factors which can affect what fluoride drinking water standard concentration should be adopted. An example of this is Senegal (Brouwer et al., 1988), where the high temperatures led to greater consumption of drinking water, which was believed to be causing higher prevalence of fluorosis than would expected for the measured concentration of fluoride in the drinking water. However the value of 10mg/l mentioned by Fawell *et al. (2006)* as a limit under which crippling skeletal fluorosis would not occur could be considered misleading, furthermore, there are no guidelines for water fluoride standards for communities at high altitude or located in tropical climates. Most countries have adopted a standard with in the WHO guidelines of 1.5mg/l. However some countries such as Tanzania have so far only adopted temporary drinking water standards, especially for areas with no alternative water supplies (Kaseva, 2006b).

The Tanzania standard for fluoride within drinking water is currently 8mg/l (Kaseva, 2006b, Ayoob and Gupta, 2006). One of the main reasons for this could be the economic stress that would be created by adopting the WHO standards, as a large proportion of Tanzania's water sources are informal, and a large proportion of the population are rural. The costs of setting up the infrastructure to monitor the water supply, in providing treatment and ensuring compliance are probably too much. It is believed that if the WHO standard was adopted, over 30% of the known water sources in Tanzania would have to be closed down (Ayoob and Gupta, 2006, Kaseva, 2006b). However, many of the population are drinking water that has well in excess of 8mg/l of fluoride. So in a way the standard itself is defunct, and in any case adopting a standard of 8mg/l of fluoride means that a number of people will suffer from dental and skeletal fluorosis while apparently drinking "safe" water.

4.1.4 Fluoride and Health

There are 3 pathways identified for uptake of fluoride in humans. These are inhalation, deposition and absorption on the skin, and ingestion (Weinstein and Davison, 2004). Ingestion is considered the main pathway for fluoride uptake by humans with over 50% of the daily intake being attributed to drinking water (Weinstein and Davison, 2004). Where the drinking water contains high concentrations of fluoride this can have serious affect on the consumer's health. This study will concentrate on the effect of fluoride via ingestion, mainly through drinking water. While ingestion via food will be discussed, drinking water will be the primary focus, i.e. uptake via inhalation and absorption will be considered negligible.

4.1.4.1 Skeletal Fluorosis

Fluoride is a natural constituent of the human skeleton. Weinstein and Davison (2004) cite that 50% of the absorbed fluoride is excreted via the urine and of the remaining absorbed fluoride over 99% is absorbed into calcified tissues, bones and teeth depending on the total exposure to fluoride. Studies such as that by Zipkin et al. (1958) showed that with a prolonged ingestion of fluoride via drinking water, the fluoride content of the bones increased linearly with an increase of fluoride concentration of the drinking water.

Seventy percent of bone is made up of hydroxyapatite, a crystalline inorganic mineral that gives strength to the bone (Heritage, 2002). Absorbed fluoride is taken up by the hydroxyapatite, forming fluoroapatite (WHO, 2002), a process which alters the structure and size of the crystals. If there is long term exposure to fluoride, the increased amount of fluoroapatite in the bones can decrease the strength and quality of the bone (Ayoob and Gupta, 2006), which may in turn lead to increased bone fracture (Li et al., 2001). This, in essence, is the cause of skeletal fluorosis which has a variety of associated health disorders, the most common being osteomalcia[9] (known as rickets in children), secondary hyperthyroidism[10], hypocalcemia[11], osteoporosis[12], osteosclerosis[13] and exostoses[14] (Tamer et al., 2007, Pettifor et al., 1989, Weinstein and Davison, 2004, Mithal et al., 1993, Wang et al., 1994). Skeletal fluorosis can usually be identified via X-ray. Commonly in a person suffering from skeletal

[9] A disease characterised by a softening of the bone with accompanying pain and weakness. Can lead to skeletal deformities.

[10] A disease characterised by a reduction of the function of the thyroid glands leading to various health complications.

[11] Abnormally low levels of calcium in the blood

[12] A disease where the bones become extremely porous, and are subject to fracture, heal slowly and often lead to spine curvature.

[13] An abnormal hardening of the bone

[14] The formation of new bone on the surface of a bone, which can cause chronic pain ranging from mild to debilitating.

fluorosis the skeleton becomes calcified and there are various other radiological changes that can be identified (Wang et al., 1994).

The severity of skeletal fluorosis can vary, and can depend on the duration of exposure, the age, the gender, the amount consumed and the fluoride concentration the person is exposed to. In its early stages skeletal fluorosis can be asymptomatic which means that it can only be identified via radiological examination. After this pain can develop in the joints, and in the final stage there can be deformity of the skeleton including kyphosis (curvature of the spine viewed from the side), scoliosis (lateral curvature of the spine), fused spine or joints, deformity of the knee joints, 'Genu Valgum' (knock knees), 'Genu vaum' (bow legs) and paralysis. Paralysis mainly occurs due to exostoses and the pressure put on the spine by the deformities, and exostoses within the ear can also lead to a loss of hearing (Khandare et al., 2007, Weinstein, 2005, Jolly et al., 1968, Ayoob and Gupta, 2006, WHO, 2002).

There are a number of classifications used to describe the varying severity of skeletal fluorosis; Table 4.1 gives one that is commonly used.

Skeletal Fluorosis Grade	Clinical Symptoms
Grade I	Mild generalised bone and joint pain.
Grade II	Moderate bone and joint pain, stiffness and rigidity, restricted movements at spine and joints.
Grade III	Severe symptoms of moderate grading with deformities of the spine and limbs, knock knees, crippled state.

Table 4.1: Grading of skeletal fluorosis in terms of clinical symptoms source: (Shashi et al., 2008)

Skeletal fluorosis with its associated bone deformities was first described in detail by Roholm (1937) in relation to workers in the cryolite industry, though this was related to ingestion of the dust from the industrial processes. In 1945 an article in the Lancet (Lyth, 1946) described a number of cases of skeletal fluorosis related to drinking water sources with a fluoride content between 2.4mg/l and 13.1mg/l in China. In the years following these founding studies there does not as yet seem to be a definitive fluoride concentration at which skeletal fluorosis occurs. There has been some thought that crippling skeletal fluorosis only occurs with drinking water with elevated fluoride concentrations of >8mg/l but there is evidence against this from studies that demonstrate cases of skeletal fluorosis where the fluoride concentration of the drinking water is <8mg/l (Disendorf, 1988). This view was still published by WHO in their fluoride in drinking water guidelines which state "*crippling skeletal fluorosis can ensue when fluoride levels exceed 10mg/l*" (Fawell et al., 2006). Another view held is that crippling fluorosis can occur with fluoride water concentrations of 5-10mg/l for a person who ingests 2 litres per day for at least 10 years (ATSDR, 2003). However current studies, mainly based in India, seem to suggest that skeletal fluorosis can occur in populations using water with fluoride concentrations of 2-3mg/l (with one report of 0.7mg/l), and that crippling skeletal fluorosis has been reported at 2.8mgF/l (Ayoob and Gupta, 2006). What has also been reported is that there can be variation in severity of skeletal fluorosis, within a population who are consuming the same level of fluoride and have similar nutrition and life habits (Wang et al., 1994). There seems to be limited information available on the susceptibility of a person to develop skeletal fluorosis. What is clear from current though is that as the concentration of fluoride increases the percentage of the population accessing that water who show symptoms of skeletal fluorosis also increases. The increase is not necessarily linear, as complicating factors such as altitude, duration of exposure, genetics, age of population and total fluoride exposure from other potential sources of fluoride need to be taken into account for different populations.

In Tanzania, there have been two major studies into populations suffering from skeletal fluorosis. Perhaps most applicable to this project is that of Christie (1980) who studied a population near Arusha in northern Tanzania, consuming drinking water containing 21mg/l of fluoride. His study population was children under the age of 16 and he found that 52% of the 251 children surveyed had deformities related to skeletal fluorosis with around 90% complaining of joint pain. These findings were confirmed with X-rays taken of a selection of the children. The number of affected children with visible skeletal deformities was spread widely across the age range of 2-16 which is well within the suggested 10 year consumption needed to develop crippling skeletal fluorosis suggested by ATSDR (2003). What is interesting though is that similar studies in India with much lower water concentrations of fluoride, found a higher prevalence of skeletal fluorosis such as a 60.6% prevalence with a 1.5-11.5mgF/l, a 70.7% prevalence with 6.0-16.2mgF/ (Jolly et al., 1968) and a 63% prevalence with 6.0mgF/l (Choubisa et al., 1997). Latham and Grech (1967) describe another study that also took place near Arusha in northern Tanzania. While the majority of the results were concerned with dental fluorosis, 112 people were X-rayed of whom 87% were identified as having skeletal fluorosis. The populations these people were taken from were accessing water sources with 1.1 to 45.5mgF/l. The figure of 87% does not indicate the prevalence of skeletal fluorosis as the 112 X-rayed were not a random sample, as those selected were suspected as having skeletal fluorosis and selected on that basis. The purpose of the study was to prove that exposure to fluoride caused bone changes in this area of Tanzania.

4.1.4.2 Dental Fluorosis

The process of dental fluorosis occurs during the crystallisation process while the teeth are forming in the gums. It affects the mineralization of the teeth and is given the term hypomineralisation (WHO, 2002). Similarly to skeletal fluorosis, the fluoride affects the hydroxyapatite structure of the teeth to form fluorapatite. Fluroapatite is more resistant to acid breakdown than hydroxyapatite, which leads to reduced incidence of caries. The reaction between fluoride and hydroxyapatite can also lead to the remineralisation of caries. However if the intake of fluoride is too high it can damage enamel-forming cells (ameloblasts) and reduce protein absorption during the enamel maturation stage, which causes increased porosity of the sub-surface enamel, leading to dental fluorosis (Aoba, 1997). The severity of dental fluorosis can vary from small white marks on the surface of the teeth to brown staining and to an eventual breaking down of the tooth enamel surface (Weinstein and Davison, 2004).

While skeletal fluorosis can occur at any age due to the process of bone remodelling in the skeleton and is also evidence of long term exposure to fluoride, dental fluorosis is shown to be only "*indicative of the level of exposure to fluoride only during the period of enamel formation*" (WHO, 2002). Since it occurs in the period of time during enamel formation, the critical period is between the ages of birth and 5 years, in some cases 8 years until the third molar teeth are fully formed (Aoba, 1997, Budipramana et al., 2002). This means that dental fluorosis seen in adults, will have been caused by consuming high levels of fluoride in their childhood. There are many studies that have looked at the severity of dental fluorosis associated with different fluoride intake levels. As previously mentioned, the standard for fluoride in drinking water is 1.5mg/l (Fawell et al., 2006), which has been decided is the level at which the dental health benefits are less than the risk of dental fluorosis. Table 4.2 shows the concentration of fluoride in the drinking water related to the severity of dental fluorosis, contained in a recent review of fluoride and health (Ozsvath, 2009). However these values do not take into account any additional factors such as exposure via food and other pathways.

Fluoride Concentrations (mg/l)	**Effect on Human Health**
<0.5	Conducive to dental caries
0.5-1.5	Promotes development of strong bones and teeth
1.5-4.0	Promotes dental fluorosis in children
>4.0	Promotes dental and skeletal fluorosis
>10	Crippling skeletal fluorosis, possibly cancer.

Table 4.2: Effects of fluoride ingestion on human health (Source: (Ozsvath, 2009))

The severity of dental fluorosis is measured using a variety of indices, all similar in that it is classified on an ordinal scale with the higher number indicating greater severity. The three most commonly used indices are the Dean's Index, the Thylstrup-Fejerskov index (TFI) and the Tooth Surface Index of Fluorosis (TSIF) (Doull et al., 2006, Rozier, 1994).

4.1.4.3 Other Health Impacts

In the literature references can be found to other health impacts caused by consuming large amounts of fluoride such as effects on children's intelligence (Xiang et al., 2003), cancer (Connett, 2007) and reproduction. This literature should be approached sceptically, as many prominent scientists and organisations such as WHO state such claims are unfounded (Ayoob et al., 2008, Weinstein and Davison, 2004, WHO, 2002). However it is important to stress that most of the literature is concerned with low concentrations of fluoride in drinking water (1-5mg/l) consumed over a long period of time. There may be different health concerns for consumers of higher fluoride concentrations over a long period of time. In some areas, such as the villages that provide the focus for this study the fluoride concentration of water is 20-35mg/l. It is not known how consuming such a high concentration of fluoride will affect the human body. For example, it has been shown that the placenta provides a barrier to fluoride between mother and foetus (Bjorvatn et al., 2000, Ozsvath, 2009). However Ozsvath (2009) points out that there has been a lack of quality investigation into the placental barrier at high levels of ingestion. A systematic review carried out by McDonagh *et al.* (2000) reviewed studies pertaining to fluoride and health. McDonagh *et al.* (2000) ranked the quality of the studies on a scale of A (low) - C (high), based on the risk of bias within the paper. All the studies related to “other health affects” such as Down syndrome, cancer and children’s intelligence scored C, and one of the conclusions of this review was that more high quality studies were needed (McDonagh et al., 2000).

4.1.4.4 Complicating Factors

As mentioned in the proceeding sections, there are a number of factors that can affect the severity of dental or skeletal fluorosis. Perhaps the three most important factors are altitude, temperature and nutrition. Altitude has been shown to be a risk factor and studies have shown that at higher altitude the prevalence of dental fluorosis increases (Pontigo-Loyola et al., 2008, Yoder et al., 1998); no studies have yet studied the link between skeletal fluorosis and altitude. The actual reasons why altitude is associated with an increase the prevalence of fluorosis is not fully understood, suggestions range from metabolic effects to iodine deficiency which occur at higher altitudes (Pontigo-Loyola et al., 2008).

The factor of temperature is mainly to do with the increase in consumption of water that comes with residing in a warmer climate. In warmer climates people will tend to drink more than in temperate climates, and ingest more fluoride and this can lead to higher prevalence levels of dental fluorosis at lower water fluoride concentrations. This was demonstrated by Brouwer *et al.* (1988) who demonstrated that in countries with higher annual temperatures and drinking water within WHO standards had a higher prevalence of dental fluorosis than expected.

Nutrition is important in regards to fluoride exposure from two aspects. First of all the fluoride content of the food can add to the overall intake of fluoride (Ayoob and Gupta, 2006), and if the food is prepared with water that is high in fluoride this will also add to the intake. An example of this in East Africa which has added to the fluorosis burden is magadi, also know as trona, a local food additive which can speed up cooking times and is used as a tenderiser for certain foods (Kaseva, 2006a). Magadi is a salt produced by evaporation of the water of Lake Magadi, Kenya. Studies have shown that in areas where the drinking water is low in fluoride, dental fluorosis can occur purely due to the use of magadi (Nielsen and Dahi, 2002, Nielsen, 1999, Kaseva, 2006a). The other aspect of nutrition is that balanced nutrition can help to reduce the adsorption of fluoride into the body and thus reduce the effect of dental or skeletal fluorosis; conversely malnutrition can exacerbate the fluorosis problem (Mithal et al., 1993, Ayoob and Gupta, 2006). For example, studies have shown that calcium is a very important nutritional aspect in relation to fluorosis (Wang et al., 1994, Mithal et al., 1993). For a consumer with a diet rich in calcium, studies have shown that when fluoride rich water is taken with a calcium-rich meal, less fluoride is absorbed (Weinstein and Davison, 2004). Thus the problems of fluorosis can be further exacerbated by a low calcium diet (Mithal et al., 1993, Pettifor et al., 1989). Tanzania is one of the many countries where the majority of the population lives under the poverty line, so malnutrition is widespread. Studies on the effect of magadi on the fluorosis burden have been carried out in Tanzania close to the study area, so this is a factor that needs to be accounted for during the study.

4.1.5 Summary of Literary review

What is clear from the literature is that drinking water that contains fluoride in excess of 1.5mg/l can lead to dental and skeletal fluorosis. The levels of fluoride consumption at which both of these conditions occur seems to vary from place to place and there are a number of factors, such as nutrition, that can influence the prevalence and severity of fluorosis. There is the possibility of other health effects at high intakes of fluoride but there is a lack of reliable studies and evidence to be sure about this. The literature on fluoride and health can be tainted by bias from both camps that are either for or against fluoridating public water supplies. Because of this potential bias the quality of studies seems to suffer and papers can seemingly contradict each other. Unfortunately this means that studies pertaining to those communities affected by naturally occurring fluoride in drinking water sources, at concentrations much greater than public fluoridated water, are often affected. The studies that have taken place in Northern Tanzania have indicated that dental fluorosis and skeletal fluorosis are present and that water fluoride concentrations can be in excess of 20mgF/l. With such high concentrations of fluoride the literature would suggest that dental fluorosis and skeletal fluorosis might affect a high proportion of the consuming population.

4.2 Materials and Methods

After establishing the fluoride concentrations in the drinking water sources across the Hai region, the villages of Mtakuja and Tindigani were considered to be the most at risk of developing dental and skeletal fluorosis. A study was carried out to assess the prevalence of dental fluorosis and skeletal fluorosis deformities in primary school-age children in two villages. The primary school in each village was chosen as a sample population and a survey was conducted among 158 children in Tindigani and 118 children in Mtakuja. The children were 5 to 17 years old, as children attending school was not mandatory in this area. The survey was carried out in each school over 2 consecutive days in November 2007. Permission for the survey was granted by COSTECH (Tanzania commission for science and technology), local community leaders and parents of the students. The community was provided with an information sheet, translated into Swahili, detailing the survey and parental permission forms for the school students involved in the survey (Appendix E). Only the children who were present and had been granted parental consent were surveyed. For each participant the following were recorded: demographic details, the location and type of drinking water source used at home, a written and photographic record of any signs of dental fluorosis or skeletal fluorosis, a history of where the children had lived throughout their lives, and a brief history of fluorosis in the family (Appendix F). The height and weight of each child was measured and their body mass index (BMI) calculated. These BMIs were compared against charts prepared by the National Centre for Health Statistics for African American males (Center for Disease Control, 2000a) and females (Center for Disease Control, 2000b) aged between 2 and 20 years. Food diaries were given out to each child who was surveyed (Appendix G). The children were asked to fill in the diaries for 3 days, indicating what they ate and how much. For younger children, they were asked to simply fill in the type of food they ate.

A value for dental fluorosis was calculated using the tooth surface index of fluorosis (TSFI) scale. This is based on a score of 0-7 and is summarised in Table 4.3.

Score	Criteria
0	Enamel shows no evidence of fluorosis.
1	Enamel shows definite evidence of fluorosis, namely, areas with parchment-white colour that total less than one-third of the visible enamel surface. This category includes fluorosis confined only to incisal edges of anterior teeth and cusp tips of posterior teeth ("snowcapping").
2	Parchment-white fluorosis totals at least one third of the visible surface, but less than two thirds.
3	Parchment-white fluorosis totals at least two thirds of the visible surface.
4	Enamel shows staining in conjunction with any of the preceding levels of fluorosis. Staining is defined as an area of definite discoloration that may range from light to very dark brown.
5	Discrete pitting of the enamel exists, unaccompanied by evidence of staining of intact enamel. A pit is defined as a definite physical defect in the enamel surface with a rough floor that is surrounded by a wall of intact enamel. The pitted area is usually stained or differs in colour from the surrounding enamel.
6	Both discrete pitting and staining of the intact enamel exist.
7	Confluent pitting of the enamel surface exists. Large areas of enamel may be missing, and the anatomy of the tooth may be altered. Dark-brown staining is usually present.

Table 4.3: Scoring System of TSFI, source: (Rozier, 1994)

As part of the survey, photographs were taken of the children's incisors and canines (6 front teeth) using a Canon Powershot G7 (www.canon.com). The settings of the camera were set to the highest quality available with an image size of 800 x 600 pixels. A tripod and a length of string (30cm) were used to ensure the photograph was taken from the same angle and distance each time. A headlamp was used to ensure the lighting remained as consistent as possible. The TSFI scores were calculated using these photographs, based on the condition of the upper and lower central incisors, lateral incisors and canines. Photographs where these teeth were not visible or where user error led to a blurred photograph were discarded.

Evident skeletal deformities were identified and recorded by a team of three local doctors. The leg deformities were categorised into 3 main types: Genu Valgum (bowed legs), Genu Vaum (knock knees, figure 4.1) and Sabre Tibia (forward bowing of the tibia), categorisations used in previous studies (Ayoob and Gupta, 2006, Christie, 1980).

Figure 4.1: Male child suffering from skeletal fluorosis (Genu Vaum) in the village of Mtakuja (October 2007)

The collected survey data was input into a database using Microsoft Access 2006 (www.microsoft.com). Statistical analysis of the data was carried out using JMP 8.0 (SAS Institute, Inc). Differences in mean TSFI scores between males and females, residents and non-residents and age groups (0-6 years, 7-9 years and 10+ years) were assessed using Student's t-test. Differences between mean TSFI scores in regards to drinking water source types were assessed using the Tukey Kramer HSD test.

4.3 Results

4.3.1 Drinking Water Source

During their lives, 75% of the study population, in Mtakuja and 94% in Tindigani were born and resided only in their village. Five different types of drinking water sources were identified. In Mtakuja and Tindigani only 3.4% and 7.6% of students, respectively, used more than one identified water source. During the school day all the children drank from the school's water source, which was also used for cooking their lunch. In Tindigani, the school's water source was a borehole and in Mtakuja a hand-dug well. The home drinking water sources for children are shown in Table 4.4.

Village	Main Drinking Water Source	No. Of Children Using Source	Percent
Mtakuja	Hand-dug Well	104	88.1
	Piped Water	10	8.5
	Hand-dug Well & Piped Water	4	3.4
	Total	**118**	**100.0**
Tindigani	Hand-dug Well	66	42.0
	Borehole	23	14.6
	Piped Water	40	25.5
	River/Stream Water	16	10.2
	Hand-dug Well & Piped Water	9	5.7
	Borehole & Piped Water	2	1.3
	Hand-dug Well & Borehole	1	0.6
	Total	**157**	**100.0**

Table 4.4: Drinking water sources used at home by school children in Tindigani and Mtakuja.

In Mtakuja, hand-dug wells were by far the most frequently used source in homes (88.1%), with only 11.9% having full or even partial access to piped water. In Tindigani, the sources were more varied with 32.5% having partial or full access to piped water and 10.2% using river water as their main source; however, the majority used groundwater via a hand-dug well or a borehole.

Fluoride concentrations were measured in all water sources identified by community leaders in both villages. Table 4.5 shows the average concentration of F measured in each source. There was only one borehole near the primary school and only one river source (the Njoro river) in Tindigani. The piped water available to both villages was from the same pipeline, but its outlets were only accessible to select parts of each village, as they were actually located in the adjacent villages of Kia and Sanya Station.

		Average Fluoride Concentration (mg/l)	Range (mg/l)
Mtakuja	**Hand-dug Well N = 9**	5.4	2.6-7.7
	Piped Water N = 1	0.4	
Tindigani	**Hand-dug Well N = 4**	23.5	21.2-26
	Borehole N = 1	25.0	
	Piped Water N = 1	0.4	
	River/Stream Water N = 1	0.2	

Table 4.5: Fluoride Concentrations of Water Sources in Mtakuja and Tindigani

All of the water sources, apart from the river and piped water, contained well above the WHO recommended concentration of 1.5 mgF/l. In general, the community at Mtakuja was drinking water with much lower fluoride concentrations than the community at Tindigani. These concentrations were comparable to those found in previous studies located in the neighbouring district of Arusha (Christie, 1980, Lathman and Grech, 1967).

4.3.2 Nutrition

Only eighty-seven food diaries were collected from students and they did not provide the data needed for an extensive analysis of the students' diet. Over 50% of the collected 3 day food dairies were incomplete. A lot of the students also found it difficult to identify how much of a particular type of food they ate. The useful evidence that was gathered from the food diaries, though, was that there was very little variation in the local diet. From the diaries collected every child ate a diet of maize, rice and beans. No child mentioned any dairy products in any of the three-day diaries collected, although from informal conversations it seemed meat and dairy products were eaten perhaps once a week in small quantities. This was important because it indicated that the children had a lack of calcium in their diet. Informal conversations also identified that magadi was often used during food preparation, which was known to potentially add to the total fluoride exposure (see section 3.1.4.4). From the health survey the children's BMI was calculated based on their sex and age . Table 4.6 shows the BMI percentiles for the children in the 2 villages.

Village	BMI Percentile	Frequency	Percent
Mtakuja	<5%	62	52.5
	5%-10%	16	13.6
	10%-25%	20	16.9
	25%-50%	17	14.4
	50%-75%	3	2.5
	75%+	0	0
	Total	118	100.0
Tindigani	<5%	71	45.2
	5%-10%	17	10.8
	10%-25%	41	26.1
	25%-50%	24	15.3
	50%-75%	4	2.5
	75%+	0	0
	Total	157	100.0

Table 4.6: Distribution (%) of BMI percentiles in children in Tindigani and Mtakuja.

The majority of the school children had a BMI that fell below the 5^{th} percentile, indicating that they were malnourished, with children in Mtakuja marginally more malnourished than those in Tindigani.

4.3.3 Dental Fluorosis

Most of the children's teeth were clearly affected by fluorosis (figure 4.2). For 15 children the photographs were blurred or did not show enough of the tooth surface for an accurate assessment and so were not included. Due to differences in tooth development, the school populations were split into three age categories based on tooth development (0-6, 7-9 and 10+ years) to allow more accurate comparison.

Figure 4.2: Young male (age 13) with dental fluorosis in Mtakuja Oct 2007

Table 4.7 shows the results by age group. There were only 3 children under the age of 6 at Tindigani and none at Mtakuja; these were therefore excluded from statistical analysis due to their small number.

Village	Age Range	N	Minimum	Maximum	Mean	SD
Mtakuja	7-9 yrs	24	3	6	4.71	0.91
	10+ yrs	94	0	7	4.91	1.22
Tindigani	0-6 yrs	3	2	6	4.33	2.08
	7-9 yrs	50	1	7	4.46	1.13
	10+ yrs	89	2	7	4.83	0.98
	Missing	15	-	-	-	-

Table 4.7: TSFI scores in different age groups in Tingidani and Mtakuja. SD – standard deviation.

The prevalence of fluorosis was over 99% for the population of both schools, recording only one child having no dental fluorosis. The majority of children had dental fluorosis with a TSFI score between 4 and 6. Table 4.7 shows the means and standard deviation (SD) for each age range. There was no statistical significant difference in TSFI between the corresponding age groups in each village (7-9 yrs p=0.35, 10+ yrs p=0.63). These results were unexpected as the water sources in Tindigani had, in nearly all cases, almost double the amount of fluoride of those found in Mtakuja, assuming that the drinking water was the main source of fluoride exposure. There were no significant differences between the male and female populations (p=0.52) for all children. There was also no significant difference between the children who were born in the villages and those who had come from outside (p=0.28). However there was a significant difference between the age groups 7-9 and 10+ years (p=0.03). There were 15 photos from Mtakuja that could not be scored due to poor lighting. Fig 4.3 shows a sample of the photographs taken during the survey.

Figure 4.3: Sample of photographs taken during survey. Photographs like these were used to calculate TSFI scores.

Table 4.8 shows the drinking water sources used in each village alongside the corresponding mean TSFI values for those drinking from each source. In both villages there was no correlation between the drinking water source and mean TSFI using the Tukey Kramer HSD test.

Village	Drinking Water Source	Mean TSFI	N	SD
Mtakuja	Hand-dug Well	4.91	104	1.12
	Piped Water	4.40	10	1.71
	Hand-dug Well & Piped Water	5.00	4	0.82
	Total	4.87	118	1.17
Tindigani	Hand-dug Well	4.58	60	1.08
	Borehole	4.55	20	1.05
	Piped Water	4.75	36	0.91
	River/Stream Water	5.07	15	1.33
	Hand-dug Well & Piped Water	5.00	8	0.76
	Borehole & Piped Water	4.00	2	2.83
	Hand-dug Well & Borehole	5.00	1	.
	Total	4.69	142	1.07

Table 4.8: TSFI means for different water sources in Mtakuja and Tindigani. SD – standard deviation

4.3.4 Skeletal Fluorosis

Results of the leg deformity survey are shown in Table 4.9. Over one quarter of the children in both schools were identified as having leg deformities (Tindigani 31%, Mtakuja 25%).

Village	Type of Deformity	Frequency	Percent
Mtakuja	**No Deformity**	88	74.6
	Knock Knee	18	15.3
	Bowed Legs	11	9.3
	Sabre Tibia	1	0.8
	Total	**118**	**100.0**
Tindigani	**No Deformity**	109	69.4
	Knock Knee	30	19.1
	Bowed Legs	12	7.6
	Sabre Tibia	6	3.8
	Total	**157**	**100.0**

Table 4.9: Leg deformities seen in children aged between 6 to 17 in Mtakuja and Tindigani

4.4 Discussion

This study has demonstrated a significant problem with dental fluorosis and skeletal fluorosis in two villages in northern Tanzania. Why children from the two villages appear to be equally affected by fluorosis despite significantly higher fluoride levels in the water sources in Tindigani is not clear. The lack of correlation between drinking water source fluoride concentration and dental fluorosis severity may partly be due to the fact that the biggest impact will be from the water source used during the first two years of life. The use of piped water, which would generally reduce the overall level of dental fluorosis, was only provided in this area over the last 10 years and it is possible that only recently families began to access it. This may contribute to the significant difference in TSFI score between the age groups, with the 7-9 years group having a lower TSFI scores, suggesting a change in fluoride intake in the younger children. Another reason could be caused by the different stages of tooth development being observed in the children, for example in the older children the heightened staining may be caused by post-eruptive effects of the fluoride, If there is a change in fluoride intake then it should be expected that an even greater difference would be seen in the next generation of school children. However it is important to note that from a clinical perspective the difference in the TSFI scores is of minor impact, in that the scores of 4.3 and 4.8, for example, are indicative of severe dental fluorosis. Moreover, a more accurate assessment of dental fluorosis, which included the posterior teeth, where fluorosis is more visible, as well as the anterior teeth, may have offered a more sensitive detection of dental fluorosis and thus better differentiated the two populations.

From the nutritional data, several factors were identified that may contribute to skeletal deformities. First, there was a lack of calcium within the children's diet. This can exacerbate the problem of skeletal fluorosis leading to osteoporosis. Second, malnourishment, which was particularly common among the children in both schools, can cause stunted growth and prevent the development of a healthy strong skeletal structure. Studies have shown that a diet with regular adequate calcium intake can reduce the effects of high fluoride, as discussed in Weinstein and Davison (2004), partly through binding fluoride in the gut, thus preventing its absorption.

One of the most notable results is that there was relatively little difference in the amount and severity of the dental and skeletal fluorosis both in Mtakuja and Tindigani, despite a difference in the concentration of fluoride within the drinking water sources. Therefore, what this may suggest is that there is a maximum level of fluoride that can be absorbed by an individual and once intake reaches this saturation level additional effects are not seen even at high water fluoride concentrations.

Another factor may be magadi, which studies in Tanzania have shown can in some cases contain high levels of fluoride (Awadia et al., 2000, Kaseva, 2006a, Nielsen and Dahi, 2002). The use of magadi in both villages may substantially add to daily fluoride intake and increase the incidence of dental fluorosis. While this may account for why there is little difference between the dental fluorosis scores, magadi is also widely used in Tindigani and so the relative difference between the concentrations of fluoride in drinking water might still be evident in the dental fluorosis scores, which again maybe further evidence of a maximum fluoride threshold.

Comparing children who had moved to each village to those who had been born in the village, the difference between the TSFI scores was similar. It is possible that children who moved into each village may have done so at a very early age, or that they had high intake of fluoride at their previous residence as well.

Since dental fluorosis occurs during the first stages of life as the teeth are developing, drinking water, nutritional habits and other factors (Den Besten, 1994) from birth (and perhaps even before) will have a major effect on the level of dental fluorosis we see in the school age children. Thus, without this retrospective information, it is difficult to make any formal conclusions as to the exact reason for the lack of difference in dental fluorosis between the populations. What is clear, however, is that dental fluorosis is endemic in both populations.

Unlike dental fluorosis, bone deformities caused by a high intake of fluoride do not necessarily occur during the first 2 years of life; rather, it is expected that these will appear during the first weight bearing stages as the bones are still developing, and will affect the major weight bearing bones, i.e. the legs. Thus, if a population of all ages began drinking water high in fluoride at the same time, we would expect to see the most obvious deformities in the younger children and, to a lesser extent, the teenagers. The results of this study suggest that all the children surveyed had been exposed to high levels of fluoride at an age when their bones were still developing.

To make certain that these bone deformities were indeed skeletal fluorosis, X-rays would also need to be taken. However, the deformities seen in this population take in conjunction with the evidence of the high levels of fluoride suggest that fluoride is likely to be the main cause. Christie (1980) carried out a study of 252 children in a community drinking water with approximately 21 mgF/l and found 52% of the children had deformities (23% knock knees, 17% bowed legs, 12% sabre tibia). One reason for the lower rates reported may have been that only visible gross deformities were recorded and more subtle deformities were not. However, the number of deformities was still very high.

Overall the results of this part of the study depend on the limitations of the methods used. One limitation was that the food diaries were not completed sufficiently by the students taking part in the study and this in turn affected the amount of detail available on the communities diet. Another limitation was that the measurement of the severity of dental and skeletal fluorosis might have been prone to subjective error by the investigator. To improve the accuracy of the results, clinically trained specialists could have conducted the surveys and been supported by the collection of additional data such as x-rays and blood work. Although there may have been issues determining the grade of severity, the results were unaffected by observer error, they clearly indicated the present of dental and skeletal fluorosis and were sufficiently robust to indicate general levels of severity.

4.5 Conclusion

Many children with seemingly different levels of exposure to fluoride (that is, lower water source fluoride levels in Mtakuja than Tindigani) appear to have similar severity of both dental fluorosis and skeletal fluorosis. It is therefore likely that other factors, such as magadi intake, calcium intake, and genetics, play an important role. What cannot be ignored is that dental fluorosis and skeletal fluorosis are major problems in this area and there is an identifiable method of prevention, either through provision of a safe piped water source or de-fluoridation of high fluoride water in situ, both at a household and community level. Although the river Njoro in Tindigani provides water with an acceptable concentration of fluoride, it runs dry for most of the year and is not accessible to some parts of the village. The next stage of the study was to investigate the cost-effectiveness, efficacy, acceptability and sustainability of different de-fluoridation techniques, such as bone char filtration and solar stills.

Chapter 5: Treatment of Fluoride in Drinking Water

As demonstrated in the previous chapter, high concentrations of fluoride within drinking water create a wide range of health issues for the community. Thus it is important that the concentrations of fluoride are reduced to a safe level. One solution is to provide water from an alternative safe source if it is readably available. However, in some cases there are no viable alternatives available which leaves fluoride removal as the only option. There are a number of ways that fluoride can be removed from drinking water. This study was interested in only those treatment methods which could be applied in the developing world, and did not aim to provide an exhaustive insight into all current fluoride removal solutions. In light of this, the literature review concentrated solely on treatment methods currently available and being used in the developing world.

5.1 Literature Review

The health impacts of fluoride were discovered in the early 19th century (see chapter 4), and as early as 1937 the scientific community realised there would be a need for a method to reduce the fluoride concentration in drinking water sources (Elvove, 1937). Elvove (1937) investigated the use of tricalcium phosphate, magnesium oxide and magnesium hydroxide as viable coagulation treatment methods. In the present day there are a number of defluoridation methods being employed across the world. Similar to any type of water treatment the removal technologies for fluoride can be split into a number of categories; coagulation, adsorption, solar, electrochemical and membrane processes. Each of these processes and the associated technologies will be looked at in turn.

5.1.1 Coagulation Technologies

Coagulation is a method that requires the adding of a chemical to the water that will bind with the fluoride to make large particles, flocs, which can then be either filtered or will naturally settle and then be removed.

Ayoob *et al.* (2008) split defluoridation techniques which utilise coagulation into two types; precipitation of fluoride and coprecipitation of fluoride. Simply put, precipitation is where fluoride is part of the flocs formed and coprecipitation is where fluoride attaches to the formed flocs. For precipitation methods there are three main chemicals mentioned in the literature: lime, magnesium oxide and calcium and phosphate compounds (Ayoob et al., 2008).

While lime is mentioned as a viable defluoridation chemical it is not often used for defluoridation of drinking water for a number of reasons, that will be mentioned shortly. Rather it is used to treat industrial wastewaters with high levels of fluoride (Huang and Liu, 1999, Islam and Patel, 2007). Lime though is often used in the developing world in combination with other chemicals and treatment methods and the chemical principles involved in how lime works are applicable to most coagulation techniques. Lime is a calcium salt, $Ca(OH)_2$, and while other calcium salts can be utilised it seems to be the primary one used in defluoridation (Ayoob et al., 2008). Lime works due its reaction with the fluoride ions to form calcium fluoride (CaF_2) which precipitates (Sawyer et al., 1994). However, it is within this reaction that a number of limitations occur that make lime unviable for use on its own. Firstly, use of lime results in a high pH of the treated water, which is undesirable, thus to keep the pH of the water within the limits required for drinking water, the dose of lime needs to be carefully managed and further treatment to correct the pH would in most cases by required (Reardon and Wang, 2000, Islam and Patel, 2007). The amount of precipitation of CaF_2 that takes place is also dependent on the solubility of CaF_2 (Ayoob et al., 2008). Ayoob *et al.* (2008) stated that the theoretical residue fluoride post liming was 7.5mg/l. Other papers have reported high residues of 10mg/l and upward, and often even industrial waters treated with lime need further defluoridation before discharge (Islam and Patel, 2007, Shen et al., 2003, Reardon and Wang, 2000). These limitations alone, in addition to the residual chemicals within the treated water and the potential environmental hazard (Castel et al., 2000), mean that lime used solely on its own is not a viable drinking water treatment solution for the developing world. Ayoob *et al.* (2008) suggests that using a $CaCl_2$-lime mixture can help with the issue of high pH but the other limitations still remain.

Magnesium oxide ($Mg(OH)_2$) works similarly to lime and reacts with fluoride ions to form magnesium fluoride (MgF_2) which will precipitate (Ayoob et al., 2008). One similar drawback to lime is that it does raise the pH level of the treated water, which needs to be adjusted before being used as drinking water. As previously mentioned Elvove (1937) suggested the use of magnesium oxide as a viable defluoridation method for drinking water and its use has been discussed in the literature again over the years, such as in 1967 when Lisle (1967) took out a patent on a defluoridation design which utilised magnesium oxide. More recently, and applicable to the developing world, a method utilising magnesium oxide has been developed in India (Rao and Mamatha, 2004). The design of this treatment system is shown in Figure 5.1.

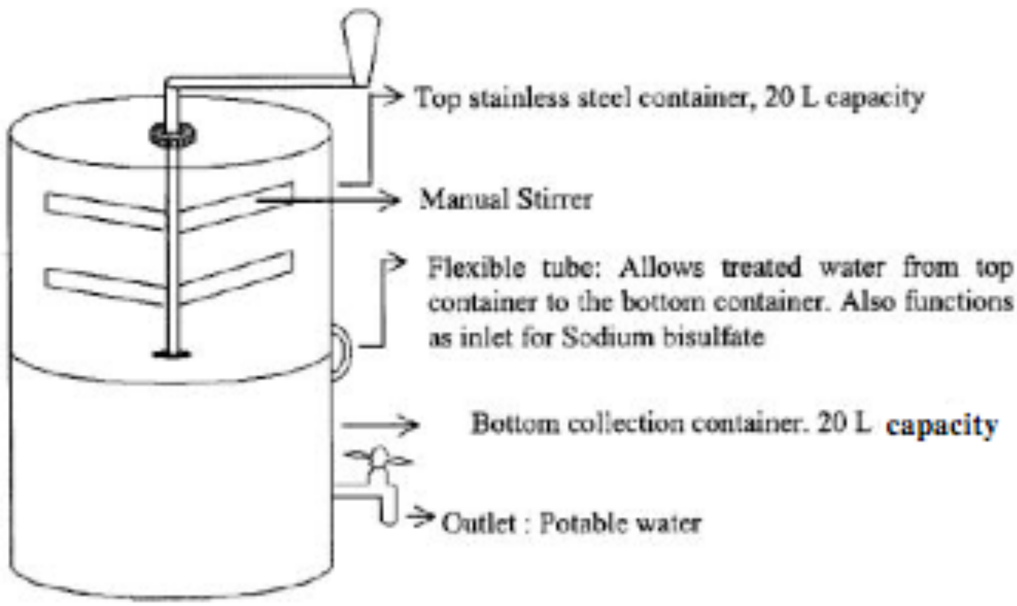


Figure 5.1 Schematic diagram of defluoridation unit (Rao and Mamatha, 2004)

Magnesium oxide is added in known quantities into the top container and manually stirred for 5 minutes to encourage flocculation. The container is then left to stand for 16 hours to allow the flocs to settle, after which the treated water can be decantered into the low container Sodium bisulphate is also added to adjust the pH to desirable levels. The method was tested on water with fluoride concentrations of 2-5mg/l which were reduced to 0.5-1.2mg/l (Rao and Mamatha, 2004). A drawback of this method, as with nearly all coagulation methods, is the generation of sludge that needs to be safely stored or disposed of. Rao and Mamatha (2004) suggested creating a concrete lined pit in which the sludge can be stored.

Fawell *et al.* (2006) discussed defluoridation using calcium and phosphate compounds and suggested that the most viable use of such compounds for defluoridation was with the use of contact precipitation. The reaction of calcium and phosphate compounds on their own is suggested to be too slow to be viable as a defluoridation method (Ayoob et al., 2008), so the addition of a contact bed usually made from bone charcoal can act as a filter for the precipitate (Fawell et al., 2006, Dahi, 1996). In 2006, this method was still being researched as a number of optimum parameters were still unknown, such as optimum contact time, currently suggested to be 20-30mins (Fawell et al., 2006). The basic set-up is a column filled with a small amount of bone charcoal, supported by a media of gravel or coarse ground bone charcoal. There is a large mixing area for the chemicals above the contact bed, and the filtered water passes through a valve, to control flow, into a drinking water tank. A set-up of this described method designed for household use is shown in Figure 5.2.

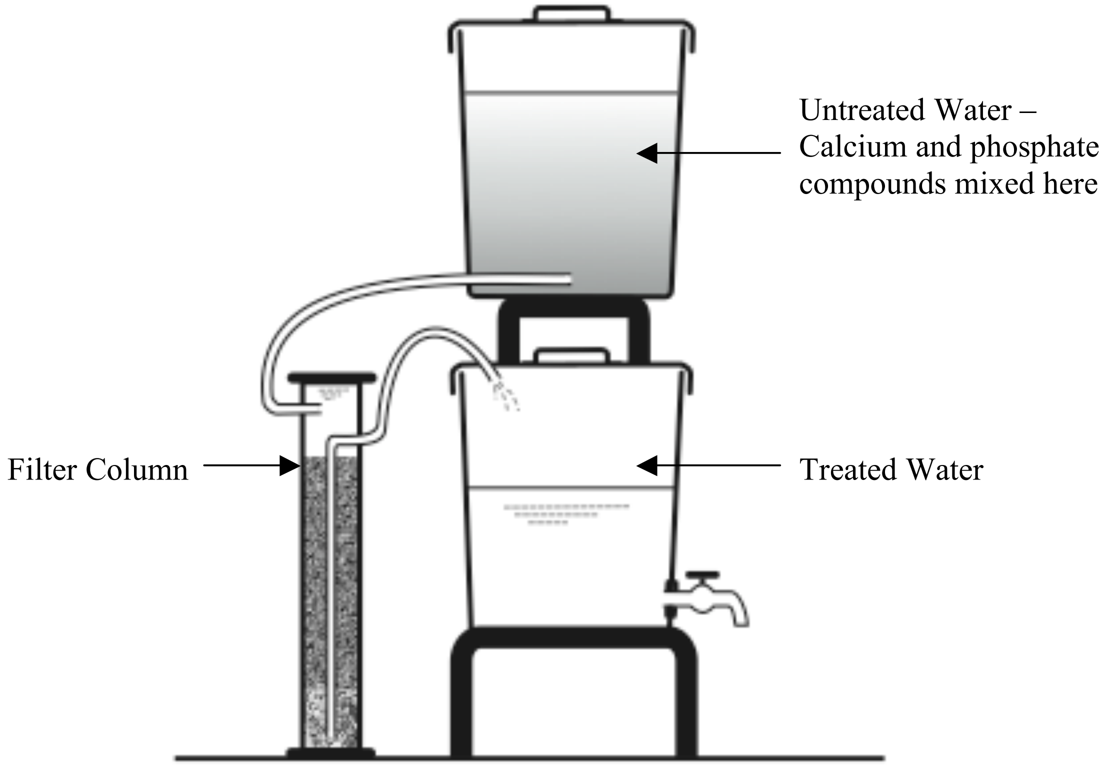


Figure 5.2 Contact Precipitation for household use (Fawell et al., 2006)

Fawel et al. (2006) also described a plant for use at the community level; they also mentioned that both community and household units are currently being operated in Tanzania.

The most commonly employed co-precipitation defluoridation technique utilises alum and lime. The technique, known as the Nalgonda Technique, was originally developed in India and is still employed as a viable defluoridation technique there and in East

Africa (Ayoob et al., 2008). The technique was adopted as the Tanzanian government solution for treating the high levels of naturally occurring fluoride. When alum in the form of aluminium sulphate is added to water it forms aluminium hydroxide flocs, and fluoride attaches to the settling flocs by electrostatic attachment (Dahi, 2000). The addition of alum acidifies the water, so lime is added to correct the pH of the treated water as well as encouraging more complete settling of the flocs. This is why alum is not used on its own for coagulation (Ayoob et al., 2008). Similarly to the contact precipitation technique both household and community set-ups for the Nalgonda technique have been developed and implemented. The principle of the method is that lime and alum are added to the raw water and mixed manually or mechanically, to encourage the formation of flocs. The raw water is then left to stand to allow the flocs to settle, and the treated raw water is then transferred to a distribution container via a filter to ensure the removal of the sludge from the treated water. The household set-up for the Nalgonda technique is shown in Figure 5.3.

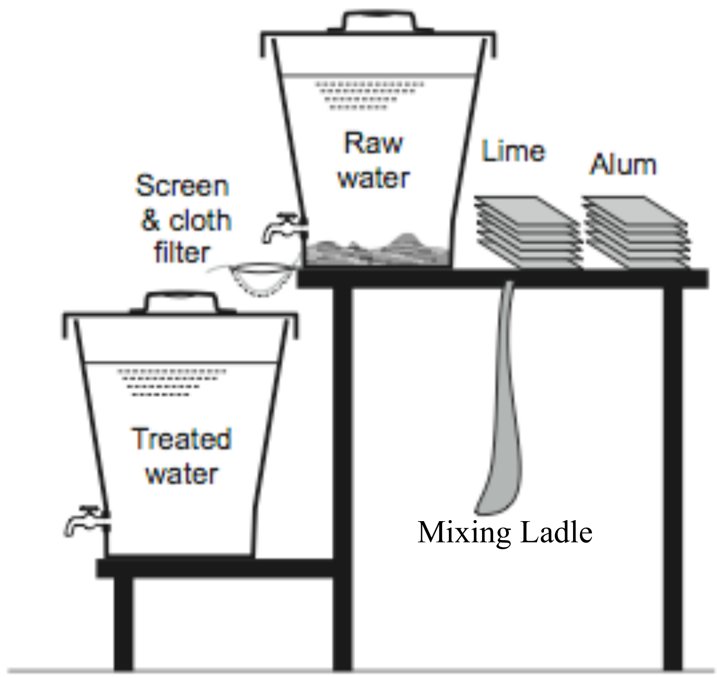


Figure 5.3 The two bucket Nalgonda defluoridation set-up (Dahi et al., 1996)

The Nalgonda technique is widely used due to the perceived low cost and availability of the chemicals, along with easy operation and maintenance (Nawlakhe and Paramasivam, 1993, Ayoob et al., 2008). However, other publications have drawn attention to some of the limitations. These include: excess residual alum in the treated water, excess sulphates in the water, suitability only for fluoride concentrations of around 10mg/l, adverse affects on taste, and the large doses of aluminium sulphate required (Agarwal et al., 1999, Mjengera and Mkongo, 2003, Fawell et al., 2006).

One of the positive aspects of coagulation techniques that has not been mentioned yet is that with any coagulation and precipitation techniques, the colour, odour, turbidity, bacteria, and organic contamination of the water can be removed (Nawlakhe and Paramasivam, 1993, Ayoob and Gupta, 2006, Fawell et al., 2006, Ayoob et al., 2008). In terms of bacterial contamination, techniques such as the Nalgonda technique suggest the addition of bleaching powder as a disinfectant to ensure that the water is microbiologically safe as well as reducing the concentration of fluoride (Nawlakhe and Paramasivam, 1993, Fawell et al., 2006, Ayoob et al., 2008).

One of the main drawbacks of coagulation techniques is that all the techniques require a regular supply of chemicals as well as initial knowledge of correct dosage and mixing procedures. Many areas affected with naturally occurring high levels of fluoride are in rural remote areas, meaning that a regular supply of chemicals is unlikely and costly in terms of transportation.

5.1.2 Adsorption Technologies

Adsorption methods generally require the water to flow through some type of media on to which the fluoride is adsorbed. The results will depend on the type of media used, the set-up of the filter and the contact time of water and media, known as retention time. There are a number of adsorbent media mentioned in the literature, the most common are bone, clay, soil, and alumina-based adsorbents.

5.1.2.1 Bone

Bone in its natural form was identified very early on as being able to absorb fluoride and suggested as viable for defluoridation (Smith and Davey, 1939). Bone however was not used on a large scale because of the high costs involved and amount of bone required. However, it was then discovered that bone char (bone that has been heated and charred in a furnace and then crushed), had the potential to remove far more fluoride than the same weight of uncharred bone, thus becoming an economically viable material (Ayoob et al., 2008). In the USA there were a number of areas that used large scale bone char defluoridation plants to remove fluoride from drinking water. These are no longer used and other more recent technology is utilised. Also there was more bone char available due to its use in the sugar industry to decolourise the sugar crystals (Ayoob et al., 2008, Fawell et al., 2006, Dahi, 2000). Using bone char to treat water can also improve the colour, taste and odour as well as removing fluoride (Fawell et al., 2006, Dahi and Bregnhoj, 1995).

Chapter 4 looked the effect of fluoride on bone in living systems. The same chemical principle is also at work in treatment, where fluoride replaces hydroxyl within apatite in the bone (Fawell et al., 2006). The amount of fluoride that can be absorbed is closely linked to quality of bone char, which is controlled by the preparation temperature and furnace type used. Bone char can be prepared in two main ways; calcination where oxygen is supplied to the bone during heating or pyrolysis where no oxygen is present during heating (Albertus et al., 2000, Dahi and Bregnhoj, 1995). Pyrolysis produces a black bone char, while calcination produces a white/grey bone char (Albertus et al., 2000). Dahi and Bregnhoj (1995) found that bone char produced via pyrolysis had optimum fluoride removal capacity, along with having the ability to improve taste, colour and odour. Bone char can also increase the pH and alkalinity of the treated water, however bone char produced via pyrolysis also reduces this effect (Dahi and Bregnhoj, 1995). A disadvantage of the process is that bone char that is incorrectly prepared e.g. with insufficient charring (Dahi, 2000, Fawell et al., 2006)) can leave a taste of rotten meat in the drinking water, which can discourage consumers from using the filter (Dahi, 2000, Dahi and Bregnhoj, 1995). As previously mentioned, bone char used to be available because of its use in the sugar industry to decolourise the sugar crystals (Fawell et al., 2006, Dahi, 2000, Ayoob et al., 2008), however it is also possible to produce bone char at the village or household level (Dahi, 2000, Fawell et al., 2006). The Catholic Diocese of Nakuru (CDN) in Kenya constructed a large kiln, with a crushing machine capable of producing enough bone char to support a community (CDNWQ and Muller, 2007). However, it is possible to construct much smaller kilns and use manual crushing techniques suitable for use in developing countries (Mjengera and Mkongo, 2003). Commonly, cattle bone is used as it is most available; one paper also talks about the viability of using fish bone to make bone char (Bhargava, 1997). Literature has also reported combining chemicals with a bone char filter, to achieve higher removal rates and reduce the time need before recharge (Mjengera and Mkongo, 2003, Albertus et al., 2000, Larsen et al., 1993).

The preparation of bone char, while simple, does have rather strict conditions that need to be met to ensure a high quality of product. Fawell et al (2006) describes the process; while there are some differences based on the size of the batch, usually the bone char will be prepared by heating animal bones in a purpose built kiln at 550°C for approximately 4 hours. Fawell et al. (2006) state that the process can take 24 hours, and indicate that too high or low a temperature, too short a duration, not enough oxygen and inhomogeneous heating can lead to a poor quality bone char and lead to some of the issues such as taste, smell and poor removal rates previously stated.

Bone char filters can be recharged using an acid wash, although this reduces the fluoride removal capacity of the bone char (Ayoob et al., 2008, Dahi, 2000, Fawell et al., 2006). Often in the developing world it is cheaper to replace the filter media rather than try to recharge them (Fawell et al., 2006). There are two main disadvantages to bone char. The first disadvantage is that the breakthrough of fluoride into the drinking water once the filter is saturated is rapid and, if there are no measurement techniques available, unnoticeable (Dahi, 1996, Dahi, 2000). This means that the filter has to be designed with a specific operation period prior to recharge. The second disadvantage is that of cultural acceptability. In some cultures the use of bones from certain animals maybe be religiously unacceptable, such as for Hindus, while the idea of filtering water through animal bones can dissuade some communities from using it (Dahi, 1996, Dahi, 2000, Ayoob et al., 2008). The cost of the filter is related to the source of the bone char. Dahi (2000) and Ayoob et al. (2008) have both reported that the cost of bone char can be reduced by adding charcoal into the production. The lowest cost for purchasing a tonne of bone char was reported in 2008 as being $167 in Tanzania (Ayoob et al., 2008).

5.1.2.2 Clay

Clay can also be used as a possible absorbent for fluoride removal, both in its natural state and fired state (Fawell et al., 2006). Clay comes in various types depending on its geological history. Clay materials can either be utilised in either packed columns or in batch processes as a powder. In the batch processes, clay powder is used as a flocculent powder as its relatively high density allows it to settle easily and the treated water is then siphoned off. In column set-ups the clay is often in the form of fired clay chips.

The removal rate of fluoride varies with the type of clay and whether or not the clay has been fired or not. In terms of actual removal rates there seems to be some conflict within the literature. Ayoob et al. (2008) compared a number of clay sorbent types, including those with maximum sorption capacities, the majority of which were between <0.01-0.4 mg/g. Within the list there were also a number of clay types with much higher sorption values of 63.3, 4.05 and 3.48mg/g for a type of bentonite and two types of kaolinite respectively, produced experimentally by Kau et al. (Kau et al., 1997, Kau et al., 1998), which do not seem to fit in with the other results. Dahi (2000) gave a possible answer to these discrepancies when he mentions a paper by Zevenbergen (1996) who reported a adsorption capacity for Ando Soil of 5.5mg/g. Dahi (2000) drew a comparison with a study by Moges et al. (1996) whose study suggested a capacity of 0.2mg/g. Dahi (2000) makes the observation that looking at these results it would seem that Ando soil would be the more efficient fluoride removal material. However Dahi (2000) goes on to make the point that if Zevenbergen's (1996) work was repeated under the same field operation conditions as Moges et al. (1996) it would also only achieve a removal rate of 0.2mg/g. Thus it is still necessary to successfully design the operating capacity of the chosen clay (Dahi, 2000, Fawell et al., 2006). The suggested fluoride sorption capacity for clay materials are 0.03mg/g and 0.1mg/g, depending on whether the clay is being used in a batch defluoridator or column defluoridator respectively (Fawell et al., 2006, Dahi, 2000).

Padmasiri (2000) reported successful use of domestic column filters in Sri Lanka. The columns were filled with chips made from locally-fired clay bricks. The raw water had an initial fluoride concentration of 1.2-3.5mg/l. The filters were monitored for 6 years and in the household where the filter media was changed regularly the filtered water had fluoride concentrations <1mg/l. Padmasiri (2000) suggested from the study's findings that it is possible to treat water with a fluoride concentration of 3mg/l while withdrawing 15 litres/day. The operation period for the filters was between 90 and 250 days (Padmasiri, 1997). A set-up of the columns are shown in Figure 5.4 (Padmasiri, 1997, Padmasiri, 2000)

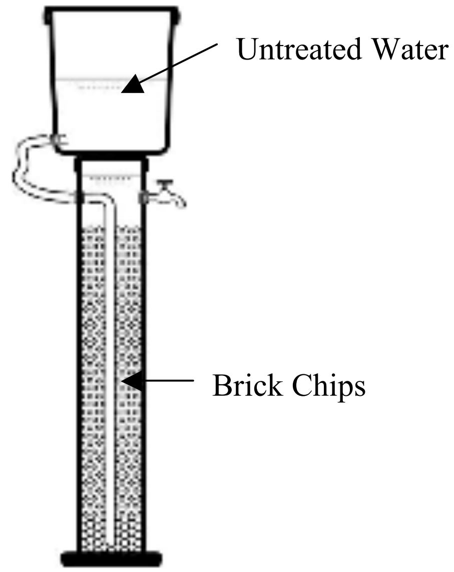


Figure 5.4 Column filled with brick chips (Dahi, 2000)

The main disadvantage of using clay is the low removal rate compared with methods such as bone char treatment. While it can be utilised for areas with relatively low fluoride concentrations, once these exceed 5mgF/l other techniques need to be considered. However, the cost is relatively low if there is a local supply of bricks, and the column can be made from locally accessible materials.

5.1.2.3 Activated Alumina

Activated alumina is another sorption material that can be utilised in the developing world. Activated alumina is a fine grained and porous material, with a relatively large surface area to increase sorption (Fawell et al., 2006). and traditionally used in packed filter beds through which the water to be treated is filtered (Rubel Jr and Woosley, 1979). In the literature, such as Hao and Huang (1986), removal amounts of 4-15mgF/l have been reported. These removal amounts are disputed, and both Fawell et al. (2006) and Dahi (2000) have suggested that field tests have had lower removal rates of 1mg/l. Dahi (2000) suggested a possible reason for this being that in the field only certain lower quality grades of activated alumina are available and in a developing country are likely to be of lower grade than that found in a laboratory. Another reason for low removal rates in the field is that the fluoride removal is dependent on the pH of the water (Dahi, 2000). Hao and Huang (1986) suggested an optimal pH of around 3-5, but in the field it may not be as easy or possible to adjust the pH for maximum removal rates (Dahi, 2000). Despite this, Ayoob et al. (2008) described activated alumina as being "*regarded one of the best available technologies worldwide.*" and it has successfully been used in the developing world to remove fluoride. One example of this was the work of Daw (2004) who described a treatment system at the drinking water source and a domestic defluoridation unit, both currently being utilised in India.

5.1.3 Solar Technologies

The solar method removes fluoride from drinking water via distillation and desalination. The traditional method involves the construction of a solar still, which comprises an evaporation basin which holds the untreated water. This basin is covered by a clear material, such as glass, and as untreated water evaporates it condenses onto the clear surface running down into a collecting basin from which it can be siphoned off for use. Delyannis (2003) looked at the history of desalination using renewable energy, such as solar water treatment and indicated that one of the first large scale solar treatment plants was built in Chile in 1872 to provide drinking water to workers and families at two local mines. The water treated was directly from a saltpeter mine, which was very high in salinity. During the 20^{th} century, various small scale demonstration plants were built and operated (Delyannis, 2003). However since the 1970s few plants have been built although it is not clear why. Delyannis (2003) did not give any particular reason for this, but did indicate increasing interest in terms of small capacity plants for households in developing countries (Delyannis, 2003). Perhaps the reason interest has waned in large scale solar treatment plants is the large surface area required to produce enough treated water each day to support a large community. Another reason may be that many developed countries where such technologies would be developed are based in temperate climates, which is not really viable for a treatment system that relies on year round sunlight. However, many developing countries are in arid parts of the world, often in rural areas with large areas of unused land, which may be the reason why this technology is gaining support here as a possible water treatment method. Two studies, both based in India, suggest that the solar still is an appropriate household treatment technology, due to its low running cost and maintenance (Khanna et al., 2008, Avvannavar et al., 2008). One of the most long term studies into the use of solar stills has been carried out on the Mexico-U.S.A. border, where various solar stills were installed and some monitored for a period of 10 years (Foster et al., 2005, Foster et al., 2002).

The solar still method has not yet been explored in its entirety, nor have extensive field tests been completed. However, it would seem to have great potential as a viable cheap treatment system especially for small households.

5.1.4 Other Technologies

There are two other techniques that are widely used for defluoridation. Firstly, electrochemical techniques work by passing an electrical current through the water supply, between an anode and a cathode. The fluoride ions are attracted to the anode and are removed as fluorine gas. The second technology is membrane filtration that works by filtering the water at high pressure through ultra fine membranes, which prevent the flow of fluoride ions. Both these methods while used in the developed world are currently not appropriate for the developing world. The technology is currently too expensive and often a regular supply of electricity is required. As the price of the materials reduces in the coming years, along with the reduction in cost of power creating devices such as solar cells, these techniques may become viable options.

5.1.5 Summary:

Table 5.1 lists a number of the common methods that have been discussed so far and using the literature gives details about each method's cost, ease of construction, ease of maintenance, waste and removal abilities.

Technology	**Method**	**Fluoride Removal**	**Cost/Maintenance**	**Advantages**	**Disadvantages**
Coagulation & Precipitation	Lime	Low – high residual fluoride level (7.5mg/l) post treatment.	Low – depending on community access to lime. Requires careful does management	Improves turbidity and colour.	pH adjustment needed post treatment. Produces sludge that requires disposal.
	Magnesium Oxide	Levels of 2-5mg/l are reduced to <1.2mg/l	Low – depending on community access to magnesium oxide. Requires careful does management.	Improves turbidity and colour.	pH adjustment needed post treatment. Produces sludge that requires disposal.
	Nalgonda Technique	Moderate – suitable for fluoride levels of around 10mg/l	Low – depending on community access to chemicals. Requires careful does management	Method is widely used and tested. Improves turbidity and colour.	Excess chemicals in the treated water. Produces sludge that requires disposal. Reported problems with taste.
Adsorption	Bone Char	High – The higher the level of fluoride the more bone char required for the same operational period.	Low/Moderate – Cost is dependant on a local source of bone. Careful preparation of bone char required for it to be effective.	Widely used and tested. Improves turbidity and colour. Exhausted bone char, can be used in filters to remove microbiological impurities.	Incorrectly prepared bone char can cause horrendous taste issues and not remove fluoride efficiently. Some communities for religious/cultural reasons may avoid use of animal bones.
	Clay	Low – Depending on the type of clay and whether or not it has been fired. Typical reported treatment values of 1.2mg/l-3.5mg/l	Low – With local access to appropriate clays.	Successfully being used in India.	Impurities from clay can potentially leach into treated water.
	Activated Alumina	High – 4-15mg/l, although disputed by some literature.	Low/Moderate – Depending on access to activated alumina. Optimum treatment requires pH of 3-5 – thus requires careful dose management and pH monitoring.	Currently being used in India.	pH adjustment needed post treatment. Some literature reports removal rates of only 1mg/l – reason being huge variations in quality of activated alumina.
Solar	Solar Still	Very High	Moderate/Low – Initial costs are high, also large glass/plastic cover required for still can be expensive in developing countries. Once filter is operational, low maintenance required.	Can treat very high levels of fluoride.	Requires year round sunlight. Large enough surface area required to produce appropriate amount of drinking water. Disposal of fluoride salts left post evaporation. Lack of extensive field tests.

Table 5.1: Summary of fluoride treatment options considered

5.2 Materials and Methods

The objectives of this part of the project were to design a viable and suitable treatment system within an identified village and to analyse the performance of the chosen treatment system in terms of:

- Fluoride removal
- Sustainability
- Acceptance of the treatment system by the community

This was accomplished in three stages, consultation, design and construction, details of the time when each stage was carried our can be found in Appendix A.

5.2.1 Consultation Stage

In Mtakuja and Tindigani village meetings were held in the schools, and to these meetings parents of the school children surveyed and village leaders were invited. The meetings had three main reasons: the first was to educate the local people about the level of fluoride in the drinking water and its health affects, the second was to discuss treatment options, and the third was to establish permission for the site of a pilot treatment plant. There was also time at the end of the meeting for members of the community to ask questions. Leaflets, translated into Kiswahili, were sent out with the school children and delivered to the village leaders, inviting them to attend the meeting, with a basic overview of the reasons for the meeting. As permission had previously been required from the parents to conduct the health survey many were already aware of the fluoride issue being investigated. The meetings were chaired by the principal investigator (i.e. by the author) with the assistance of a local translator.

The meetings in both schools were well attended with over 60 adults attending in each case. In the local culture the elderly members of the community are held in high esteem and it was important to understand these cultural elements as the final decision for permission would come from the village elders. The meetings were translated into the local language. In Mtakuja, the meeting was held in English and translated into Kiswahili. At Tindigani, a large proportion of the community were part of the Masai tribe and did not speak Kiswahili or English, thus the proceedings were translated from English to Kiswahili and then to the local Masai dialect. The language barrier was an important issue, as in Kiswahili, and more so in Masai, a lot of the terminology used to explain the fluoride situation was not easily translatable. For example, words like fluoride and chemical are currently not in the Masai language, thus the translator had to work around these issues. The danger in this is that some concepts may be misunderstood. Another issue related to this was the level of education of the audience, many of whom had not received formal education. Knowledge that is taken for granted in an educated setting, such as submicroscopic molecules, and chemicals that can't be seen, are concepts that are difficult to translate and understand. The principal investigator spent time working with a local translator simplifying the explanations of fluoride and its impact as much as possible.

The two meetings were different in that the communities' reactions to the problem differed. In Tindigani, the problem was well understood, and at the end of the presentation a helpful discussion and question and answer session took place, with the community actively discussing among themselves what they could do, the results of which are reflected upon later (section 5.6). The community also granted permission for a pilot treatment plant to be built at the school. A lot of the questions at Tindigani were about the long-term implications for the children affected and what options were available for treatment. The meeting at Mtakuja was a much more hostile experience. While the problem was understood, the question and answer session was not as helpful. A few of the community leaders suggested that the principal investigator should in fact pay for the whole village to receive treated water. When it was explained that the principal investigator personally did not have the funds it was suggested that the principal investigator should return to the United Kingdom to obtain them. Discussions on how the community could be involved with obtaining clean water through their own means unfortunately became a heated political discussion. Permission was not granted at that time to build a treatment plant at the school. It is important that these differences are recorded. The two villages are about 20km apart and mostly made up of the same tribal culture, however the responses were very different. Often working in the developing world there is a one-size fits all approach, however each community can be very different and can require different approaches and solutions. Mtakuja was also a demonstration of the negative impact that charitable work can have in the developing world. Unlike Tindigani, Mtakuja had received a number of visits and had been built wells, pumps and buildings – which may explain the attitude of waiting for someone to come and solve the problem on their behalf. Other studies have shown the importance of community involvement in the long-term success of community water and sanitation improvement projects (Prokopy, 2005).

5.2.2 Design Stage

Fortunately for this project, contact was made with Prof. E. Dahi, a WHO consultant in the area of low cost defluoridation who currently resides in Tanzania. Contact was made with him by the principal investigator after communicating with him over one of his previous publications in this area. In consultations with him a design was established for a pilot plant at the Tindigani primary school.

There were a number of challenges in building a treatment plant in Tindigani:

- The site was in a very remote area, around about an hour and 30 minutes from the nearest town by vehicle.
- The access to the site was poor; there were a few roads that led to the village and nearly all required at least one river crossing requiring a suitable four-wheel drive vehicle. During the rainy season access by vehicle was impossible due to washed out roads, flooding and mud.
- The population was extremely poor and in nearly all cases had limited or no monetary income. Subsistence living was the norm, with money coming from the selling of crops or animals.
- The area was barren and had limited available materials. Bricks were made in nearby town, but were relatively expensive for the local people and of poor quality.
- Most of the population was uneducated.
- The concentration of fluoride in the groundwater was extremely high – most defluoridation methods have not been tested at fluoride concentrations of >20mg/l.

All of these challenges needed to be considered and the treatment method chosen would obviously be influenced by these considerations. For example, due to poor access, the treatment system needed to require infrequent input from outside of the community and the technology needed to be simple. Some of the challenges could not be easily overcome, and the lack of materials meant that at least some would have to be bought in from outside the community, raising the cost of any treatment system. While the community in Tindigani was willing to pay due to their understanding of the problem, they did not currently have the means to pay. Thus in a way it wouldn't matter how cheap the system was, if the people didn't have the cash to pay. To overcome this obstacle there were a number of options in terms of payment, firstly many organisations offer small community loans that can be paid back over time. Another option to reduce costs for the community was for the community to do as much of the work as possible themselves. It was decided with this particular project, as it was a pilot plant for a research study, that the community would not pay for its construction and a partnered school based in the UK provided money for the construction.

After considering the viable options available the method of defluoridation chosen was to use a bone char filter for a number of reasons.

- There was a regular supply of bone char.
- The water fluoride concentration was very high
- Bone char filtration can also remove microbiological contamination
- The volume of water required each day was high
- The technology was relatively easy to install and run.
- Any maintenance and recharge of the filter would be infrequent so that the access would not be a regular issue.
- Professor Dahi lived near to the site and would be able to assist with maintenance.

Initially, one of the aims of the design was to keep the delivery system to the filter as simple and cheap as possible. Using a hand pump was avoided due to its expense; instead a rope and a bucket system would be used to draw water from the well. Once the water was drawn it would be poured into a bowl filled with gravel, which would flow via a connecting tube into the bone char filter. To ensure a good flow of water, the top of the well was raised up and concreted over to allow the water to flow by gravity to the treatment system. It was planned that the children would take it in turns each morning to fill up the filter. This was received favourably by the village compared to the 10 minute walk carrying large containers which was currently the way in which the school obtained water.

One of the initial calculations was to establish the amount of bone char required to reduce the fluoride concentration in the well water to acceptable levels. The concentration of fluoride in the well was 25mg/l. However it was understood that this concentration could change throughout the year during the different seasons, but due to the limitations of this particular study this variation was not established. Using the calculations published in a WHO 2006 publication (Fawell et al., 2006) it was possible to estimate the size and amount of bone char required (Table 5.2).

Parameters		Value	Units
D	Daily Personal Water Demand	1.00	l
N	Number of Users	110.00	p
OP	Operational Period	3.00	Months
Γ_0	Operation Sorption Capacity	3.00	g/kg
Σ	Bulk Density of Medium	0.83	kg/l
F_i	Raw Water Fluoride Concentration	25.00	mg/l
F_t	Treated Water Average Fluoride Concentration	2.00	mg/l
$VR_{SW/M}$	Volume Ratio Supernatant water/medium	2.00	-
$VR_{CW/M}$	Volume Ratio Clean Water container/medium	0.00	-
Derived:			
$Q = D \times N$	Daily Water Treatment	110.00	l/d
$V_T = OP \times Q$	Total Volume of Water Treated in a Filter Period	10037.50	l
$F_T = V_T \times (F_i-F_t)/1000$	Total Fluoride Removed in a Period	230.86	g
$M = F_T/\Gamma_0$	Amount of Medium Required for Renewal	76.95	kg
$V_M = M/\sigma$	Volume of Medium in the Filter	92.72	l
$BV = VT/V_M$	Number of Bed Volumes Treated in a Filter Period	108.26	-
$V_{SW} = VR_{SM/M}/V_M$	Volume Capacity of Supernatant Water	185.43	l
V_{CW}	Volume Capacity of Clean Water Container	0.00	l
$V_F = V_M + V_{SW} + V_{CW}$	Total Volume of Filter	262.39	l
Φ	Filter Diameter	60.00	cm
$H_F = V_F/(\pi\phi^2)$	Total Height of Filter	92.85	cm

Table 5.2: Calculations for Bone Char Filter Design

Due to the high concentration of fluoride present, the filter had to be recharged with new bone char every 3 months. The filter was only designed for 110 children to account for school holidays, weekends and that the children generally drink from other sources in the morning. On average 110-120 children attend the school each day, and in 3 months the children will attend school for around 53 days. If each child on average uses 1.5 litres during a school day, the total amount needed during this period would be 9000-9400 litres; the design above had a capacity for 10,000 litres. The design was also constrained by the size of containers available; the size available at the time of design was a drum 60cm in diameter and 110cm in height. Another important factor in the design process is the operational sorption capacity. The sorption capacity can vary depending on the type of bone, the technique used in producing the bone char and the quality in the final bone char product. The bone char source that would be used for this treatment system had a sorption capacity of 3g of fluoride per kg of bone char (Fawell et al., 2006). Another design decision that was made was to allow the treated fluoride concentration to be 2mg/l rather than 1.5mg/l; this was due to the size of drum that was available as well as reducing the amount of time between the bone char being replaced. In practice the filter would remove nearly all of the fluoride at the beginning of operation and towards the end of the operation period the fluoride would begin to break through. Due to the safety limits built into the equations, a major breakthrough of fluoride should not have occured until after the operation period had expired, but this would need to be monitored. The post-treatment 2mgF/l drinking water concentration also falls within the Tanzanian standard, and was far less detrimental to health than consuming drinking water containing 25mg/l.

5.2.3 Construction Stage

Construction of the pilot plant began in January 2008. The construction was split into 4 stages. The first stage was to construct a well within the school grounds. The second stage was to seal the well, and raise the height of the well by building a platform over it. The third stage was to build a stand for the filter and clean water tank. The final stage was to lay the pipe work and install the filter.

Some members of the local community constructed the well. It was planned to be dug during the dry season, which meant that the ground water level would be at its lowest. This meant that during future dry seasons the well would hopefully not run dry. Using local tools, a well 8m deep and 1.5m in diameter was hand dug. The top 2m in depth of the well was dug out to a diameter of 3m, where the foundations for the wellhead were laid, as well as effectively sealing the well.

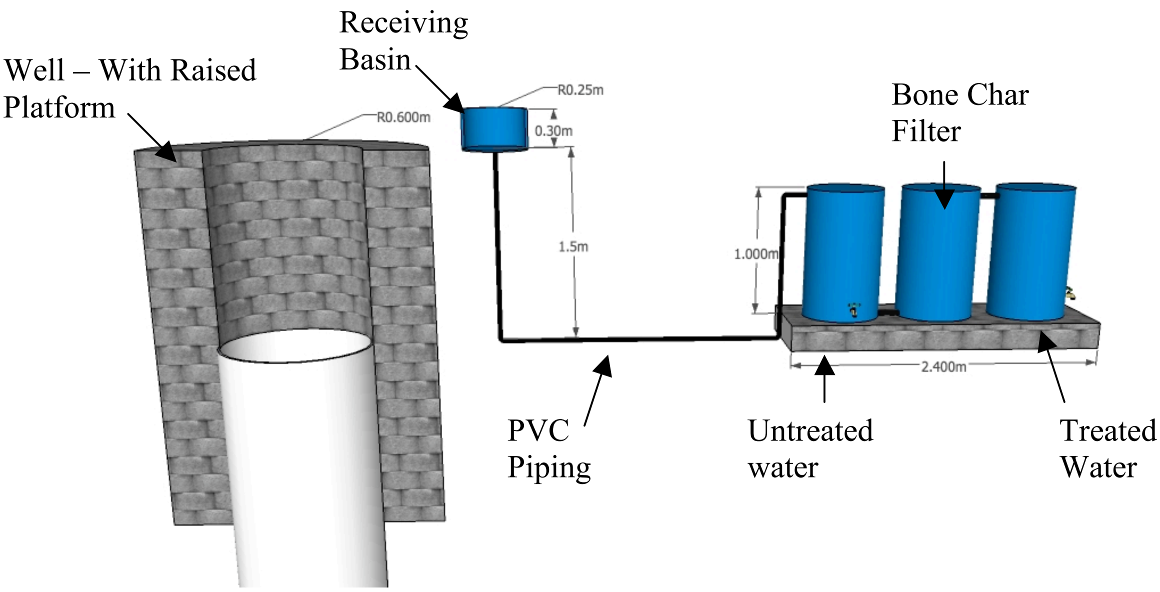


Figure 5.5: Bone Char Treatment Design Draft

Above the well a brick platform 1.5m high was constructed and the top sealed with a concrete slab. Into this slab was built a hatch, which a large bucket could be passed through. This extra height would allow the water to flow via gravity to the filtration system. A concrete stand was constructed on the school grounds where the 3 drums that would make up the filtration system would stand.

The pipe work from the well to the filter was laid and the filter installed. There were three barrels in series, a raw water barrel, the filter and a barrel for the treated water. Both the raw water and treated water barrel had a tap. The raw water could be used for washing hands so that the treated water could be solely used for drinking (figure 5.6).

The construction of the system began in January 2008 and was due to finish in March 2008. However due to an exceptionally heavy and prolonged rainy season, which prevented access to the site, construction was not completed until July 2008. The principal investigator managed the project and visited the site daily, directing the construction that was carried out by local community members. Operation did not begin until September 2008.

Figure 5.6: Photograph of treatment system, March 2008

5.2.4 Operation Stage

Operation of the plant began in September 2008, and initial data collected at that time showed treated water with a fluoride concentration of <0.1mg/l. The plan was to collect regular samples from the system and monitor for a breakthrough. Unfortunately 2 months into operation a freak storm and flash flood hit the area and damaged the pilot plant to the point where it was inoperable. At the same time the district water authority corrected the pressure problem that had prevented the community accessing a piped water supply. It was decided by the local community and Prof. E. Dahi that it was not economical to repair the filter, and this filter is currently in storage ready to be used if another viable location is found.

5.3 Conclusion

During the installation of the pilot plant, piped water with 3 outlets were supplied to Tindigani. Before this study began the local water authority had stipulated that it was not possible to pipe water to Tindigani due to insufficient pressure in the system. However following the village meeting about the fluoride problem and separately from this study the community mobilised to dig a 5km trench to the closest pipeline, and the water authority laid a pipe. This was a good solution for the Tindigani community in terms of accessing safe water, and also a great example of how a community when presented with information in their language can mobilise together to solve a problem. Unfortunately, though, as previously stated there is not currently sufficient pressure in the system for flow to be maintained during the dry season. This means that the community and the school are using the bone char filter system at these times. The community is also contributing to ongoing running and maintenance of the filter now that the project has ended. Professor Dahi is also responsible for regularly checking the fluoride concentration in the treated water. While the bone char filter was successful in terms of removing fluoride and treating larger quantities of water for a school sized population, due to its initial cost and ongoing maintenance perhaps a more sustainable solution would be to develop household solar stills. As for the village of Mtakuja, reports from Tanzania suggest that they have been inspired by the mobilisation of Tindigani and are looking into different ways of providing piped water to their community.

Chapter 6: Overall Discussion

Very few publications have investigated the holistic view of fluoride in drinking water, from identifying the cause, measuring the impact and investigating potential interventions. This study aimed to bring these three aspects of fluoride in drinking water under the umbrella of one study, concentrating on one particular study area and the population present there. This holistic view added to the knowledge of the scale and impact of fluoride in drinking water in the Hai district of Tanzania, an area where this had not been studied previously. In terms of how this study compares with others that provided the basis for this particular investigation, it is most feasible to look at each aim in turn.

The first aim was to identify the causes and magnitude of fluoride occurrence in drinking water. It was already documented in the literature that the study area would more than likely have instances of high fluoride present in the drinking water (Ayoob and Gupta, 2006). What was not understood though was;

- Where was the drinking water being sourced?
- How widespread was the problem of fluorosis across the Hai district?
- What was the cause of the high concentrations of fluoride in the drinking water?

This study demonstrated that the high levels of fluoride were located in the south west of the Hai district, and that the drinking water that had fluoride concentrations over the WHO recommended value of 1.5mg/l. It was also established that the drinking water that had the highest concentrations of fluoride was groundwater accessed via hand dug wells. The geological map for the area indicated that geology in the south west of the Hai district was a different geological system to the rest of the Hai district; this was further backed up by the rock samples analyzed from this area. Fluorite was identified in the rock sample (TIND) that was analyzed from this area. Whilst fluorite is relatively stable, Edmunds and Smedley (2005) indicated that the absence of calcium can cause the dissolution of fluoride. The water samples analyzed with high concentrations of fluoride also had low concentrations of calcium, which suggested that it was in fact the dissolution of the fluorite that was responsible for the elevated concentrations of fluoride. Edmunds and Smedley (2005) also indicate that arid conditions can also increase the solubility of fluorite, conditions present in the Hai district of Tanzania.

The second aim was to investigate the impact of high concentrations of fluoride in the drinking water. Prior to this study there was a wealth of information on the impact of drinking water containing high concentrations of fluoride. The issues of dental fluorosis and skeletal fluorosis and their relationship to high levels of fluoride are also well documented. The results that were gathered from the survey of two village primary schools in the affected areas did correspond to a study carried out in the neighbouring Arusha district (Christie, 1980). What set this study apart though was the high concentrations of fluoride present in the consumed drinking water and how this related to the prevalence of fluorosis. Despite the two villages accessing drinking water with differing concentrations of fluoride the prevalence of fluorosis was similar, which was unexpected. Tindigani, accessing drinking water with higher concentrations of fluoride, was expected to have a high prevalence of fluorosis. As the dietary activities and populations were similar in each village, this led to the proposed hypothesis that there is an absorption threshold to the amount of fluoride that the body can absorb (Shorter et al., 2010).

The third aim was to identify appropriate treatment methods to reduce the concentration of fluoride to acceptable levels. Studies on low cost treatment methods were plentiful, however less plentiful are studies on treating water with fluoride levels higher than 20mg/l. This study demonstrated that it was possible to construct an affordable bone char filtration system that could treat water with a fluoride concentration of >20 mg/l, that was able to provide safe drinking water to a school population of 200 students. This study also added to the understanding that one of the best means of prevention is education. As both village communities became aware of the issues through the community meetings, they mobilized to provide piped water to the villages to prevent further generations of the village being affected by fluorosis. This understanding while not new to the area of research is still one often overlooked when considering water treatment for low economically developed countries.

Carrying out field-testing in most cases presents more complex obstacles to designing an appropriate methodology to acquire the best possible results. Nearly all the data collected during this study was collected in the field in rural Tanzania. The best possible care was taken to ensure that field data was as accurate as possible, and water samples that were returned home when analyzed match those readings for fluoride, pH and conductivity recorded in the field. One aspect where the study could have been improved would have been to consider more samples from different sources across the region, not just the main sources of drinking water. It also could have been beneficial to create a watershed map of the entire Hai region, to understand better the flow of surface water and its source. The only surface water that had fluoride concentrations above the recommended 1.5mg/l were connected to groundwater springs with high concentrations of fluoride. A watershed map would have enabled us to better understand the origin of the different waters that were encountered across the region. To do this successfully, however, would have required surveying a much larger area, including the Kilimanjaro region to the north, and the Arusha region to the west – which resources at this time would not have allowed. Also a more extensive geological survey could have been carried out of the area; this would have validated the hypothesis that the high concentrations of fluoride were due to particular geological conditions.

In terms of understanding the impact of drinking high concentrations of fluoride an improvement would have been to take X-rays and blood tests of all the students who were surveyed. This would have permitted more accurate measurement of the prevalence of skeletal fluorosis, and also generated more information on the relationship of high levels of fluoride in the drinking water to the levels of fluoride in the blood. This study would have required further Tanzanian research clearance. The health survey could also be expanded to include more elementary schools in the area as a comparison to the schools in Mtakuja and Tindigani. The survey could have also included babies and pre-school children, as this is the age when fluorosis first develops.

In terms of investigating appropriate treatment options, a lack of resources also led to the study of the bone char treatment plant not being as extensive as it could have been. While the results did demonstrate that a large-scale bone char treatment plant could treat the drinking water with high concentrations of fluoride, the study was unable to establish the operating time for the treatment plant. It would also have been beneficial to set-up a number of different treatment options in the same village and to compare their operation and how the community accessed them.

The implications of this study were that a considerable area of the southwestern Hai district is at risk of drinking water with unsafe concentrations of fluoride present. These concentrations are leading to a high prevalence of skeletal and dental fluorosis, especially evident among the children and teenagers of this area. The groundwater in this area, that is being access for drinking, is high in fluoride with its most probable cause being the dissolution of fluorite in the surrounding geology. The recommendation was that the community must treat the groundwater prior to use or alternative water sources must be found. These results were presented to the local Hai Water authority and the two village communities. Work has been carried out since this study to provide piped water to both villages so that groundwater no longer has to be accessed. A further recommendation of this study was that similar surveys should be carried out in the neighbouring districts. As both communities were relatively unaware of the problem of dental and skeletal fluorosis, it is important that education is increased across similarly affected areas. The communities were aware of the brown stains and bone deformities linked to fluorosis and the water authority should immediately recognise these as indicators of possible high fluoride concentrations within the drinking water. As previously mentioned these results were presented to the district water authority. If alternative water sources are not available, this study demonstrated that it is possible to build a bone char filter capable of treating the drinking water with high concentrations of fluoride. However, each community that requires the water to be treated needs to be involved in coming up with a treatment solution that is most compatible with how they live. For example, while a centralised bone char treatment system worked for the village of Tindigani where the village was centred around the school, many communities were spread out across a large area. In such cases individual solar stills may be more appropriate treatment methods.

Chapter 7: Conclusion and Recommendations for Further Work

The aim of the study was:

To investigate the causes, scale, impacts and treatment of fluoride in the drinking water of the Hai district of Tanzania.

The aim was broken down into a number of objectives which will be looked at in turn to demonstrate how this study met these objectives, where it was not able to and further work which would add validity or which has been inspired by this study.

7.1 To identify the causes and scale of fluoride in the drinking water:

One of the first objectives was to identify the causes and scale of fluoride in the drinking water in the Hai district of Tanzania. There were two studies that were carried out to try and meet this objective. The first was a survey of the drinking water sources across the Hai district of Tanzania, measuring the concentration of fluoride present. This was tied in with GPS data allowing a map to be created of the region, which clearly demonstrated the scale of the problem. From the map (Figure 2.1) it was clear that the south western region of the district had the highest levels of fluoride in the drinking water sources. The second study collected and analysed rock samples and geological maps of the area to try to identify the cause of the high levels of fluoride. While this second study proved nothing conclusive, it did present a number of possibilities. Within the samples taken from one of the most affected areas, fluorite, a fluoride-bearing mineral, was identified and there seemed to be some evidence that the fluorite was being replaced. This replacement suggested that perhaps the fluorite was being dissolved, thus causing the high levels of fluoride in the drinking water.

However, what was clear from this study was that the geology in the affected area is a different geological system to that in the rest of the region where the fluoride levels are relatively low. It had already been identified that places around Meru have high concentrations of fluoride in the drinking water, and the geological maps suggested that the affected area in the high region has geology created by Mount Meru.

Further work which could be carried out to help validate some of these results would be for a more detailed geological survey to be carried out by those with experience of mapping volcanic rocks. A greater number of rock and soil samples would need to be taken from the affected area and analysed in depth for fluoride content. These samples could then be compared with samples taken from other identified areas of high fluoride from around Meru to see if that is in fact the cause. A larger geological survey of the area could also be carried out to include neighbouring districts and again this could be compared with the geology to see if there is a certain geological system responsible for the high levels of fluoride.

7.2 To investigate the impact of fluoride in the drinking water

The second objective of the study was to investigate the impact of the high fluoride drinking water. Following the study of the drinking water sources, two communities (Mtakuja and Tindigani) were identified as being the communities most at risk of consuming drinking water high in fluoride. Two of the best measures of the health impact of drinking high concentrations of fluoride are the prevalence of dental and skeletal fluorosis. A survey of school age children was carried about in both villages. A high prevalence of skeletal and dental fluorosis was found in the villages of Mtakuja and Tindigani. While this prevalence is obviously unacceptable, what was unexpected is that the levels of fluoride measured in the community drinking water sources would suggest that much higher levels of prevalence for both skeletal and dental fluorosis should be present. A number of explanations were presented, one was that the level of fluoride in the water may not have been constant, thus at sometime in the past the children may have been drinking water low in fluoride. Since the literature demonstrated that the most crucial time especially for the development of dental fluorosis is in the first few years of life, this may have affected the prevalence that was recorded. Another explanation is that there are limited studies for communities that are consuming such high levels of fluoride in their drinking water. Thus a suggestion made by this study is that there is a threshold in terms of how much fluoride can be absorbed, which could potentially be governed by a person's genes. Further work that could be carried out is a more extensive survey of all ages of the community, especially looking at children between 0-3 years of age. Other communities that also have been identified outside of the region could also be surveyed and compared. Surveys could also be carried out post treatment to see how the treatment of water affects the prevalence of dental and skeletal fluorosis in the population. In terms of some of the questions raised about genetic propensity towards fluorosis, or there being a fluoride absorption threshold in the body, an extensive medical study would be required. In terms of contributing factors to the fluorosis problem, the diet of the school children particularly was looked at. The findings from this suggested that the children did have a low calcium diet which is believed to affect the severity of fluorosis, also a lot of the food they eat such as rice and ugali (a maize meal) is highly absorbent, and is obviously cooked with water that is high in fluoride. Thus the greatest cause of the fluorosis is directly (through drinking) or indirectly (through food preparation) consuming the water.

7.3 Identify appropriate treatment:

The final objective was to identify an appropriate treatment system, and then to design, build and test the treatment system. Tindigani was chosen as a base for a pilot treatment plant, and a bone char system was chosen as the method. Following the design of the system, it was built in the grounds of the primary school where the survey had been based. Unfortunately, following unusually poor weather, the system was damaged, thus extensive testing of the system could not be carried out in terms of its operational capacity. The positive factors resulting from this process are that the community was involved with the project and educated into the reason behind the need for a treatment system. In addition, for the short time the system was in place the community was using it, demonstrating that it was an acceptable and appropriate solution. However, educating the community about this problem inspired them to construct a pipeline, and provide piped water to the community that was within the safe limits for fluoride. Further work that could be carried out would be to move the pilot plant to another community that has need of it and monitor the system over an entire operational period. While the plant design was appropriate for a small community, further work could also be carried out on household treatment systems, such as building individual solar stills for households to treat their own water for cooking and drinking.

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Appendix A: Project Diary

Oct 2006: Initial Project Work

Nov 2006 – Mar 2007: Background study on the project, especially concentrating on previous studies carried out in Tanzania. Contacts in Tanzania to aid with accommodation, transport and other field work logistics established. Application for Tanzanian research clearance with COSTECH submitted.

Apr 2007 – Jul 2007: First field trip to Tanzania.

Apr - May 2007: A number of meetings were held at Boman'gombe. The first meetings were with the Hai district medical officer and Hai district water authority director to establish permission to carry out the study. A meeting was then held with the medical officer supervisors, and representatives from each village in the Hai district to discuss the project. At this large meeting information was given on the project in the local language to inform the local villagers.

May – Jul 2007: The survey of drinking water supplies in the Hai district was carried out. On average 3 villages were visited each day – villages could only be visited when accompanied by a medical officer representative and when the roads were passable. There was nearly 2 weeks where the roads where impassable due to heavy rains, and another week when the vehicle provided was severely damaged when returning from a survey site, and parts had to be shipped form Nairobi. By the end of July all the villages in the Hai district had been visited.

Aug – Sep 2007: Initial analysis of data. The GPS and fluoride data was compiled, samples brought back from Tanzania where tested in the Newcastle University laboratories. The results were mapped and villages most at risk of high levels of fluoride were established. An outline for a health survey was drawn up with assistance from the

Dr. Anne Maguire from the Newcastle University Dental School and Dr. Richard Walker of North Tyneside General Hospital.

Oct 2007 – Apr 2008: 2nd Field Trip to Tanzania

Oct – Dec 2007: Meetings held in the villages of Mtakuja and Tindigani to inform the community of the problem and provide a forum for them to ask questions. Permission was also asked to carry out a survey of the school children in the village to establish prevalence of dental and skeletal fluorosis. The final survey was established and translated into Kiswahili. Permission letters were also sent out with the school children to be signed by a parent or guardian. A post survey meeting was held in both villages to discuss some of the initial findings in December. Both villages were asked for permission to establish a pilot treatment plant in the school to look at treating the drinking water used by the school children. Permission was only granted for Tindigani.

Jan – Apr 2008: A series of meetings with Prof. Eli Dahi, led to a final design of a pilot bone char treatment plant for the school. Building materials were acquired and local men from the community employed to help with the construction. The construction began at the end of February 2008. During this time the results of the survey were inputted into a database to aid with analysis. From March-April 2008 heavy rains washed out the road to Tindigani, after two failed attempts to reach the pilot site work was delayed until after the rains.

May 2008 - June 2010: Project Analysis and Writing Stage

May 2008: PGR conference

June 2008: Overseas Conference at Duke University North Carolina

Sep 2008: Thin sections of rock samples made and powdered samples sent to the University of Leicester for analysis.

Sept 2008: Bone char pilot plant completed at Tindigani

Dec 2008: Pilot plant damaged by storm at Tindigani. Community mobilizes to provide piped water to village.

Aug 2009: Optical analysis of rock samples

Sep 2009 – Dec 2010: Paper written and submitted to journal.

Oct 2009 - Apr 2010: Rock analysis work carried out at University of New Mexico – time on the machine limited.

June 2010: Provisional acceptance of journal paper

July 2010: Project finished

Appendix B: Summary of Observations Made in the Field

The following table includes observations taken between April and July 2007. The table includes water fluoride concentrations determined in the field using a fluoride ion selective electrode. Conductivity and pH was also measured in the field using a pH probe and conductivity probe respectively. The table also includes the villages the samples were taken from and the location of the rock samples collected.

Village	Sample Name	Type	F (mg/l)	Conductivity (µs/cm)	pH	Rock Sample
Shiri Njoro	Standpipe 1	Standpipe	0.2	915	6.77	
Shiri Njoro	Well 1	Spring	0.5	454	6.28	1A/1B
Shiri Njoro	Njoro Stream	Stream	0.5	197	7.27	
Shiri Njoro	Well 2	Spring	0.3	122	7.22	2A/2B
Mungushi	Well 3	Stream	0.2	211	7.67	
Mungushi	Well 4	Stream	2.4	311	8.31	
Mungushi	Standpipe 2	Standpipe	0.1	390	7.94	
Kware	Well 5	Surface water	0.5	416	6.99	
Kware	Well 6	Stream	0.2	117	7.62	
Usori	Well 7	Stream	0.2	740	7.42	
Usori	Standpipe 3	Standpipe	0.4	136	8.32	
Orori	Well 8	Stream	0.2	650	7.42	
Orori	Well 9	Stream	0.1	111	6.90	
Orori	Well 10	Spring	0.3	176	5.96	
Orori	Well 11	Stream	0.2	650	7.02	

Mtakuja	Well 12	Well	2.6	914	6.58	
Mtakuja	Well 13	Well	2.9	890	9.24	
Mtakuja	Well 14	Well	5.8	904	10.69	4A/4B
Mtakuja	Well 15	Well	6.8	1161	8.80	
Mtakuja	Well 16	Well	4.2	1034	7.70	
Mtakuja	Well 17	Well	5.5	981	8.57	
Kia	Well 18	Borehole	1.9	1113	8.70	5
Kwa Sadala	Standpipe 4	Standpipe	0.2	700	7.01	
Kwa Sadala	Well 19	Stream	0.4	149	7.05	
Kwa Sadala	Well 20	Shallow open well	0.7	215	7.36	
Kikavu Chini	Well 21	River	0.2	112	7.08	
Kikavu Chini	Well 22	Spring	0.4	273	6.30	6A/6AW
Kikavu Chini	Well 23	Stream	0.2	750	7.14	
Kikavu Chini	Well 24	Well	0.5	265	7.40	
Kikavu Chini	Well 25	Well	1.1	738	6.96	6B
Mijongweni	Well 26	Well	0.9	313	7.42	
Mijongweni	Well 27	River	0.2	680	6.99	
Mijongweni	Well 28	Stream	0.2	710	7.02	
Bon'ongome	Well 29	Well	0.8	382	5.10	
Bon'ongome	Well 30	Well	0.6	434	7.41	
Bon'ongome	Well 31	Spring	33.2	1418	7.42	
Bon'ongome	Well 32	Stream	21.2	1190	7.41	
Sanya Station	Well 33	Well	26.0	1189	7.01	
Sanya Station	Well 34	Well	21.2	1052	7.01	
Sanya Station	Well 35	Well	24.0	1153	8.14	
Sanya Station	Well 36	Well	23.0	1213	8.17	
Mulama	Well 37	River	0.3	880	4.47	

Mulama	Well 38	Spring	0.2	990	7.01	
Mulama	Standpipe 5	Stream	0.5	590	7.00	
Mulama	Well 39	Standpipe	0.3	530	7.01	
Tella	Well 40	River	0.4	590	7.01	
Tella	Well 41	Spring	0.3	113	7.01	
Tella	Well 42	Stream	0.2	740	7.01	
Muroma	Standpipe 6	Standpipe	0.3	830	7.04	
Muroma	Well 43	Stream	0.2	600	7.03	
Isuki	Well 44	Stream	0.1	460	7.35	
Mashua	Well 45	Stream	0.2	950	7.12	
Lukani	Well 46	Stream	0.1	370	7.03	
Kwuu	Well 47	Stream	0.3	510	7.02	
Kwuu	Well 48	Spring	0.1	640	7.03	
Losaa	Well 49	Stream	0.2	350	7.03	
Losaa	Well 50	Stream	0.2	320	7.02	
Nguni	Well 51	Stream	0.1	380	7.00	
Nguni	Well 52	Stream	0.1	220	7.02	
Nshara	Well 53	Stream	0.4	550	6.87	
Nshara	Well 54	Stream	0.3	380	7.21	
Nshara	Well 55	Spring	0.1	660	6.98	
Nshara	Well 56	Stream	0.2	390	6.99	
Nshara	Well 57	Spring	0.2	540	6.98	
Nshara	Well 58	Stream	0.3	460	7.14	
Nshara	Well 59	Spring	0.7	900	7.02	
Kimashuka	Well 60	Stream	0.3	430	7.02	
Kimashuka	Well 61	Spring	1.6	104	7.02	
Kimashuka	Well 62	Stream	0.2	420	7.56	

Kimashuka	Well 63	Stream	0.8	200	7.85	
Kimashuka	Well 64	River	0.3	590	7.03	
Shiri Mgungani	Well 65	Stream	0.6	172	7.20	
Shiri Mgungani	Well 66	Stream	0.6	222	7.02	
Rundugai	Well 67	Borehole	0.8	638	7.00	
Rundugai	Well 68	Deep Spring	0.7	344	7.01	
Rundugai	Well 69	Spring	0.6	305	7.01	
Rundugai	Well 70	Spring	0.8	388	7.01	
Rundugai	Well 71	Spring	0.5	354	7.09	
Kware	Well 72	Stream	1.8	345	7.01	
Kware	Well 73	Stream	1.1	296	7.32	
Kware	Well 74	River	2.1	915	8.04	
Kware	Well 75	Spring	0.4	620	7.02	
Lyamungo	Standpipe 7	Standpipe	0.1	970	7.19	
Lyamungo	Well 76	Stream	0.1	680	6.99	
Lyamungo	Well 77	Spring	0.1	880	7.00	
Lyamungo	Well 78	River	0.3	640	7.00	
Lyamungo Kivu	Well 79	Stream	0.1	530	7.00	
Lyamungo Kivu	Well 80	Spring	0.0	580	7.00	
Kilanya	Well 81	Stream	0.1	188	7.00	
Kilanya	Well 82	Stream	0.0	246	7.01	
Uduru	Well 83	Spring	0.1	840	7.00	
Uduru	Well 84	Stream	0.2	620	7.01	
Nkuusinde	Well 85	Spring	0.1	950	7.00	
Nkuusinde	Well 86	Stream	0.2	510	6.73	
Nkuundoo	Well 87	Protected Spring	0.2	420	7.00	
Nkuundoo	Well 88	Stream	0.2	320	7.00	

Mkalama	Well 89	Stream	0.4	220	7.90	
Mkalama	Well 90	Borehole	0.9	457	7.01	
Mkalama	Well 91	Stream	1.2	357	7.01	
Longoi	Well 92	Stream	1.2	395	7.01	
Mbatakero	Well 93	Well	1.4	970	7.01	
Mbatakero	Well 94	Well	0.9	419	7.01	
Mbatakero	Well 95	Stream	0.9	419	7.01	
Mbatakero	Well 96	River	0.2	680	7.01	
Uswaa	Well 97	River	0.3	860	7.00	
Uswaa	Well 98	Stream	0.2	680	7.00	
Mamba	Well 99	Spring	0.1	830	7.00	
Mamba	Well 100	Spring	0.1	101	7.00	
Shiri	Well 101	Spring	0.1	740	7.01	
Shiri	Standpipe 8	Standpipe	0.1	860	7.01	
Shiri	Well 102	Spring	0.1	710	7.00	
Nkwansira	Well 103	Stream	0.2	780	7.01	
Mbosho	Well 104	Stream	0.2	960	7.00	
Lemira Kati	Well 105	Stream	0.2	710	7.00	
Foo	Well 106	Spring	0.1	860	7.00	
Foo	Well 107	Protected Spring	0.2	510	7.00	
Foo	Well 108	Spring	0.1	700	7.00	
Foo	Well 109	Stream	0.1	500	7.00	
Foo	Well 110	Stream	0.2	380	7.19	
Wari	Well 111	Spring	0.1	870	7.00	
Wari	Well 112	Stream	0.2	390	7.01	
Wari	Well 113	Protected Spring	0.3	530	6.98	
Wari	Well 114	Stream	0.1	650	7.01	

Wari	Well 115	Protected Spring	0.1	760	7.01	
Nronga	Well 116	Protected Spring	0.4	620	7.61	
Nronga	Well 117	Stream	0.3	500	7.01	
Nronga	Well 118	Spring	0.1	720	7.50	
Roo	Well 119	Stream	0.6	181	7.01	
Roo	Well 120	Spring	0.2	135	7.63	
Roo	Well 121	Spring	0.4	117	7.46	
Mudio	Well 122	Spring	0.2	116	7.01	
Mudio	Well 123	Stream	0.1	117	7.01	
Mudio	Well 124	Spring	0.1	107	7.01	
Mudio	Well 125	Stream	0.1	980	7.01	
Mudio	Well 126	Spring	0.1	850	6.84	
Mudio	Well 127	Spring	0.1	550	7.40	
Mudio	Well 128	Spring	0.1	600	7.30	
Mudio	Well 129	Spring	0.1	640	7.01	
Mudio	Well 130	Spring	0.1	129	7.50	
Sonu	Well 131	Spring	0.1	289	7.14	
Sonu	Well 132	River	0.3	260	7.33	
Ngira	Well 133	Stream	0.1	269	7.73	
Ngira	Well 134	Spring	0.1	313	7.28	
Kyeeri	Well 135	Stream	0.3	440	6.78	
Kyeeri	Well 136	Stream	0.1	490	6.46	
Sawee	Well 137	Protected Spring	0.3	830	7.05	
Sawee	Well 138	Spring	0.1	400	7.03	
Sawee	Well 139	Stream	0.1	220	7.02	
Sawee	Well 140	Stream	0.1	480	7.01	
Mtakuja	Well 141	Well	5.5	895	8.41	

Mtakuja	Well 142	Well	7.4	852	7.87	
Mtakuja	Well 143	Well	7.7	891	7.79	

Appendix C: Composition of Rock Samples

The following table is the composition of the rock samples collected in the field determined via XRF analysis at the University of Leicester Department of Geology.

(wt%)	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SO_3	LOI	Total
5	48.82	3.21	14.50	13.75	0.175	4.52	8.06	3.73	1.724	0.436	0.059	0.58	99.56
6B	48.26	3.07	15.44	16.05	0.263	2.11	6.01	3.59	2.139	1.051	0.018	1.20	99.19
TIND	47.12	1.97	16.14	8.33	0.189	2.34	5.66	5.71	4.456	0.583	0.020	6.88	99.40
1B	55.43	1.14	21.80	5.60	0.189	0.73	1.78	4.32	4.588	0.323	0.009	3.48	99.38
2B	56.15	0.94	18.81	6.32	0.187	0.77	1.93	7.62	5.742	0.253	0.013	0.36	99.08
6A	56.19	1.01	19.62	5.06	0.189	0.93	2.43	7.71	4.850	0.486	0.039	0.51	99.02
(wt%)	As	Ba	Ce	Co	Cr	Cs	Cu	Ga	La	Mo	Nb	Nd	Ni
5	3.1	1047.0	100.2	43.9	117.5	<1.79	24.0	25.8	50.2	4.0	49.2	48.7	20.7
6B	7.0	1223.4	228.0	36.1	51.7	<1.75	15.3	29.4	189.7	3.2	104.6	133.9	<1.00
TIND	5.5	1473.8	188.5	17.4	38.7	<1.60	20.6	23.3	126.0	0.3	190.2	77.6	<0.73
1B	4.0	1205.3	156.9	9.0	19.6	<1.49	5.9	31.9	78.1	4.6	374.4	58.9	<0.65
2B	1.6	594.6	345.2	6.7	100.2	9.0	9.0	34.7	174.5	11.5	453.8	112.6	<0.69
6A	2.7	1471.7	265.7	7.3	117.0	<1.48	9.8	29.7	147.0	8.3	363.3	90.8	<0.66
(wt%)	Pb	Rb	Sb	Sc	Se	Sn	Sr	Th	U	V	W	Y	Zn
5	4.8	23.6	<1.02	23.7	3.4	<1.12	775.5	3.9	<0.50	268.8	<0.87	28.8	115.0
6B	10.8	38.8	<1.06	27.6	4.3	3.3	702.0	9.5	1.7	145.5	3.2	79.1	163.1
TIND	10.1	141.1	<0.90	9.3	2.3	<0.98	1299.9	11.0	<0.45	117.4	0.8	29.7	93.6
1B	4.5	128.4	<0.83	6.2	2.8	3.4	832.9	33.1	5.1	19.6	1.3	23.4	105.4
2B	16.5	232.1	<0.87	4.6	3.5	6.2	128.9	54.5	8.6	5.4	4.9	56.8	136.2
6A	4.7	150.4	<0.85	6.0	3.5	4.5	914.6	30.7	3.4	13.4	2.4	49.8	107.5
(wt%)	Zr												
5	256.2												
6B	552.5												
TIND	250.7												
1B	1386.6												
2B	1916.1												
6A	1343.9												

Appendix D: Well Water Composition

Composition of well water samples taken from the field in Tanzania analysed by ICP-OES and Ion Chromatography at Newcastle University.

	Al (mg/l)	As (mg/l)	B (mg/l)	Ca (mg/l)	Cd (mg/l)	Co (mg/l)	Cr (mg/l)	Cu (mg/l)	Fe (mg/l)	K (mg/l)	Li (mg/l)	Mg (mg/l)	Mn (mg/l)
Well 1	0.4	0.01	<0.1	6	<0.01	<0.01	<0.01	<0.01	0.06	7.9	<0.1	3	<0.01
Well 4	0.1	0.01	<0.1	6.4	<0.01	<0.01	<0.01	<0.01	0.1	7.5	<0.1	3.3	<0.01
Well 10	<0.1	0.01	<0.1	6.5	<0.01	<0.01	<0.01	<0.01	<0.01	5.6	<0.1	2.8	<0.01
Well 12	<0.1	0.02	<0.1	45	<0.01	<0.01	<0.01	<0.01	<0.01	103.9	0.1	6.3	<0.01
Well 13	<0.1	0.02	<0.1	56.9	<0.01	<0.01	<0.01	<0.01	<0.01	74.5	0.1	9.9	<0.01
Well 14	0.2	<0.01	<0.1	1.8	<0.01	<0.01	<0.01	<0.01	0.06	53.2	0.2	0.2	<0.01
Well 15	<0.1	0.01	<0.1	8	<0.01	<0.01	<0.01	<0.01	0.02	57.6	0.2	2.5	<0.01
Well 16	<0.1	0.02	<0.1	39.3	<0.01	<0.01	<0.01	<0.01	<0.01	60.8	0.1	8.3	<0.01
Well 17	<0.1	0.01	<0.1	30.7	<0.01	<0.01	<0.01	<0.01	<0.01	40	0.1	24.3	<0.01
Well 18	<0.1	0.02	<0.1	40.1	<0.01	<0.01	<0.01	<0.01	<0.01	37.5	0.1	49.1	<0.01
Well 25	<0.1	0.01	<0.1	49	<0.01	<0.01	<0.01	<0.01	<0.01	39.7	0.1	9.6	<0.01
Well 31	0.1	0.02	<0.1	1.9	<0.01	<0.01	<0.01	<0.01	<0.01	54.6	0.1	0.3	<0.01
Well 32	<0.1	0.02	<0.1	3	<0.01	<0.01	<0.01	<0.01	<0.01	69.5	0.2	0.3	<0.01
Well 33	<0.1	0.01	<0.1	3.3	<0.01	<0.01	<0.01	<0.01	<0.01	52.6	0.2	1.6	<0.01
Well 34	<0.1	0.01	<0.1	2.75	<0.01	<0.01	<0.01	<0.01	<0.01	37	0.1	1.1	<0.01
Well 35	<0.1	0.02	<0.1	3.8	<0.01	<0.01	<0.01	<0.01	<0.01	51.2	0.1	1.9	<0.01
Well 36	<0.1	0.01	<0.1	5.4	<0.01	<0.01	<0.01	<0.01	<0.01	50	0.2	2.6	<0.01
Well 68	<0.1	<0.01	<0.1	32.8	<0.01	<0.01	<0.01	<0.01	<0.01	6	<0.1	23.4	<0.01

	Na (mg/l)	Ni (mg/l)	Pb (mg/l)	Se (mg/L)	Si (mg/l)	Sr (mg/l)	Zn (mg/l)	Cl (mg/l)	NO_3 (mg/l)	PO_4 (mg/l)	SO_4 (mg/l)	F (mg/l)	TIC (mg/l)	Charge Balance (%)
Well 1	5.1	<0.01	<0.1	<0.1	21.4	0.1	<0.01	7.80	3.11		3.51	0.5	16.5	-28.41
Well 4	33.1	<0.01	<0.1	<0.1	10.0	0.1	<0.01	7.67	0.30		14.48	2.4	21.0	-3.78
Well 10	17.5	<0.01	<0.1	<0.1	18.8	0.1	<0.01	4.30			2.11	0.3	10.0	18.11
Well 12	149.7	0.01	<0.1	<0.1	35.5	1.2	<0.01	50.23	5.45		46.27	2.6	88.0	9.20
Well 13	150.1	0.01	<0.1	<0.1	41.3	1.2	<0.01	55.84	11.09		47.28	2.9	72.4	15.13
Well 14	236.6	<0.01	<0.1	<0.1	18.3	0.1	<0.01	17.37	2.7594		17.93	5.8	116.3	3.77
Well 15	247.1	<0.01	<0.1	<0.1	16.0	0.2	<0.01	22.09	18.51	1.81	17.80	6.8	123.2	3.45
Well 16	131.8	<0.01	<0.1	<0.1	36.0	0.4	<0.01	35.08	9.79		49.41	4.2	71.2	8.85
Well 17	166.1	<0.01	<0.1	0.1	33.4	0.9	<0.01	40.07	7.34		61.01	5.5	101.7	2.27
Well 18	148.3	0.01	<0.1	0.3	38.4	0.7	0.13	27.15	2.41		19.60	1.9	137.2	2.90
Well 25	113.7	0.01	<0.1	<0.1	38.8	0.2	<0.01	71.55	74.00		27.70	1.1	41.8	11.39
Well 31	374.4	<0.01	<0.1	0.2	15.0	0.1	<0.01	26.78	9.50		38.20	33.2	167.3	1.15
Well 32	290.2	<0.01	<0.1	<0.1	16.3	0.1	<0.01	16.74	20.81		26.38	21.2	135.8	2.77
Well 33	319.3	<0.01	<0.1	0.1	20.5	0.2	<0.01	29.52	15.38	1.80	38.91	26.0	136.6	2.75
Well 34	150.8	<0.01	<0.1	<0.1	9.0	0.1	<0.01	21.81	14.02		28.74	21.2	132.0	-27.34
Well 35	303.0	<0.01	<0.1	0.3	19.4	0.1	<0.01	32.82	7.10	1.76	40.57	24.0	78.0	20.92
Well 36	316.6	<0.01	<0.1	0.1	16.4	0.1	<0.01	37.23	16.50	2.30	59.57	23.0	155.7	-3.96
Well 68	43.0	<0.01	<0.1	0.1	33.0	0.1	<0.01	9.62	1.48		11.36	0.7	46.2	11.91

Appendix E: Project Info Sheet and Survey Consent Form

The following project info sheet and survey consent form were provided to the community members of Tindigani and Mtakuja. A local translator translated all forms into Kiswahili, the translated forms follow the corresponding English form.

<u>Fluorosis study for the Hai District</u>

You are being invited to take part in a research project for people with who may have fluorosis of the bones or teeth due to exposure to high fluoride in drinking water. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with friends and relatives. Ask us if there is anything that is not clear or if you would like more information. Thank you for reading this.

What is the purpose of the research?

Drinking water with high fluoride can lead to staining of the teeth (dental fluorosis), and at higher levels can cause bending of the legs (skeletal fluorosis). Skeletal fluorosis was originally identified as a problem in the Hai district in 1995 in Rundugai, a village in the lowland area. The staple diet of maize is low in calcium, coupled with limited intake of dairy products. All the affected children were exposed to drinking water with very high fluoride concentrations and a low calcium intake. Shortly after this safe piped water was provided to this village and there has been no new cases since. In 2004 a similar problem developed in 2 further lowland villages, Tindigani and Mtakuja. The majority of the wells used in Tindigani and Mtakuja are very high in fluoride. There is also evidence of dental fluorosis and skeletal fluorosis in children from both schools. However, unlike Rundugai gravity fed piped water to the village is impossible and other solutions, such as a solar pump, are impractical.

Professor Dahi, based near Arusha, has developed an effective technique for removing fluoride from water using locally prepared bone char filters which also remove infective organisms. However, this has not been used with water containing such high levels of fluoride. It is important that we understand how common the problem is and why some people are more affected than others. It is then important to provide long term, sustainable, interventions to remove the fluoride from drinking water in the affected villages.

Why has my child been chosen?

Your child has been chosen because they live in Tindigani or Mtakuja and may be exposed to high fluoride in drinking water. Some children have evidence of teeth or bone problems related to high fluoride.

Does my child have to take part?

It is up to you and your child to decide whether your child takes part. If you decide they should take part, you will be given this information sheet to keep, and be asked to sign a consent form. If you decide they should take part, they are still free to withdraw at any time without giving a reason. You may decide for them not to take part at all.

What will happen to my child if they take part?

Details of your child including name, age and sex will be recorded. They will be asked questions about their diet. They will have their height, weight, size of upper arm and skin thickness measured and any evidence of damage to the teeth from fluoride, or to the bones from fluoride, will be recorded, along with a photograph of their front teeth.

They will also be provided with a food diary in which they will record what they eat over three days.

What do I have to do?

If you are agreeable to this please complete the attached consent form and give it to your child to hand in at school.

What are the possible Disadvantages of my child taking part in the study?

The process of filling out of the questionnaires and carrying out the examination will take around 10 minutes and will take place during the school day. The interview process can be stopped at any time.

You will need to help your child to record what they eat for three days.

What are the possible Benefits of taking part in the study?

Your child will undergo an assessment by the research team and advice will be given based on the findings. We hope the research will lead to prevention of problems related to fluoride in the village in the future.

What happens when the study stops?

No changes will be made to the health care services available to you after the study has ended.

Filters, funded by organisations from the UK, will be provided for both the primary schools. Work will be carried out to investigate the feasibility of providing filters for the whole community.

Will my child's taking part in this study be kept confidential?

If you consent for your child to take part in this study the information you give would be used by the doctors running the study to fulfil the objectives of the study. Outside of this, the information will be kept confidential.

Who is organising the research?

Locally in the Hai district Dr Gabriel Masuki, District Medical Officer, Dr John Massawe, Assistant Medical Officer, and your village enumerators. James Shorter, an engineer from the UK who has expertise in the measurement of fluoride in water, will be overseeing the project on a day-to-day basis in the Hai District.

Contact for further Information?

If you require further information, please contact any member of the local Adult Mortality and Morbidity Project (AMMP) team. There will be an AMMP enumerator in your village who can arrange to put you in contact with the relevant person. The AMMP supervisor for your area is Mr John Massawe.

Thank you for your time.

Utafiti wa Florosisi kwa Wilaya ya Hai

Unakaribishwa kushiriki kwenye Mradi wa utafiti kwa watu ambao wana florosisi ya mifupa au meno kutokana na kunywa maji ambayo yana kiasi kikubwa cha floraidi. Kabla hujaamua ni muhimu kuelewa ni kwa nini utafiti huu unafanyika na ni nini kitahusika. Tafadhali chukua muda wa kutosha kuyasoma maelezo yafuatayo kwa makini na kujadiliana na Ndugu na marafiki zako. Tuulize sisi ikiwa kuna jambo lolote ambalo haliko wazi au kama unahitaji maelezo zaidi. Asante kwa kulikubali hili.

Madhumuni ya utafiti huu ni nini?

Kunywa maji yenye kiasi kikubwa cha floraidi kunaweza kuleta hali ya meno kubadilika rangi (florosisi ya meno), na kama kiasi chake ni kikubwa sana kunaweza kusababisha Miguu kujikunja (florosis ya mifupa). Florosis ya mifupa iligundulika kama tatizo katika Wilaya ya Hai mwaka 1995 katika Rundugai, kijiji kilicho eneo la bondeni. Chakula kikuu cha mahindi kina kiasi kidogo cha kalisi, hii ikiwa ni pamoja na kula kiasi kidogo cha bidhaa za maziwa. Watoto wote walioathirika walikuwa wanatumia maji ya kunywa yenye kiasi kikubwa sana cha floraidi na kula Chakula chenye kiasi kidogo cha kalisi. Muda mfupi baada ya kuletwa maji salama ya bomba hapo kijijini kumekuwa hakuna hakuna watu wapya waliopata tatizo hili. Mwaka 2004 tatizo kama hili lilijitokeza katika vijiji viwili vya mabondeni, Tindigani na Mtakuja. Sehemu kubwa ya visima vinavyotumika Tindgani na Mtakuja vinakiasi kikubwa cha madini haya ya floraidi. Pia kuna ushahidi wa florosisi ya meno na ile ya mifupa. Kwa watoto wa shule zote mbili. Hata hivyo, tofauti na Rundugai kuleta maji ya bomba hapo kijijini bila kutumia pampu haiwezekani, na ufumbuzi mwingine, kama kuweka pampu ya kutumia nguvu za jua, hautaweza kufanya kazi

Profesa Dahi, anayekaa karibu na Arusha, amegundua mbinu ya kuondoa floraidi kwenye maji kwa kutumia vichujio vya makaa ya mifupa yaliyotengenezwa nyumbani, ambavyo pia huondoa vimelea vya magonjwa. Hata hivyo, mbinu hii haijawahi kutumika kwenye maji yenye viwango vikubwa kiasi hiki cha floraidi. Ni muhimu tufahamu ni tatizo hili limeenea kiasi gani na ni kwa nini baadhi ya watu huathirika kuliko wengine.

Kwa nini mwanangu amechaguliwa?

Mwanao amechaguliwa kwa sababu anaishi Tindigani au Mtakuja na inawezekana anatumia maji yenye kiasi kikubwa cha floraidi

Mwanangu analazimika kushiriki?

Ni juu nyako wewe na mwanao kuamua kama ashiriki au la. Kama mtaamua ashiriki utapewa karatasi hii ya maelezo ukae nayo, na utaombwa kuweka sahihi kwenye fomu ya Kukubali. Kama mtaamua ashiriki, bado atakuwa huru kujitoa wakati wowote bila kutoa sababu. Unaweza kuamua asishiriki hata kidogo.

Mwanangu atapatwa na nini kama atashiriki?

Taarifa za mtoto wako ikiwa ni pamoja na jina, umri na jinsia zitachukuliwa. Ataulizwa maswali kuhusu chakula anachokula. Watapima urefu wake uzito pamoja na ukubwa wa mkono wake kwa juu na unene wa ngozi na pia kama kuna uharibifu wowote kwa meno au mifupa kutokana na floraidi. Haya yote yataandikwa pamoja na kupigwa picha ya meno ya mbele.

Pia atapewa dayari ya chakula aweze kuandika kila atakachokula kwa muda wa siku tatu. Watoto wachache watachaguliwa kwa utafiti wa ziada ambapo kipimo cha mkojo wa saa 24 kitachukuliwa. Utaarifiwa kama hili litafanyika kwa mwanao.

Ninatakiwa kufanya nini?

Ukikubaliana na hili tunaomba ujaze fomu ya kukubali iliyoambatanishwa na kumpa mwanao aipeleke shuleni.

Ni madhara gani Yanaweza kutokea mtoto wangu akishiriki katika utafiti huu?

Zoezi la kujaza dodoso na kumpima litachukua kiasi cha dakika 10 na litafanyika wakati akiwa shuleni. Zoezi lausaili linaweza kusitishwa wakati wowote.

Utahitaji kumsaidia mwanao kukumbuka vitu alivyokula kwa siku tatu. Kama mwanao atachaguliwa kwa ajili ya utafiti wa ziada, atahitaji kukusanya mkojo wake kwa saa 24.

Ni faida gani unaweza kupata kwa kushirika katika utafiti huu?

Mwanao atachunguzwa na timu ya utafiti na ushauri utatolewa kufuatana na yale watakayogundua. Tunatumaini utafiti utapelekea kuzuia madhara yatokanayo na na floraidi katika kijiji siku zijazo.

Kutatokea nini pale utafiti utakapokoma?

Hakuna mabadiliko yatakayofanyika kwa huduma ya afya utakayokuwa unapata baada ya utafiti kukamilika.

Vichujio,vilivyolipiwa na shirika la Uingereza, vitatolewa kwa hizi shule mbili. Kazi itafanyika kuona kama ni jambo litakalowezekana kuipatia jamii nzima vichujio.

Je, ushiriki wa mwanagu katika Mradi huu utatunzwa kama siri?

Ukikubali mwanao ashiriki kwenye utafiti huu, maelezo utakayotoa yatatumiwa na madaktari wanaoendesha utafiti huu kutimiza malengo ya utafiti. Nje ya hayo maelezo yatakuwa siri kabisa.

Matokeo ya utafiti yatafanywaje?

Tunatumaini kwamba baada ya utafiti kukamilika matokeo yake yatachapishwa kwenye jarida la Kidaktari (medical journal). Tunaweza kufanya mpango wa kukupatia nakala yake ukipenda. Utafiti umepangwa kukamilika mwezi Oktoba 2009.

Ni nani anaratibu Utafiti huu?

Mtafiti Mkuu wa Mradi ni Dr Richard Walker, Bingwa tabibu Mwandamizi kwenye Tyneside General Hospital Uingereza. Mtafiti Mkuu wa Tanzania ni Dr Joyceline Kaganda, mtaalamu wa lishe anayekaa Dar-es-Salaam. Kwa hapa Wilaya ya Hai ni Dr

Gabriel Masuki, Mganga Mkuu wa Wilaya, Dr John Massawe, Mganga Msaidizi, na wanakijiji wenu wanaohesabu. James Shorter, mhandisi kutoka Uingereza ambaye ana utaalamu wa kupima kiasi cha floraidi kwenye maji, atakuwa anasimamia Mradi huu siku kwa siku katika Wilaya ya Hai.

Mawasiliano kwa maelezo zaidi?

Kama utahitaji maelezo zaidi, naomba uwasiliane na yeyote kati ya wajumbe wa timu ya Mradi wa Vifo na magonjwa ya Watu Wazima (Adult Mortality and Morbidity Project - AMMP). Kutakuwa na mtu wa kuhesabu wa AMMP katika kijiji chako ambaye anaweza kufanya mpango wa kukunganisha na mtu anayehusika. Mwangalizi wa eneo lako ni Bwana John Massawe

Asante kwa muda wako.

CONSENT FORM FOR PARENT/GUARDIAN-Child with potential exposure to high fluoride in drinking water

Fluorosis Study for the Hai District

Name: Ballozi: Village:

Have you read the information sheet? Yes No

Have you had the opportunity to ask questions and discuss the study?
Yes No

Have you had all your questions answered appropriately? Yes No

Who have you spoken to?____________________________________

Do you understand that you can withdraw your child from the study:

- at any time,
- without having to give a reason,
- without affecting their future care. Yes No

Do you agree to take part in the fluorosis study for the Hai District?
Yes No

Signature of person consenting

Print name ______________________________ Date …../…../…..

Relationship to patient – parent/other relative (state)/other (state) ___________

FOMU YA KUKUBALI KWA MZAZI/MLEZI-mtoto mwenye anayekunywa maji yenye kiasi kikubwa cha floraidi

Utafiti wa Florosisi kwa Wilaya ya Hai

Jina la mtoto/watoto: Balozi: Kijiji:

Umeshaisoma karatasi ya maelezo? Ndiyo Hapana

Umepata fursa ya kuuliza maswali na kujadili utafiti huu? Ndiyo Hapana

Umejibiwa maswali yako yote kwa usahihi? Ndiyo Hapana

Umeongea na nani?_____________________________________

Unaelewa kwamba unaweza kumwondoa mwanao kutoka kwenye utafiti huu:

- wakati wowote,
- bila kutoa sababu,
- bila kuathiri matunzo yaoke ya baadaye. Ndiyo Hapana

Unakubali kushiriki katika huu utafiti wa florosisi kwa Wilaya ya Hai?
Ndiyo Hapana

Sahihi ya mtu anayekubali

Jina la mzazi/mlezi (*andika kwa herufi kubwa*)
__________________________________ Tarehe …../…../…..

Uhusiano na mgonjwa – mzazi/ndugu mwingine (eleza)/mwingine (elezea)_______

Jina (*andika kwa herufi kubwa*) ______________________ *Tarehe* ……/……/……

Appendix F: Health Survey

The following form was used for the health survey as referred to in chapter 4.2.

Health Survey
a part of the
Hai Defluoridation Project 2007-2008

Study Number: □□□-□□□

Food Diary: FD□□□

GUIDANCE FOR COMPLETING FORM

1 Please note that if you are recording numbers that do not "require" all the boxes make sure that you complete all the boxes that are not required with a 0. For instance, when recording a number 2 record this as 002 not 2- -
2 Where a stem to a question says "state" please give full details.
3 Dates should be day, month, year.
4 Time is recorded according to the 24 hour clock. Eg 3:15pm recorded as 1515hrs

Please write any extra details you regard as relevant next to the respective boxes. For answers to "other" please write details. Some positive answers have "state" – please write details. If in doubt about any item write details.

A DEMOGRAPHIC DETAILS

1. **Name:** ______________________________

2. **Date of Birth:** ___/___/_______

3. **Age**: |__|__| Yrs   4. **Sex**: 1. Male 2. Female |__|

5. **Balozi:** ______________________________

6. **Date of interview** ___/ 02 / 2008___

7. **Study number** |__|__|__| - |__|__|__|

8. **Tawi/Village name** ______Mtakuja_______

9. **Tribe**
   1. Zaramo
   2. Ndengereko
   3. Chagga
   4. Masai
   5. Pare |____|
   6. Nyamwezi
   7. Sukuma
   8. Other – state ______________________
   9. M.V.

10. **Have you lived in this village all your life** |____|
    If NO what village have they moved from ___________________

B DRINKING WATER

1. Where do you mainly get your drinking water from?

____

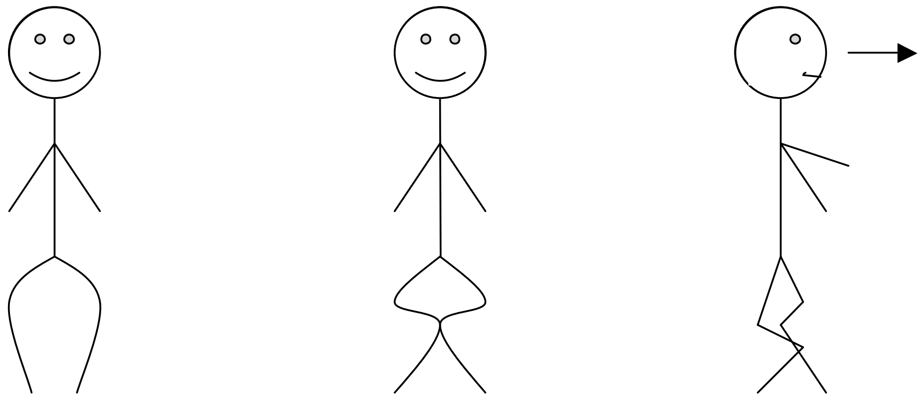
C FLUORIDE RELATED EXAMINATION

1. Picture of front teeth – picture number T□□□

2. Any signs of Skeletal fluorosis – describe

____

Bowed Legs **Knock Knees** **Sabre Tibia**



□ □ □

May have sabre tibia as well as the other deformities, in which case tick both boxes

3. Picture of deformities – picture number D□□□

4. Do they experience any pain or discomfort related to joints/fluoride YES/NO

5. At what age were they (or their family) first aware of the problem

□□□ months

6. a) Does anyone else in their direct family suffer from either skeletal or dental fluorosis (indicate how many in the boxes)

Father □ Mother □ Grandfather □ Grandmother □

Brother □ Sister □

b) If YES who – indicate if any of them are at this school.

Name ______________________ Relation ______________________
Name ______________________ Relation ______________________
Name ______________________ Relation ______________________
Name ______________________ Relation ______________________
Name ______________________ Relation ______________________

D GENERAL EXAMINATION

1. Body circumferences

a. Hip |__|__|__| Cm
b. Waist |__|__|__| Cm

2. Height: |__|__|__| Cm

3. Weight: |__|__|__| Kg

4. Complete Anthropometric measurements on the both sides of the body.

i) Mid arm point right ☐ cm

left ☐ cm

ii) Mid upper arm circumference (MAC) Right ☐ cm

Left ☐ cm Centile ☐

iii) Triceps skin fold (TSF) Right 1 ☐ mm

Right 2 ☐ mm Mean value ☐ mm

Right 3 ☐ mm Centile ☐

iv) Mid arm muscle circumference (MAMC) (cm) = MAC – (0.3142 x TSF).

= ☐ Centile .

Appendix G: Food Diary

A sample food diary is shown below which was provided to the surveyed students, an English translation is shown on pg. 159.

Diary Ya Chakula

Mradi wa Kurekebisha Floridi Hai

2007 -2008

FD□□□

SN □□□-□□□

Siku za kumbukumbu:

1……………………………………………….

2……………………………………………….

3……………………………………………….

Tarehe:11 Nov 2007

Wakati	Chakula / Kinywaji	Kupika /Njia ya kutayarisha	Kiasi ulichokula au kunywa	Matumizi ya Ofisi tu	
Saa 12 Asubuhi	Uji	Kikombe kimoja cha unga wa mahindi kwa vikombe vinne vya maji	Kikombe kimoja 1		
	Chai		Kikombe 1		
	Sukari		Vijiko 2		
Saa 4 asubuhi	Maji	Toka kwenye kisima cha nyumbani	Kikombe 1		
Saa 7 mchana	Ugali	Vikombe viwili vya unga wa mahindi kwa vikombe vitatu vya maji	Vikombe 2		
	Maharage	Yaliyopikwa	Kikombe 1		
Saa 7 mchana	Maji	Toka kwenye kisima cha shule	Kikombe 1		
Saa 12 jioni	Chai		Kikombe 1		
Saa 2 usiku	Ugali	Vikombe viwili vya unga wa mahindi kwa vikombe vitatu vya maji	Vikombe 2		
Saa 2 usiku	Mchicha	Uliopikwa	Kikombe 1		

Date ……………….

Time	Type of Food	How was food prepared?	Amount of food consumed (cups)	For office use	

Appendix H: Data Collated from Health Survey

Study No.	Age	Sex	Village	Drinking Water Source	TFSI Score	Description of Deformities	BMI	Have your resided in this village all your life?
F(MT)-(001)	13	Male	Mtakuja	Well	5		15.6	No
F(MT)-(002)	12	Female	Mtakuja	Well	3	Bowed Legs	15.4	No
F(MT)-(003)	8	Male	Mtakuja	Well	4	Knock Knees	16.1	No
F(MT)-(004)	9	Male	Mtakuja	Well	5		14.3	No
F(MT)-(005)	14	Female	Mtakuja	Piped Water	4		15.2	Yes
F(MT)-(006)	13	Female	Mtakuja	Well	6		13.3	No
F(MT)-(007)	11	Female	Mtakuja	Well	5		13.8	No
F(MT)-(008)	7	Male	Mtakuja	Piped Water	5		14.7	No
F(MT)-(009)	9	Male	Mtakuja	Well	4	Bowed Legs	14.3	No
F(MT)-(010)	15	Female	Mtakuja	Piped Water, Well	4		13.5	Yes
F(MT)-(011)	11	Male	Mtakuja	Well	7		15	No
F(MT)-(012)	9	Male	Mtakuja	Piped Water	6		13.9	No
F(MT)-(013)	9	Male	Mtakuja	Well	5		13.9	Yes
F(MT)-(014)	9	Female	Mtakuja	Well	3		14.2	Yes
F(MT)-(015)	10	Male	Mtakuja	Well	6		14.1	No
F(MT)-(016)	10	Female	Mtakuja	Well	5	Knock Knees	15.4	Yes
F(MT)-(017)	9	Male	Mtakuja	Well	6		15.1	No
F(MT)-(018)	8	Female	Mtakuja	Well	3		14.1	Yes
F(MT)-(019)	7	Female	Mtakuja	Well	4		13.4	No
F(MT)-(020)	8	Female	Mtakuja	Piped Water	4	Knock Knees	12.6	Yes
F(MT)-(021)	8	Male	Mtakuja	Well	5		13	No
F(MT)-(022)	8	Female	Mtakuja	Well	5		16	No
F(MT)-(023)	8	Female	Mtakuja	Well	6		14.8	No
F(MT)-(024)	8	Female	Mtakuja	Well	4		18.6	No

F(MT)-(025)	10	Female	Mtakuja	Well	4	Bowed Legs	14.5	No
F(MT)-(026)	12	Female	Mtakuja	Well	6		15.6	No
F(MT)-(027)	11	Female	Mtakuja	Well	5		15.7	No
F(MT)-(028)	11	Female	Mtakuja	Well	5		15.4	No
F(MT)-(029)	12	Male	Mtakuja	Well	5		15.3	No
F(MT)-(030)	10	Male	Mtakuja	Well	6		17.2	No
F(MT)-(031)	12	Male	Mtakuja	Well	5		14.6	No
F(MT)-(032)	11	Female	Mtakuja	Well	5		14.3	No
F(MT)-(033)	9	Female	Mtakuja	Well	5		13	No
F(MT)-(034)	12	Female	Mtakuja	Piped Water	5		14.6	No
F(MT)-(035)	9	Male	Mtakuja	Well, Piped Water	5		15	No
F(MT)-(036)	12	Female	Mtakuja	Well	6	Knock Knees	13.9	No
F(MT)-(037)	12	Male	Mtakuja	Well	5	Knock Knees	14.6	No
F(MT)-(038)	12	Female	Mtakuja	Well	6		14.4	Yes
F(MT)-(039)	12	Male	Mtakuja	Well	5	Bowed Legs	12.8	Yes
F(MT)-(040)	11	Male	Mtakuja	Well	5		15	No
F(MT)-(041)	10	Male	Mtakuja	Well	7	Knock Knees	14.7	No
F(MT)-(042)	10	Female	Mtakuja	Well	5		14.2	No
F(MT)-(043)	11	Female	Mtakuja	Well	7	Knock Knees	15	No
F(MT)-(044)	12	Female	Mtakuja	Well	4	Knock Knees	13.9	No
F(MT)-(045)	9	Male	Mtakuja	Well	6	Knock Knees	13.2	No
F(MT)-(046)	11	Female	Mtakuja	Well	3	Bowed Legs	13.8	No
F(MT)-(047)	11	Female	Mtakuja	Well	6	Knock Knees	14.4	No
F(MT)-(048)	11	Female	Mtakuja	Well	6		15	No
F(MT)-(049)	11	Female	Mtakuja	Well	5		16.2	Yes
F(MT)-(050)	11	Male	Mtakuja	Well	7	Bowed Legs	17.1	No
F(MT)-(051)	11	Female	Mtakuja	Piped Water	6	Knock Knees	17.6	No
F(MT)-(052)	12	Female	Mtakuja	Well	4		15.2	No
F(MT)-(053)	11	Female	Mtakuja	Well	5		15.9	No
F(MT)-(054)	12	Female	Mtakuja	Well	2		17.9	Yes
F(MT)-(055)	11	Female	Mtakuja	Well	5	Bowed Legs	13.9	No

F(MT)-(056)	12	Male	Mtakuja	Well	4		15.7	No
F(MT)-(057)	11	Female	Mtakuja	Well	3		17.1	Yes
F(MT)-(058)	11	Female	Mtakuja	Well	4		14	No
F(MT)-(059)	11	Female	Mtakuja	Well	7		13.5	No
F(MT)-(060)	10	Female	Mtakuja	Well	5		13.9	Yes
F(MT)-(061)	14	Female	Mtakuja	Well	4		13.5	Yes
F(MT)-(062)	8	Female	Mtakuja	Well	5		12.6	No
F(MT)-(063)	8	Female	Mtakuja	Well	4		15	No
F(MT)-(064)	8	Female	Mtakuja	Well	4		14.1	No
F(MT)-(065)	9	Male	Mtakuja	Well	5	Bowed Legs	14.8	No
F(MT)-(066)	9	Male	Mtakuja	Well	6		15.3	Yes
F(MT)-(067)	12	Female	Mtakuja	Well	6		14.5	Yes
F(MT)-(069)	12	Female	Mtakuja	Well	6		15.8	No
F(MT)-(070)	11	Female	Mtakuja	Well	4		13.5	No
F(MT)-(071)	12	Male	Mtakuja	Well	4		15.4	No
F(MT)-(072)	12	Female	Mtakuja	Piped Water, Well	6		13.6	Yes
F(MT)-(073)	14	Male	Mtakuja	Well	4		15.4	Yes
F(MT)-(074)	13	Female	Mtakuja	Well	3		17.3	Yes
F(MT)-(075)	12	Male	Mtakuja	Well	1		17.1	Yes
F(MT)-(076)	14	Female	Mtakuja	Well	5		14.8	No
F(MT)-(077)	13	Male	Mtakuja	Well	6		14.2	No
F(MT)-(078)	12	Male	Mtakuja	Well	6		15.3	No
F(MT)-(079)	12	Female	Mtakuja	Well	4		13.3	No
F(MT)-(080)	13	Male	Mtakuja	Well	4		17.5	No
F(MT)-(081)	11	Male	Mtakuja	Piped Water, Well	5		13.8	No
F(MT)-(082)	11	Female	Mtakuja	Well	4		12.6	No
F(MT)-(083)	12	Male	Mtakuja	Well	5		14.9	Yes
F(MT)-(084)	11	Male	Mtakuja	Well	5		14.2	No
F(MT)-(085)	13	Female	Mtakuja	Piped Water	5		14.3	Yes
F(MT)-(086)	14	Male	Mtakuja	Well	5		14	No
F(MT)-(087)	12	Male	Mtakuja	Piped Water, Well	5		13.9	No

F(MT)-(088)	11	Male	Mtakuja	Well	6		14.3	Yes
F(MT)-(089)	13	Male	Mtakuja	Well	5		13.3	No
F(MT)-(090)	11	Female	Mtakuja	Well	4		9.2	No
F(MT)-(091)	13	Male	Mtakuja	Piped Water	0		14.9	No
F(MT)-(092)	12	Female	Mtakuja	Well	4		14.3	Yes
F(MT)-(093)	13	Female	Mtakuja	Well	5		14.5	No
F(MT)-(094)	12	Male	Mtakuja	Well	6	Knock Knees	14.4	No
F(MT)-(095)	13	Male	Mtakuja	Well	5		15.2	No
F(MT)-(096)	13	Male	Mtakuja	Well	6		14.8	No
F(MT)-(097)	13	Female	Mtakuja	Well	5		17.8	No
F(MT)-(098)	13	Male	Mtakuja	Well	4		14	Yes
F(MT)-(099)	13	Female	Mtakuja	Well	7	Knock Knees	15.2	Yes
F(MT)-(100)	13	Female	Mtakuja	Well	5		17.8	Yes
F(MT)-(101)	13	Male	Mtakuja	Well	6	Bowed Legs	12.9	No
F(MT)-(102)	13	Male	Mtakuja	Well	5	Knock Knees	17.1	No
F(MT)-(103)	15	Male	Mtakuja	Well	4		15.5	No
F(MT)-(104)	13	Female	Mtakuja	Well	6		15.3	No
F(MT)-(105)	14	Male	Mtakuja	Well	5	Knock Knees	14.7	Yes
F(MT)-(106)	14	Male	Mtakuja	Well	5	Knock Knees	16	Yes
F(MT)-(107)	14	Female	Mtakuja	Well	4	Bowed Legs	13.7	No
F(MT)-(108)	12	Female	Mtakuja	Well	6		14.2	No
F(MT)-(109)	12	Female	Mtakuja	Well	6		14.8	No
F(MT)-(110)	13	Male	Mtakuja	Well	6	Sabre Tibia	13.3	No
F(MT)-(111)	13	Female	Mtakuja	Well	4	Knock Knees	13.9	No
F(MT)-(112)	10	Male	Mtakuja	Well	4		14.5	Yes
F(MT)-(113)	12	Female	Mtakuja	Well	7	Knock Knees	15.3	No
F(MT)-(114)	12	Male	Mtakuja	Well	4		14.7	No
F(MT)-(115)	11	Male	Mtakuja	Well	5		14.2	No
F(MT)-(116)	9	Female	Mtakuja	Piped Water, Well	4		14	No
F(MT)-(117)	12	Male	Mtakuja	Well	5	Bowed Legs	13.7	No
F(MT)-(118)	15	Female	Mtakuja	Well	4		18.6	No

F(MT)-(68)	12	Female	Mtakuja	Well	4		12.8	No
F(TI)-(001)	11	Male	Tindigani	Well, Piped Water	5	Knock Knees	15.1	No
F(TI)-(002)	14	Male	Tindigani	Well	6		16.9	No
F(TI)-(003)	12	Male	Tindigani	Well	5	Knock Knees	16.4	No
F(TI)-(004)	16	Female	Tindigani	Well	5		17.9	No
F(TI)-(005)	12	Male	Tindigani	Well	4		14.6	No
F(TI)-(006)	7	Male	Tindigani	Well	4	Knock Knees	14.5	No
F(TI)-(007)	11	Male	Tindigani	Piped Water	4	Knock Knees	13.6	No
F(TI)-(008)	9	Male	Tindigani	Well	No Photo	Knock Knees	15.7	No
F(TI)-(009)	6	Male	Tindigani	Well	6	Knock Knees	13.9	No
F(TI)-(010)	12	Male	Tindigani	River	7	Bowed Legs	13	No
F(TI)-(011)	7	Male	Tindigani	Well	4		16.2	No
F(TI)-(012)	7	Male	Tindigani	Well	No Photo	Knock Knees	13.7	No
F(TI)-(013)	11	Male	Tindigani	Well	5	Bowed Legs	14.6	No
F(TI)-(014)	11	Female	Tindigani	Piped Water	4		13.9	No
F(TI)-(015)	12	Male	Tindigani	Well	4		14.3	No
F(TI)-(016)	15	Female	Tindigani	Well	4		19	Yes
F(TI)-(017)	13	Male	Tindigani	Njoro Stream	4		13.5	No
F(TI)-(018)	13	Male	Tindigani	Well	7		14.8	Yes
F(TI)-(019)	13	Male	Tindigani	Borehole, Piped Water	2		14	Yes
F(TI)-(020)	10	Male	Tindigani	Borehole	5		14.9	No
F(TI)-(021)	10	Female	Tindigani	Well	5		14.5	No
F(TI)-(022)	8	Male	Tindigani	Borehole	4		15.6	No
F(TI)-(023)	8	Female	Tindigani	Borehole, Well	5		14.4	No
F(TI)-(024)	9	Male	Tindigani	Well	5		15.1	No
F(TI)-(025)	12	Female	Tindigani	Borehole	5		13.8	No
F(TI)-(026)	10	Female	Tindigani	Piped Water	5		14.5	Yes
F(TI)-(027)	10	Female	Tindigani	Piped Water	4		13.7	No
F(TI)-(028)	8	Male	Tindigani	Piped Water	4		14.7	No
F(TI)-(029)	12	Female	Tindigani	Borehole, Piped Water	6		14.3	Yes
F(TI)-(030)	9	Male	Tindigani	Well	4	Bowed Legs	14.8	No

F(TI)-(031)	12	Female	Tindigani	Borehole	6		15	No
F(TI)-(032)	7	Female	Tindigani	Borehole	5		15	No
F(TI)-(033)	13	Male	Tindigani	Well	4		14.9	No
F(TI)-(034)	8	Female	Tindigani	Borehole	3		15	No
F(TI)-(035)	7	Male	Tindigani	Piped Water, River Njoro	No Photo		14.6	No
F(TI)-(036)	12	Male	Tindigani	Well	5		16.7	No
F(TI)-(037)	7	Female	Tindigani	Borehole	No Photo		15.9	No
F(TI)-(038)	9	Female	Tindigani	Borehole	4		13	No
F(TI)-(039)	8	Female	Tindigani	Well	6		13.4	No
F(TI)-(040)	15	Female	Tindigani	Borehole	7		17.4	No
F(TI)-(041)	10	Male	Tindigani	Borehole	5	Knock Knees	15	No
F(TI)-(042)	10	Male	Tindigani	Borehole	5		16.4	No
F(TI)-(043)	6	Female	Tindigani	Well	2		15.7	No
F(TI)-(044)	11	Female	Tindigani	Piped Water	No Photo		17	Yes
F(TI)-(045)	7	Female	Tindigani	Borehole	No Photo		14.6	No
F(TI)-(046)	8	Male	Tindigani	Borehole	4	Knock Knees	13.9	No
F(TI)-(047)	12	Male	Tindigani	Borehole	4		16.5	No
F(TI)-(048)	8	Female	Tindigani	River	6	Bowed Legs	13.4	No
F(TI)-(049)	10	Female	Tindigani	Piped Water, River Njoro	6		14.1	No
F(TI)-(050)	7	Female	Tindigani	Piped Water	4		12.5	No
F(TI)-(051)	12	Male	Tindigani	Piped Water, River Njoro	5	Bowed Legs	15.5	No
F(TI)-(052)	12	Female	Tindigani	Piped Water	5		15.6	No
F(TI)-(053)	17	Male	Tindigani	Piped Water	5	Bowed Legs	19.6	Yes
F(TI)-(054)	10	Female	Tindigani	Piped Water	5		15.6	Yes
F(TI)-(055)	8	Male	Tindigani	Piped Water	4		14.6	No
F(TI)-(056)	9	Male	Tindigani	Well	5		12.8	No
F(TI)-(057)	8	Male	Tindigani	Well	3		14.1	No
F(TI)-(058)	6	Female	Tindigani	Well, River Njoro	5		14.1	No
F(TI)-(059)	14	Male	Tindigani	Well	6	Bowed Legs	14.2	No

F(TI)-(060)	11	Male	Tindigani	Well	6		14.2	No
F(TI)-(061)	8	Male	Tindigani	Well	5	Knock Knees	15	No
F(TI)-(063)	7	Male	Tindigani	Piped Water	3		13.2	No
F(TI)-(064)	12	Male	Tindigani	Piped Water	4		14.6	No
F(TI)-(065)	7	Female	Tindigani	Well	6		13	No
F(TI)-(066)	10	Female	Tindigani	Piped Water	6		17	No
F(TI)-(067)	8	Female	Tindigani	Piped Water	5		13	No
F(TI)-(068)	10	Female	Tindigani	Piped Water	6	Knock Knees	13.6	No
F(TI)-(069)	10	Female	Tindigani	Well	5		16.1	No
F(TI)-(070)	9	Female	Tindigani	Well, Piped Water	4		16	No
F(TI)-(071)	7	Female	Tindigani	Well	5	Bowed Legs	13.6	No
F(TI)-(072)	7	Female	Tindigani	Well, Piped Water	6	Knock Knees	11.5	No
F(TI)-(073)	15	Female	Tindigani	Piped Water	6		13.9	No
F(TI)-(074)	11	Female	Tindigani	Well	4		14.4	No
F(TI)-(075)	8	Female	Tindigani	Piped Water	6	Knock Knees	14.8	No
F(TI)-(076)	10	Female	Tindigani	Piped Water	6		13.6	No
F(TI)-(077)	10	Female	Tindigani	Piped Water	7		14.1	No
F(TI)-(078)	13	Female	Tindigani	Well	4		17.4	No
F(TI)-(079)	7	Male	Tindigani	Borehole	3	Knock Knees	14.3	No
F(TI)-(080)	8	Male	Tindigani	Well	3	Bowed Legs	12.5	No
F(TI)-(081)	10	Male	Tindigani	Piped Water	4		14.2	No
F(TI)-(082)	10	Male	Tindigani	Piped Water	4	Knock Knees	12.8	No
F(TI)-(083)	14	Male	Tindigani	Well	4		16.4	No
F(TI)-(084)	13	Male	Tindigani	Piped Water	4		14.6	No
F(TI)-(085)	13	Male	Tindigani	Borehole	4		14.3	No
F(TI)-(086)	12	Male	Tindigani	Well	4		18.1	Yes
F(TI)-(087)	13	Male	Tindigani	Piped Water	4	Knock Knees	13.5	No
F(TI)-(088)	9	Male	Tindigani	Well	6	Sabre Tibia	14.6	No
F(TI)-(089)	16	Male	Tindigani	Well	4	Sabre Tibia	16	No
F(TI)-(090)	10	Male	Tindigani	Well, Piped Water	5	Knock Knees	15.3	No
F(TI)-(091)	10	Male	Tindigani	Well	6	Knock Knees	16.6	No

F(TI)-(092)	12	Male	Tindigani	River Njoro	6	Sabre Tibia	14.8	Yes
F(TI)-(093)	13	Male	Tindigani	Piped Water	4		15.6	No
F(TI)-(094)	10	Male	Tindigani	Well, Piped Water	6	Knock Knees	13.4	No
F(TI)-(095)	10	Male	Tindigani	Well	4	Sabre Tibia	13.7	No
F(TI)-(096)	9	Male	Tindigani	Borehole	4		14.3	No
F(TI)-(097)	9	Male	Tindigani	Piped Water	4		15.2	No
F(TI)-(098)	10	Male	Tindigani	Well	4		14.9	No
F(TI)-(099)	10	Male	Tindigani	Well	3	Knock Knees	12.9	No
F(TI)-(100)	12	Female	Tindigani	Borehole	6		15.5	No
F(TI)-(101)	13	Female	Tindigani	Piped Water	5		14.4	No
F(TI)-(102)	5	Female	Tindigani	Piped Water	No Photo	Knock Knees	13.9	No
F(TI)-(103)	8	Male	Tindigani	Well	4	Knock Knees	14.5	No
F(TI)-(104)	8	Male	Tindigani	River Njoro	6	Bowed Legs	13.2	No
F(TI)-(105)	7	Female	Tindigani	Well	No Photo		14.1	No
F(TI)-(106)	13	Female	Tindigani	Well	6		13.3	No
F(TI)-(107)	13	Male	Tindigani	Well, River Njoro	4	Knock Knees	16	No
F(TI)-(108)	7	Male	Tindigani	Piped Water	No Photo		13.7	No
F(TI)-(109)	12	Female	Tindigani	River Njoro	4	Knock Knees	14	No
F(TI)-(110)	11	Female	Tindigani	Piped Water	4		15.8	No
F(TI)-(111)	12	Female	Tindigani	Piped Water	5		13.5	No
F(TI)-(112)	13	Female	Tindigani	Well, Piped Water	5	Knock Knees	16	No
F(TI)-(113)	11	Female	Tindigani	Piped Water	5		13.3	No
F(TI)-(114)	7	Male	Tindigani	River Njoro	7		13.3	No
F(TI)-(115)	15	Female	Tindigani	Piped Water	4		15.8	No
F(TI)-(116)	9	Male	Tindigani	Well, River Njoro	6	Knock Knees	14.1	No
F(TI)-(117)	10	Male	Tindigani	Well	5	Knock Knees	13.4	No
F(TI)-(118)	7	Male	Tindigani	Borehole	3	Knock Knees	13.2	No
F(TI)-(119)	8	Female	Tindigani	Well	3		15.2	No
F(TI)-(120)	10	Female	Tindigani	River Njoro	3		13.9	No
F(TI)-(121)	10	Male	Tindigani	River Njoro	6		16	No
F(TI)-(122)	10	Male	Tindigani	River Njoro	4		12.1	No

F(TI)-(123)	9	Female	Tindigani	Well	5		15.8	No
F(TI)-(124)	10	Female	Tindigani	Well	No Photo		14.6	No
F(TI)-(125)	10	Female	Tindigani	Well	5		16.1	No
F(TI)-(126)	10	Female	Tindigani	Well, River Njoro	3		14.6	No
F(TI)-(127)	8	Female	Tindigani	River Njoro	3	Bowed Legs	11.5	No
F(TI)-(128)	11	Female	Tindigani	Piped Water	5		13.9	No
F(TI)-(129)	12	Male	Tindigani	Piped Water	4		17	No
F(TI)-(130)	7	Male	Tindigani	Well	No Photo		14.3	No
F(TI)-(131)	8	Female	Tindigani	Well	No Photo	Sabre Tibia	13.6	No
F(TI)-(132)	10	Female	Tindigani	Well	4		9.7	No
F(TI)-(133)	7	Female	Tindigani	Borehole	No Photo		9.5	No
F(TI)-(134)	8	Male	Tindigani	Well	4		13.2	No
F(TI)-(135)	8	Female	Tindigani	Well, River Njoro	4		13.4	No
F(TI)-(136)	9	Female	Tindigani	Piped Water	5		12.5	No
F(TI)-(137)	8	Male	Tindigani	Borehole	4		15.5	No
F(TI)-(138)	12	Male	Tindigani	Well	5	Sabre Tibia	16.1	No
F(TI)-(139)	12	Female	Tindigani	Piped Water	6		13.9	No
F(TI)-(140)	7	Female	Tindigani	Well, River Njoro	5	Knock Knees	12.4	No
F(TI)-(141)	11	Female	Tindigani	River Njoro	4		14.1	No
F(TI)-(142)	7	Female	Tindigani	Well, Piped Water	4		13.6	No
F(TI)-(143)	12	Female	Tindigani	River Njoro	5	Bowed Legs	13.4	No
F(TI)-(144)	10	Female	Tindigani	River Njoro	6		14.6	No
F(TI)-(145)	12	Female	Tindigani	Well	5		13.4	No
F(TI)-(146)	10	Female	Tindigani	Borehole	5		15.1	No
F(TI)-(147)	13	Female	Tindigani	Borehole	5		14.7	No
F(TI)-(148)	11	Female	Tindigani	Well, Njoro River	5		15.1	No
F(TI)-(149)	8	Female	Tindigani	River Njoro	No Photo		13.1	No
F(TI)-(150)	8	Female	Tindigani	Well	1		13.6	No
F(TI)-(151)	11	Female	Tindigani	Well	4		13.4	No
F(TI)-(152)	8	Female	Tindigani	Well	5		16	No
F(TI)-(153)	11	Female	Tindigani	River Njoro	5		15.3	No

F(TI)-(154)	8	Female	Tindigani	Well, Piped Water	No Photo		13	No
F(TI)-(155)	8	Female	Tindigani	Well	5		14	No
F(TI)-(156)	9	Female	Tindigani	Well	5		12.7	No
F(TI)-(157)	7	Female	Tindigani	Well, Piped Water	5	Knock Knees	14.1	No
F(TI)-(158)	8	Female	Tindigani	Well	5		14.3	No