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Distribution of High-Fluoride Groundwater in Dong Xuan District (Phu Yen Province), Vietnam, and Assessment of the Human Health Risk

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

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ABSTRACT

Consumption of groundwater containing elevated concentrations of dissolved fluoride (F^-) from shallow domestic wells has caused health problems for residents in some areas of central coastal Vietnam. In Phu Yen province, groundwater is the main source of drinking water and the population in certain areas of the province have been identified as suffering from fluorosis in earlier studies. A study of shallow groundwater in the Khanh Hoa province to the south of Phu Yen province conducted eight years previously found occurrences of high F^- containing water in numerous domestic wells.

The primary objective of this study was to investigate the extent of high F^- groundwater in wells of the Dong Xuan district of Phu Yen province and to delineate areas of fluorosis risk in the district through the production of a fluorosis risk map. A secondary objective was to re-analyse water from selected wells from the earlier study in Khanh Hoa province to elucidate the temporal variability in F^- content and so assess the viability of a GIS database in the future management of F^- in the drinking water supply of Dong Xuan district. It was further proposed to improve procedures for measuring F^- in groundwater "on-site" using a Fluoride Ion Selective Electrode (FISE) that would produce accurate results over a wide range of F^- concentrations. Accuracy of the FISE determinations was evaluated by comparison with results obtained from High Performance Ion Chromatography (HPIC) on the same water samples.

Fifty-seven wells from Ninh Hoa district that were sampled in the earlier study by Vu were re-sampled and results showed that although there was some variation, their categorisation with respect to the human health risk essentially remained unchanged. Only a small percentage of the re-sampled wells (15%) changed their status from safe in the earlier study to being marginally unsafe in this study. It was concluded that the majority of wells that were sampled would not change their categorisation from safe to unsafe and to ensure the local inhabitants were consuming well water that is safe, periodic sampling of marginally safe wells is needed.

A total of 384 wells were sampled in Dong Xuan district and measured by FISE using refinements to the method employed in the previous study in Ninh Hoa district. Of these, 209 samples were transported to the EIGG laboratories at Curtin University in Perth, Western Australia, for analysis using HPIC. Comparison between the HPIC and FISE results produced excellent correlation, confirming the accuracy of the newly refined FISE method.

The results of the sampling identified the communes of Xuan Phuoc, Xuan Quang 1, 2 and 3, and Xuan Lanh as having high-risk of F^- to human health. The commune of Xuan Son Nam was also identified has having a localised incidence of high F^- groundwater. Based on the values of sampled wells, a F^- distribution map was produced for Dong Xuan and from this, a fluorosis risk map was produced using five zones of risk: no risk, low risk, moderate risk, high risk and extremely high risk.

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1 INTRODUCTION

1.1 Fluoride and the History of Fluorosis

Fluorine (F), (atomic number 9) sits at the top of Group 17 in the periodic table, making it the most electronegative element. It is able to remove an electron from any other element except helium and neon. Consequently, fluorine does not exist in nature in its elemental form, but is found in its ionic state fluoride (F^-), in numerous organic and inorganic compounds. Fluorine is the thirteenth most abundant element in the Earth's crust, occurring predominantly as the minerals fluorite (CaF_2) and fluorapatite ($Ca_5(PO_4)_3F$).

Fluoride was first recognised as playing an important role in human health in 1931 when it was identified as the culprit of stained and mottled teeth that had been observed in localised populations for about 30 years. Earlier examinations had revealed that these teeth, although stained and mottled, had less dental caries compared to unaffected teeth. Some researchers had long suspected there was a connection between the staining of teeth and the local water supply, but attempts to identify the cause had been unsuccessful. In 1931, detailed analyses of water supplies revealed F^- to be the common agent in water samples where cases of stained teeth had been reported (Churchill 1931). The condition became known as fluorosis, or more specifically, dental fluorosis. It was the strong suspicion that F^- was also responsible for the lower rate of dental caries that drove further studies over the next ten years. The outcome showed that fluorosis was rarely observed where local water supplies had F^- concentrations below 1 mg/L, and this concentration appeared to be optimal for protection against dental caries (Mullen 2005). The first city to introduce artificial fluoridation of a domestic water supply was Grand Rapids, Michigan, USA, in 1945 as part of a six-year trial to confirm the effectiveness of fluoridation. This and subsequent trials performed in other parts of the world confirmed that F^- was effective in reducing the occurrence of tooth decay (Ast 1967; Arnold 1962).

While the F^- concentration in domestic water supplies is controlled widely in the developed world, dental fluorosis is a concern for many populations in developing countries. Unlike artificial fluoridation, naturally occurring fluoridation is

uncontrolled and in endemic areas where F^- concentrations are high, and where local populations rely on water for drinking, cases of fluorosis are abundant. Many under-developed countries have reported high incidence of dental fluorosis and the problem is exacerbated where economic conditions and lack of resources preclude technological remedies. According to Ayoob and Gupta (2006), an estimated 200 million people worldwide are exposed to the risks of fluorosis in over 25 nations, with the greatest numbers in China and India; the world's two most populous countries.

The health concerns of fluorosis are two-fold with the condition varying depending on the degree of F^- exposure. Moderate concentrations of F^- in drinking water results in the aforementioned dental fluorosis. This condition not only stains and mottles teeth but results in cracked and broken teeth due to their increased brittleness. The second condition, skeletal fluorosis, is of greater concern as this occurs where F^- exposure is high and may become a crippling condition in which bones become brittle and deformed (Ayoob and Gupta 2006).

1.2 Background to Study

The use of groundwater from shallow wells for domestic purposes by rural communities in Phu Yen province, Vietnam, has long been practiced. It had been recognised through reconnaissance studies (Gianelli *et al.* 1997) that some of the groundwater contained elevated concentrations of dissolved F^-. Knowledge of water quality is a vital issue when communities rely on groundwater for their domestic drinking water supply. In areas where groundwater F^- concentrations are high, adverse health problems in the form of dental fluorosis and the more serious skeletal fluorosis can arise, being particularly prevalent amongst children. While the chronic human health effects of excess F^- intake may be readily observed, the dissolved F^- is colourless, tasteless and without smell. It was the aim of this study to investigate the extent and distribution of such F^- enrichment in the groundwater.

1.3 Objectives and Significance of the Study

The study consisted of two study areas. The first study area was the primary study, and was an investigation of high F^- containing groundwater in the Dong Xuan district of Phu Yen province (Figure 2.1). This focused on the spatial distribution of F^- and its concomitant health risk. The second study area was a smaller exercise that served to validate previous work done by Vu (2008) several years earlier in the Ninh Hoa district of the Khanh Hoa province (Figure 2.5) as a means of assessing and managing the F^- health risk. This involved re-sampling and analysis of groundwater from a subset of wells featured in Vu's earlier study to determine the extent of temporal variation of F^- concentration in the groundwater.

Many rural communities in Vietnam, although warned of a possible excess of F^- in groundwater and aware of the adverse health effects of excess F^- consumption, have neither the technical nor the financial resources to determine the risk associated with individual local water sources. This study seeks to provide this much-needed information, thereby assisting the local community in the first steps to managing effectively the problem of high F^- groundwater.

A primary goal of this research was to provide the local communities in Dong Xuan district with knowledge of the F^- concentration by analysing a maximum number of individual drinking water sources, via an easily accessible GIS and fluorosis risk map. A secondary goal was to re-sample and analyse selected wells from the earlier study by Vu (2008) in the adjacent province of Khanh Hoa. The measured F^- concentrations in these groundwater sources, when compared with the values obtained by Vu, could enable the extent of temporal variation in the distribution of F^- in the shallow groundwater to be determined. Accordingly, the long-term viability of an interactive GIS as a tool for the assessment and management of the F^- health risk could be determined. The third goal of the study was to develop a Fluoride Ion Selective Electrode (FISE) method that would provide accurate results over a wide range of F^- concentrations in groundwater. FISE analyses are cheaper to setup and perform than the High Performance Ion Chromatography (HPIC) method. Unlike FISE analyses, an HPIC setup requires expensive equipment and is not portable. The results from the FISE using the new method would be compared to results obtained from the HPIC analysis.

This study does not attempt to assess the severity of fluorosis amongst the local communities, but rather provide a systemic study of water quality distribution thereby allowing local authorities to develop management strategies. Although groundwater that contains low F^- is a concern for increased dental caries, this is not the focus of this study.

1.4 Previous Fluorosis Studies in Vietnam

Serious problems of fluorosis in the people of Vietnam were first highlighted in 1987, during geological mapping of the Khanh Hoa province by the Vietnamese - Czech Republic Association (1987). With increased awareness of the problem, UNICEF funded a project to make ceramic jars of 2000 litre capacity available to the population to capture and store rainwater. However, the project was of limited success as the storage capacity of the jars was insufficient to provide drinking water throughout the extended dry season and they rapidly deteriorated causing them to leak UNICEF (1999).

Since 1999, another UNICEF supported project has seen the utilisation of 1200 domestic defluoridator units using activated alumina as a sorption medium in Kanh Hoa province. The units were relatively cheap to buy and only required recharging once or twice a month at very low cost (Dzung *et al.* 2004). Initial results indicated good performance and were readily accepted by the community but during the field study of Vu (2008) the defluoridator units that were observed were found to be ineffective for several reasons. In some cases, the units were being used on groundwater that was naturally low in F^-. In other cases, the defluoridators had never had the sorption medium re-charged, thereby providing no F^- removal capacity. Further cases were observed where families had purchased the apparatus and had stopped using them, as they are unsure if they were required or not. There had been no systematic follow-up study to inform residents whether they needed them or not, and no measures were in place to ensure that the units were being used correctly (R. Watkins *pers. comm.*).

The first investigation into F^- levels in groundwater in the Phu Yen province was that of Thanh (2002), who reported cases of fluorosis in the population who resided in

close proximity to fluorite mines. Phuong et al. (2003) investigated the incidence of fluorosis amongst populations in two south central coastal provinces (Phu Yen and Khanh Hoa) as well as north-western and north-eastern provinces of Vietnam. Findings showed that although there was high incidence of fluorosis in areas having fluorite mines in the central provinces, no such cases were reported in the northern provinces, where fluorite mining had also occurred.

Thang et al. (2004) investigated three communes in Dong Xuan district (Xuan Quang, Xuan Phuoc, and Xuan Lanh) and observed that the local population in these areas exhibited a high incidence of dental fluorosis. Findings showed that each of these areas had high F^- groundwater and it was suggested that this was due to the close proximity of hot springs and F^--bearing granites. However, this and subsequent studies (Thuan *et al.* 2006; Viet *et al.* 2006), focused essentially on health issues. A recent report to the Environmental Protection Agency of Phu Yen province (Binh 2012), related a high incidence of fluorosis due to high F^- containing groundwater in the Xuan Lanh and Xuan Phuoc communes. To date however, there have been no systematic or detailed studies of F^- distribution in the groundwater of Dong Xuan district.

A detailed study by Vu (2008) in the district of Ninh Hoa, in the adjacent province of Khanh Hoa, revealed groundwater from wells with F^- concentrations as high as 28 mg/L, with an average concentration of just over 2 mg/L. Over one-third of the domestic wells and bores analysed exceeded the World Health Organisation's recommended maximum guideline value of 1.5 mg/L.

As all literature in Vietnam is written in Vietnamese, it needs to be recognised that retrieval of accurate information due to translation and documentation availability can be a limitation. It is thereby acknowledged that although every attempt has been made to present Vietnamese research and geographic information as accurately as possible there may be more thorough or more current information available elsewhere in Vietnamese literature.

1.5 Fluoride in the Body

It has long been considered that F^- is an essential trace element in humans, although this is now questioned by some researchers, as discussed by Barbier *et al*. (2010).

1.5.1 Fluoride Intake and Bioavailability

The recommended adult human daily intake for F^- is considered to be approximately 0.05 mg/kg/day, which is about 4 mg/day for an 80 kg adult and about 0.8 mg/day for a 2 year old child. The acute toxicity has been estimated to occur with daily intakes of 16 – 64 mg/day for adults and 3 – 16 mg/day for children (Barbier *et al.* 2010).

Dietary F^- intake in humans is essentially through ingestion, with insignificant amounts being inhaled (Hodge and Smith 1977). The majority is supplied as F^- in water, beverages and dental products, with relatively small amounts from food (Murray 1986). Essentially all food contains some F^-, with fish being the highest with typical F^- concentrations of 2 – 5 mg/kg. Of particular importance is that F^- is concentrated in bones, so this concentration is much higher in canned salmon and sardines where the bones are consumed as well. Fish protein concentrates can have F^- concentrations as high as 370 mg/kg. Most vegetable and fruit have low amounts of F^-(0.1 – 0.4 mg/kg), but rice and barley have higher amounts (2 mg/kg) (Murray 1986).

Intake of F^- via beverages varies greatly depending on the concentration of F^- in the water from which it is prepared. Tea infusions are the most significant beverage that contributes to dietary F^- intake as tea leaves have high amounts of F^- with older leaves containing as much as 400 mg/kg (Wagner 1993). The tea plant *Camellia sinensis* is a F^- accumulator, which concentrates F^- from the soil, and as much as 84% of the F^- can be extracted from the leaves in boiling water over six hours (Fung *et al.* 1999). Daily F^- intake from tea can be 0.04 – 2.7 mg per day, and as with other beverages, the level of F^- in tea can increase depending on the concentration of F^- in the water from which it has been prepared (Wagner 1993).

Dental products can also be an important contributor to F^- intake where typical fluoridated toothpaste contains 1.0 – 1.5 g/kg F^-. It has been estimated by Murray

(1986) that swallowed toothpaste by children can contribute to 0.5 – 0.75 mg/L F^- per day; similar to the total dietary F^- intake for a child. In young children who have difficulty in controlling their swallow reflex, intake of F^- via fluoridated toothpaste can even exceed the dietary F^- intake (National Research Council 1993). However, these relative F^- intakes via dental products when compared to total dietary F^- intake are western estimates and are based on total F^- intakes where the domestic water supply has been artificially fluoridated. In endemic areas, such as that of the study area, where dietary F^- intakes are potentially high due to high F^- groundwater concentrations, the relative F^- intake via dental products would be considered small. Nevertheless, dental products can contribute to significant F^- intake.

Absorption rates from water and beverages are almost 100%, while between 50 – 80% of the F^- in food is absorbed (*Nutrient reference values* 2005). Fluoride clearance from the body is almost entirely by renal excretion, with approximately 50 – 60% of absorbed F^- being retained in adults, and up to 80 – 90% being retained in children, with approximately 99% stored in bones and teeth (Barbier *et al.* 2010; Australian Government 2005).

The amount of F^- absorption does not appear to be affected to any great extent by water hardness (Maguire *et al.* 2005). The role that aluminium plays in F^- absorption remains inconclusive. Studies on rats and rabbits by Jackson *et al.* (2002) have indicated that aluminium may reduce the absorption of F^-; however, more recent studies have suggested that some alumino-fluoride complexes may increase biological activity of F^- (Barbier *et al.* 2010). It has been suggested that if these alumina-fluoride complexes are metabolised, both F^- and the possibly harmful aluminium could be released into the body (Selinus 2005).

1.5.2 Fluoride Effects on Teeth and Bone

Dental

The roles that F^- plays in reducing dental caries and promoting fluorosis are believed to involve somewhat different mechanisms of action. Although 99% of F^- is stored in teeth and bone, it is not systemic absorption of F^- by blood that gives teeth their improved resistance to decay. Instead, it is the topical interaction of F^- in the mouth cavity that provides the protection. Two mechanisms are believed to exist. Firstly, F^- replaces the hydroxyl group (OH^-) of the hydroxyapatite in the tooth surface enamel to produce fluoroapatite, which is thought to be more resistant to the acids produced by bacteria. Secondly, the F^- at the surface enamel acts as a catalyst promoting the deposition of calcium and phosphate thereby repairing damage done by decay (Fagin 2008). Some researchers, as discussed by Pizzo *et al.* (2007), doubt the first mechanism and suggest it is solely the action of F^- in the saliva that reduces demineralisation and promotes remineralisation. Either way, the action of F^- in decay prevention is post-eruptive, i.e. prevention occurs after the tooth has formed.

The mechanism that causes fluorosis is somewhat different. In this case, the blood supplies F^- systemically during the pre-eruptive stage of tooth formation. During the formation of the permanent teeth, proteins called amelogenins, which regulate the mineralisation, control development of new hydroxyapatite crystals. It is believed that if excess F^- is supplied at this time, the regulation of hydroxyapatite is altered and irregular mineralisation occurs, resulting in hypomineralisation (enamel porosity). The effect is seen as chalky white areas due to the refraction of light caused by the porosity in the enamel. Staining and discolouration of the enamel occurs post-eruption and is dependent on the degree of hypomineralisation and also on dietary habits. If hypomineralisation is excessive, post-eruptive pitting can also occur where the weakened superficial enamel breaks away (Fejerskov *et al.* 1990; Fagin 2008).

While some health authorities consider dental fluorosis as a mere cosmetic condition, Ayoob and Gupta (2006) discussed the psychological and social effects the condition can cause. Sufferers at an early age can be socially isolated and discriminated against, leading to deep psychological depression and anxiety. The visual aspect of

the disease can cause an inferiority complex and the loss of self-esteem. Brouwer *et al*. (1988) described the condition as an "especially serious aesthetic problem in Senegal" where sufferers would try to file or scrape of the stains, causing further damage. The United States National Research Council (USNRC), in referring to the EPA's 'cosmetic' stance on fluorosis, stated that in more severe cases, it may be more than a cosmetic defect if the lost tooth enamel causes pain and affects eating habits (*Health effects of ingested fluoride* 1993). Cao et al. (2005) even warned that dental fluorosis in children could be a warning sign of early-stage skeletal fluorosis. Since the development of fluorosis only occurs during the pre-eruptive stage of tooth development, only children with growing permanent teeth are at risk of dental fluorosis.

Skeletal

With the overwhelmingly majority of F^- being stored in the bones, it is of little surprise that bones are at the forefront of F^- toxicity. Fluoride is not distributed equally in all bones, with the pelvis and vertebrae becoming more enriched in F^- than the limb bones (Ayoob and Gupta 2006).

The effects of skeletal fluorosis occur in various stages, both clinical and pre-clinical. Pre-clinical skeletal fluorosis is the early stage involving changes in blood and bone composition, but in which the patient experiences no symptoms. Early stages of clinical skeletal fluorosis involve pains in joints, muscle weakness, and changes in the pelvis and spinal column that can be detected in x-rays. In the later stages, ligaments start to calcify and osteoporosis (demineralisation of bone tissue) and osteosclerosis (abnormal hardening and increase in bone mass) begin to develop. Advanced skeletal fluorosis, also known as crippling skeletal fluorosis, sees the stiffening of joints and the ossification of the spinal column (Ayoob and Gupta 2006).

It has been shown in osteoporosis patients that high concentrations of F^- may cause the proliferation of bone building cells called osteoblasts. This results in bone that is harder and denser but weaker in tensile strength due to the alteration of the bone tissue mineralisation (Henderson and Goltzman 2000).

1.5.3 World Health Organisation Guideline Values

The World Health Organisation (WHO) has set a maximum guideline value for F^- in drinking water of 1.5 mg/L. This is based on an average per capita daily water consumption of two litres, where F^- intake should not exceed 3 mg/day (WHO 2006). It has been noted by many researchers that this value may be inappropriate for hot tropical locations where daily water consumption may be as high as 10 litres (Tekle-Haimanot *et al.* 1995). In one study (Ayoob and Gupta 2006) it was shown that even groundwater at F^- concentrations as low as 0.6 mg/L still gave rise to dental fluorosis. Whereas WHO does recognise that this value may be too high in warmer climates and stresses the importance of climatic conditions, volume of water consumed, and other factors (e.g. F^- from other sources), there has been no attempt by the organisation to set specific target limits based on temperature or water consumption. However, as early as 1957, a formula was proposed to calculate optimum F^- concentration for local water supplies (Galagan and Vermillion 1957), based on a fluid intake study and takes into account the average maximum local temperature.

$$\text{Optimum concentration (mg/L)} = \frac{0.34}{(0.0062 \times \text{mean max temp (°F)}) - 0.038}$$

However, this does not consider F^- uptake from other sources, including foodstuffs and dental products. Viswanathan *et al*. (2009) highlighted that this extra source of F^- varies between counties and in India only 41% dietary F^- uptake was via drinking water.

1.5.4 Other Health Aspects of Fluoride

Any discussion about the health aspects of F^- in drinking water often involves the debate of artificial water fluoridation. As a result, much of the study into the various health aspects of F^- has been fuelled by the controversial nature of this topic, and outlined below are the findings of some of those studies. However, even though this study involves naturally fluoridated drinking water, it must be acknowledged that it is the result of artificial fluoridation that much research has been performed to establish the effects of F^- on the human body.

Carcinogenic concerns

Since the early 50s experiments done on animals have suggested that a possible link exists between F^- in drinking water and cancer. Such suggestions have fuelled much further work and in 1977, Yiamouyiannis and Burk (1977) published a statistical study that supported the hypothesis that F^- in water causes cancer in humans. This claim was refuted by Kinlen and Doll (1981) when the datum was re-examined using different standardisation techniques. Other researchers (Chilvers 1983; Cook-Mozaffari *et al.* 1981), using different data sets also failed to find a connection. However, some researches (Tohyama 1996; Takahashi *et al.* 2001) using different datum again, did suggest a possible link of F^- to cancer.

A paper by Bassin *et al*. (2006) raised concern that a link may exist between F^- and osteosarcoma, a bone cancer that usually develops during the adolescent growth spurt. The results of the study were consistent with previous studies on animals; however, a subsequent study by Kim *et al*. (2011) failed to support this conclusion. A detailed review to assess both the positive and negative effects of water fluoridation for the prevention of dental caries was undertaken by the University of York (McDonagh *et al.* 2000). The review also included 26 studies that looked at the association of water fluoridation to cancer incidence and found "no clear association". After considering available data from studies on animals, WHO (2004) stated that the evidence was inconclusive and such evidence did not support the hypothesis that F^- caused cancer in humans. However, WHO did state that the study on bone cancer (osteosarcoma) was "relatively limited".

Neurological concerns

Fluoride is also suspected for various neurological disorders and recent research has suggested the formation of the alumino-fluoride complex AlF_4^- , as a mechanism due to its biological similarity to ɣ-phosphates (Barbier *et al.* 2010). However, once again results are inconclusive with those on either side of the fluoridation debate pointing to research that supports their particular viewpoints.

1.6 Fluorine in the Environment

1.6.1 Sources of Fluorine

Lithosphere

Fluorine is an incompatible lithophile element, and so crystallises late during cooling and differentiation of magmas. The late crystallisation is due to the inability of most common rock forming minerals to accept fluorine into their crystal lattices. Only when OH-bearing minerals start to crystallise late in the crystallisation process, can fluorine finally be substituted into the minerals. Fluorine-bearing minerals, such as fluorite, fluorapatite, and fluorine-enriched micas and amphiboles, are thus typically found in pegmatites, hydrothermal vein deposits and granites formed from highly evolved magmas (Korning 1978).

Fluorine containing minerals

Of the minerals in which fluorine is essential, only two are rock forming: fluorite (CaF) and topaz ($Al_2SiO_4(OH^-,F^-)_2$). All others are accessory, such as villiaumite (NaF) and cryolite (Na_3AlF_6). However, about 60 percent of fluorine-bearing minerals contain fluorine as a non-essential component, either through isomorphous substitution of OH^- (e.g. hydroxyapatite-fluoroapatite series) or by camouflage in the OH^- site (e.g. micas and amphiboles) (Korning 1978).

The fluorine content of igneous rocks varies widely from as low as 20 mg/kg to over 1000 mg/kg. There is a general trend of increasing F^- content with increasing SiO_2 content, but this trend is not observed in alkalic rocks, which have the highest average fluorine content (1000 mg/kg) but often have lower SiO_2 content. Korning (1978) mentioned that even ultramafic rocks, which average the lowest fluorine content, could contain in excess of 200 mg/kg, such as in some phlogopite-bearing griguates and kimberlites. Stueber *et al.* (1968) concluded that such high variability of F^- in ultramafic rocks could be due to the ease of which fluorine is incorporated during secondary alteration.

Where significant fluorine is present in metamorphic rocks it is generally associated with late-stage metasomatism and skarn formation that is common around the

periphery of granitic intrusions. Greisenised granite may contain very high fluorine contents mainly within topaz, lithionite, zinnwaldite and fluorite. In regionally metamorphosed rocks, fluorine appears mainly in OH-bearing minerals, such as micas, amphiboles and chlorites. Fluoride-rich amphiboles, such as tremolite, actinolite and anthophyllite, are sometimes found in skarns (Korning 1978).

Owing to its similar ionic size to the hydroxyl ion (OH^-), F^- is incorporated into many OH-bearing minerals, making it the most abundant halogen in sedimentary rocks. Typically, fluorine concentrations in sedimentary rocks range from approximately 200 mg/kg in limestone to 1000 mg/kg in shales (Korning 1978). In clastic sediments about 80 - 90% of fluorine is contained in illite, muscovite (and other mica related minerals), with montmorillonite, kaolinite and apatite containing the remainder (Korning 1978). Fluorite is the main fluorine containing mineral in carbonate rocks (Frencken 1992).

1.6.2 Geochemistry of Fluorine

The interaction of groundwater results in the dissolution of fluorine from the various fluorine-bearing minerals in the rock. Such reactions are highly dependent on the particular minerals present, and the hydrochemistry of the groundwater (International Groundwater Resources Assessment Centre n.d.).

The numerous reactions that can occur involve the dissolution of silicates and carbonates. Equation 1 shows the generalised dissolution of silicates, which results in the release of cations, and equation 2 shows the dissolution of carbonates (Subba Rao 2011; Su *et al.* 2012; Ayoob and Gupta 2006; Handa 1975).

$$\underset{\text{cation – Al-silicates}}{2NaAlSi_3O_8} + H_2CO_3 + 9H_2O \rightarrow \underset{\text{hydradated Al-silicates}}{Al_2Si_2O_5(OH)_4} + \underset{\text{dissolved silica}}{4H_4SiO_4} + HCO_3^- + 2Na^+ \quad \ldots(1)$$

$$CaCO_3 + H^+ + 2F^- \leftrightarrow CaF_2 + HCO_3^- \quad \ldots(2)$$

The F^- content of groundwater is further controlled by ion exchange occurring with clays (equation 3, where X is the clay mineral) replacing Na^+ with Ca^{2+} (Ayoob and Gupta 2006).

$$2NaX + Ca^{2+} \leftrightarrow CaX_2 + 2Na^{+} \quad \ldots(3)$$

When the dissolution of Ca^{2+} results in its over saturation in respect to $CaCO_3$, it precipitates out of solution as $CaCO_3$. In the presence of CaF_2, this removal of Ca^{2+} from the groundwater allows more fluorite to dissolve, satisfying the equilibrium shown in equation 4.

$$CaF_2 \leftrightarrow Ca^{2+} + 2F^{-} \quad \ldots(4)$$

Furthermore, due to its similar ionic radii, ion exchange may occur between F^- and OH^- on the surface of minerals. Replacement of F^- by OH^- at high pH, may increase the F^- concentration in water (Hem 1985). Synthetic phosphate fertilisers used in agriculture contain varying amounts of fluorine and may present an anthropological source of F^- in water (Handa 1975).

2 STUDY AREAS

The major part of this study was conducted in Dong Xuan district of Phu Yen province. A subsidiary component of the research was performed in Ninh Hoa district of Khanh Hoa province, some 100 km to the south of Dong Xuan. Only the Dong Xuan study area is discussed in detail here, as Ninh Hoa was the subject of only a brief comparative study and is documented in detail by Vu (2008).

2.1 Dong Xuan Study Area

Dong Xuan district is a rural district consisting of ten communes and one town (the capital La Hai). The district covers an area of 1,063 km^2 and contained at the time of the 2003 census a population of 59,260 (*Electronic government portal of the Socialist Republic of Vietnam* n.d.). The study area comprised the entire district, with water sampling undertaken in La Hai and all ten communes. Since water sampling was focussed upon domestic water sources (wells), only populated regions were sampled and these mainly existed along river valleys and on plains. Table 2.1 shows the area and population of individual communes of Dong Xuan as of 2003 (*Electronic government portal of the Socialist Republic of Vietnam* n.d.).

Table 2.1: Dong Xuan commune population and area

Commune	Population	Area (km^2)
La Hai	10,074	21.0
Xuan Quang 1	4452	114.3
Xuan Quang 2	3796	50.6
Xuan Quang 3	6051	21.4
Xuan Phuoc	8549	81.9
Xuan Long	2115	71.5
Xuan Lanh	8246	133.6
Xuan Son Nam	2657	27.3
Xuan Son Bac	2898	38.5
Da Loc	4281	49.3
Phu Mo	2571	454.0

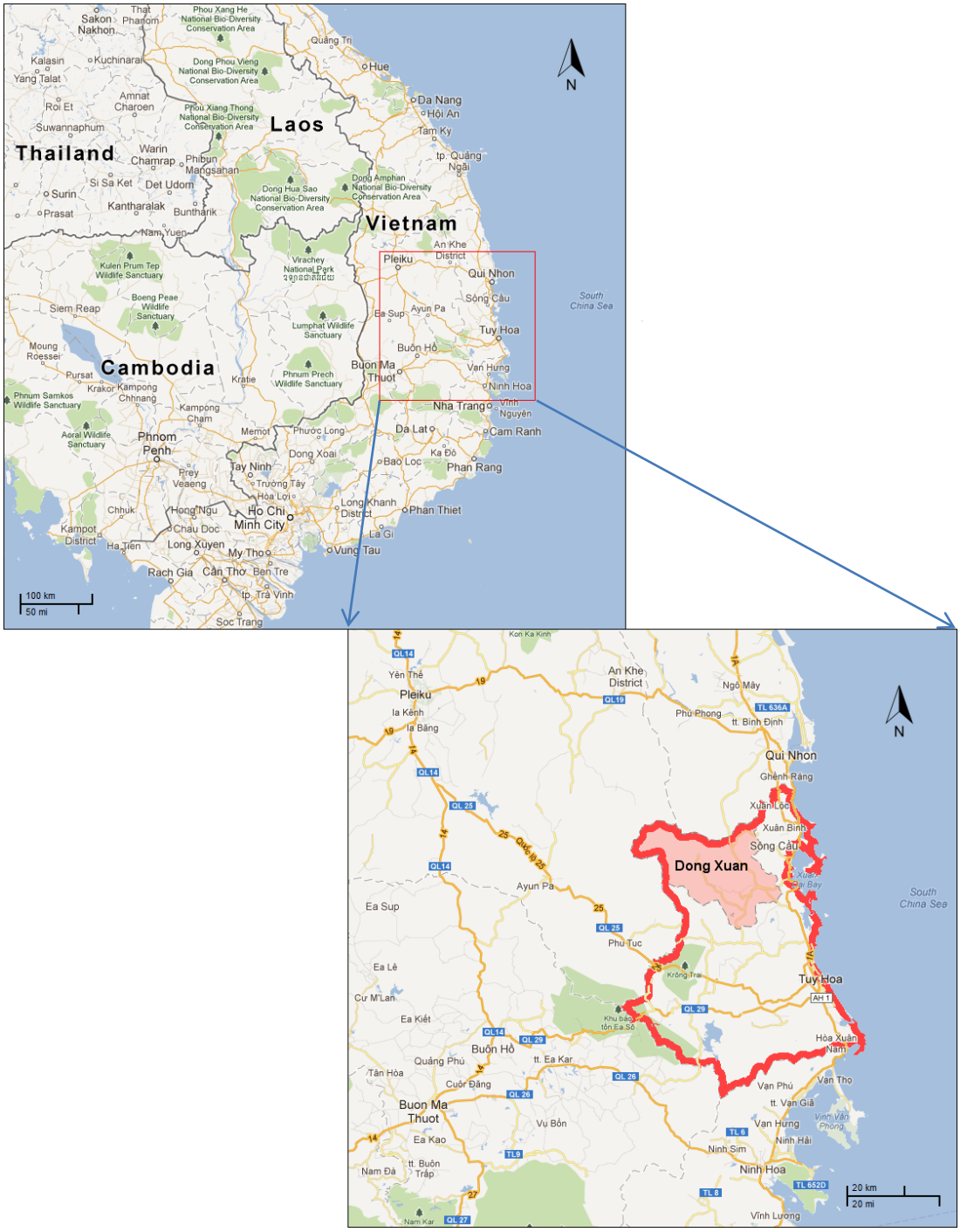


Figure 2.1: Location of Dong Xuan district (pink shading) in Phu Yen province (red outline). (Google Maps)

2.1.1 Location

The district of Dong Xuan is one of seven in Phu Yen province. Phu Yen province borders Binh Dinh province in the north, Khan Hoa province in the south, and Gia Lai and Dak Lak provinces in the west. To the east lies the South China Sea (Figure 2.1).

Dong Xuan district lies in the north of Phu Yen province (Figure 2.1) and extends from latitude 13° 14′ to 13° 36′ North and from longitude 108° 42′ 30″ to 109° 9′ 2″ East. It borders Song Cau district to the east, the eastern districts of Gia Lai province to the west, Van Canh district of Binh Dinh province to the north, and the districts of Son Hoa and Tuy An to the south (Figure. 2.2).

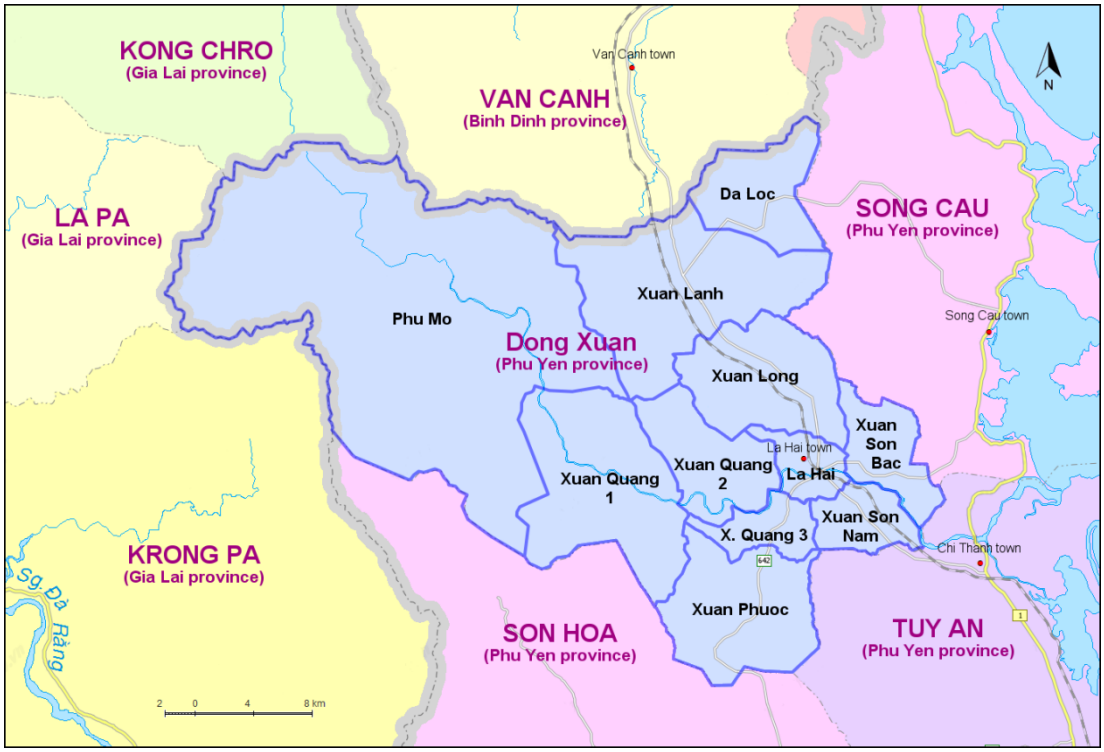


Figure 2.2: Dong Xuan and its communes (named in black), and surrounding districts. (*Vietnamese electronic information portal*)

2.1.2 Topography

The topography of Dong Xuan district is varied and complex. Two general terrain types are present:

1. Highlands: Approximately 80% of land in Dong Xuan district consists of mountainous and hilly terrain. The most mountainous terrain occurs predominately in the west and northeast of the district, with a general altitude decrease from west to east. Peaks are generally between 500 – 1300 m above sea level and the most mountainous communes are Phu Mo and Xuan Quang 1.

2. Lowlands: These consist of two large river valleys and narrow plains, and occur in all communes. Essentially all populated areas occupy these terrains. The plains slope gradually from west to east and some areas are subjected to flooding during the rainy season (Binh 2012).

2.1.3 Climate

Dong Xuan has a tropical humid climate, which is influenced by proximity to the ocean. There are two distinct seasons: a 4-month rainy season from September to December, and an extended dry season from January to August. Mean annual temperatures in regions with elevations below 100 meters are 26° – 27°C. Those in regions with altitudes from 300 – 1000 metres are 24° – 25°C, while those in higher regions are below 21°C. Typical annual maximum and minimum temperatures for the region are 40°C and 11°C, respectively.

Rainfall in the rainy season averages 1200 – 1900 mm and accounts for 70 – 80% of the total average annual rainfall. The remaining eight months average a total of 300 – 700 mm. There are two prevailing winds in the district, the hot and dry westerlies and the northeast monsoon.

2.1.4 Geology

Tectonically, Vietnam is divided into five structural blocks: Northeast, Northwest, Truongson, Kontum and Nambo (Figure 2.3). The Northeast block lies on the South China Tectonic Plate while the others form part of the Indochina Plate. The study area is located on the Kontum block which is considered a stable uplifted massif, and contains Archaean stratigraphy, the oldest in Vietnam (Nam 1995).

2.1.4.1 Stratigraphy

The stratigraphy exposed in the study area lacks Archaean and Proterozoic rocks, and comprises predominately of Mesozoic sedimentary and volcanogenic sedimentary rock, Mesozoic igneous intrusive rocks, and Quaternary sediments. The far western side of Dong Xuan district contains Palaeozoic rocks; however, the western third of the district is extremely remote and relatively unpopulated, and therefore was not included in the study area.

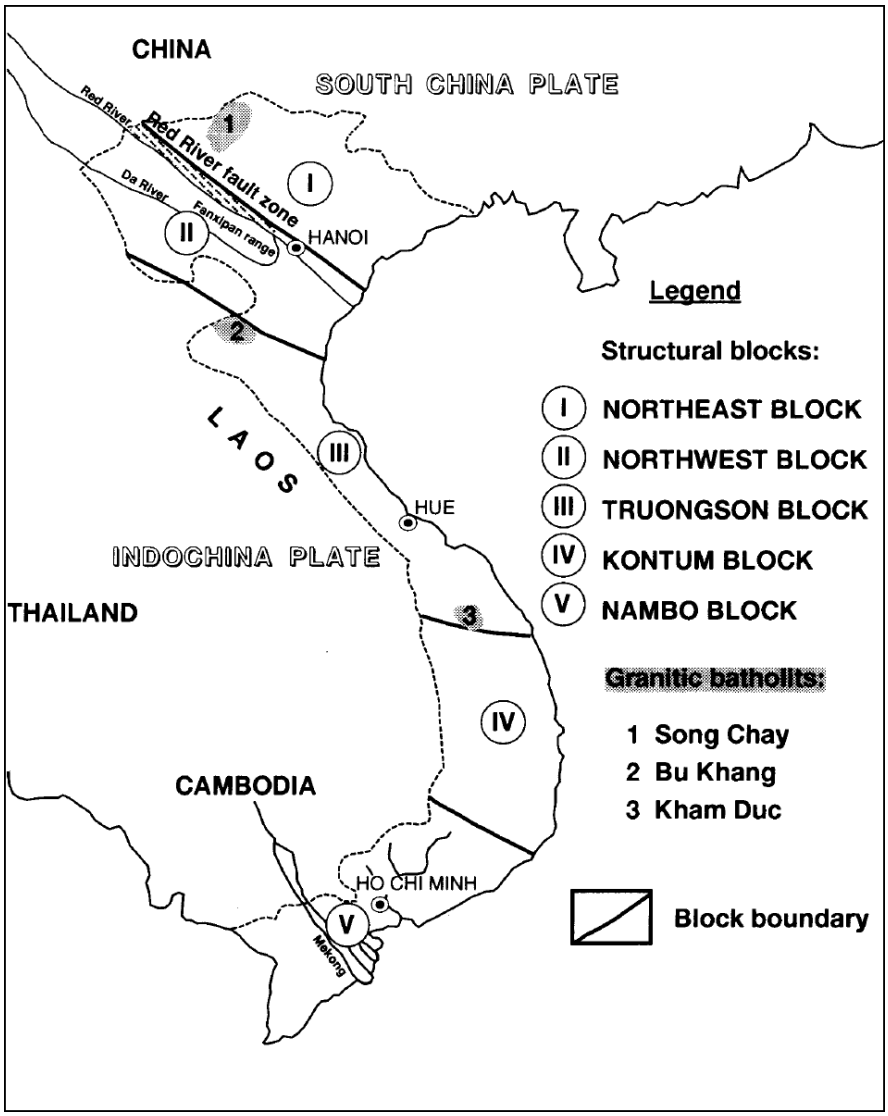


Figure 2.3: Tectonic divisions of Vietnam showing the five structural blocks (Nam 1995).

The following account of stratigraphy and rock ages has been obtained from Le Tien Dung (1998a, 1998b, 1998c) and the Geology and Mineral Resources Maps of Vietnam (1998) unless otherwise stated.

Mesozoic Stratigraphy

Mang Yang Formation (T_2my)

This is a thick formation consisting of volcano-sedimentary beds that incorporates the previously designated Mang Giang Formation of the Lower Middle Triassic and the Chu Klin and Song Bung Formations of Middle Triassic age.

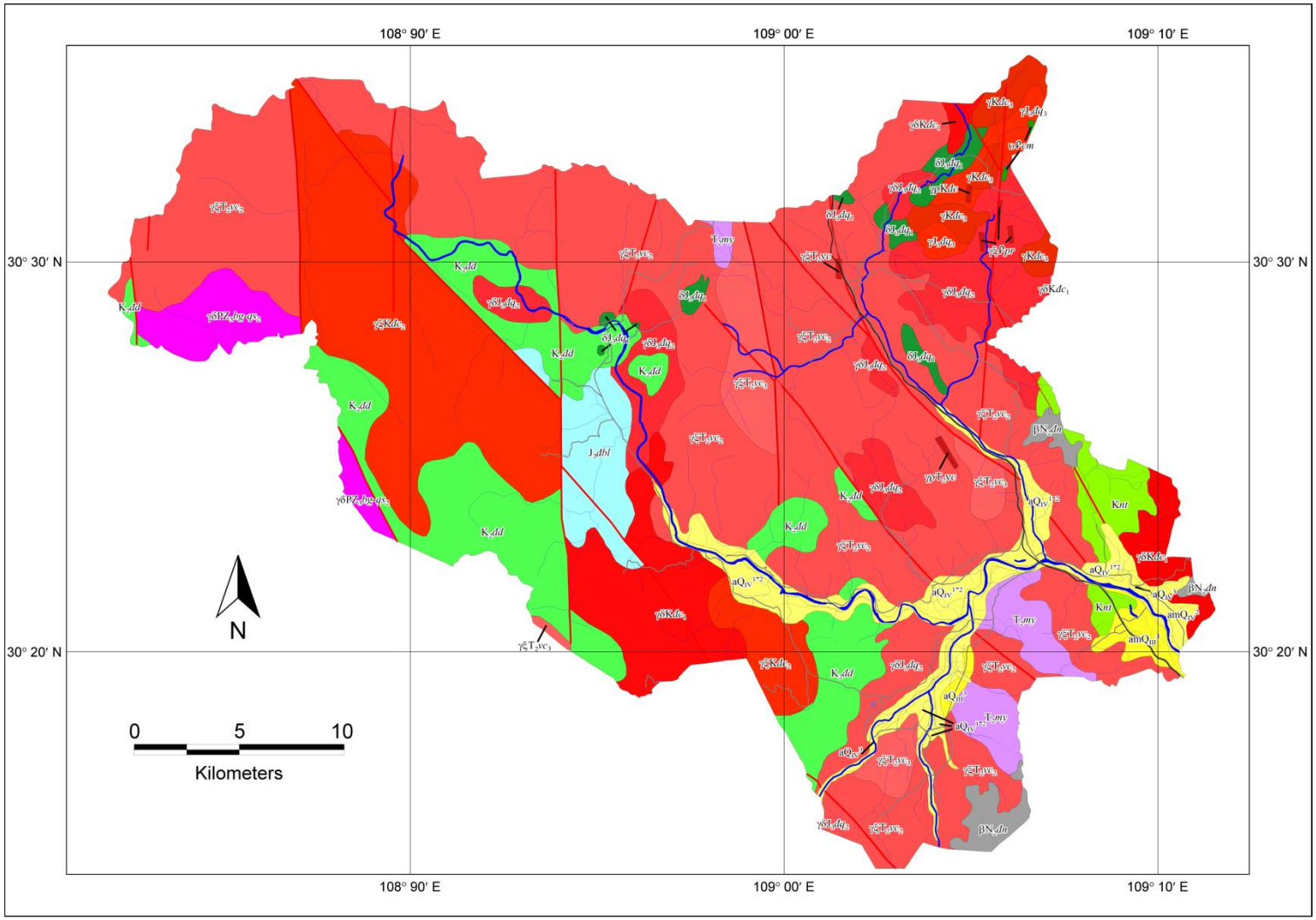
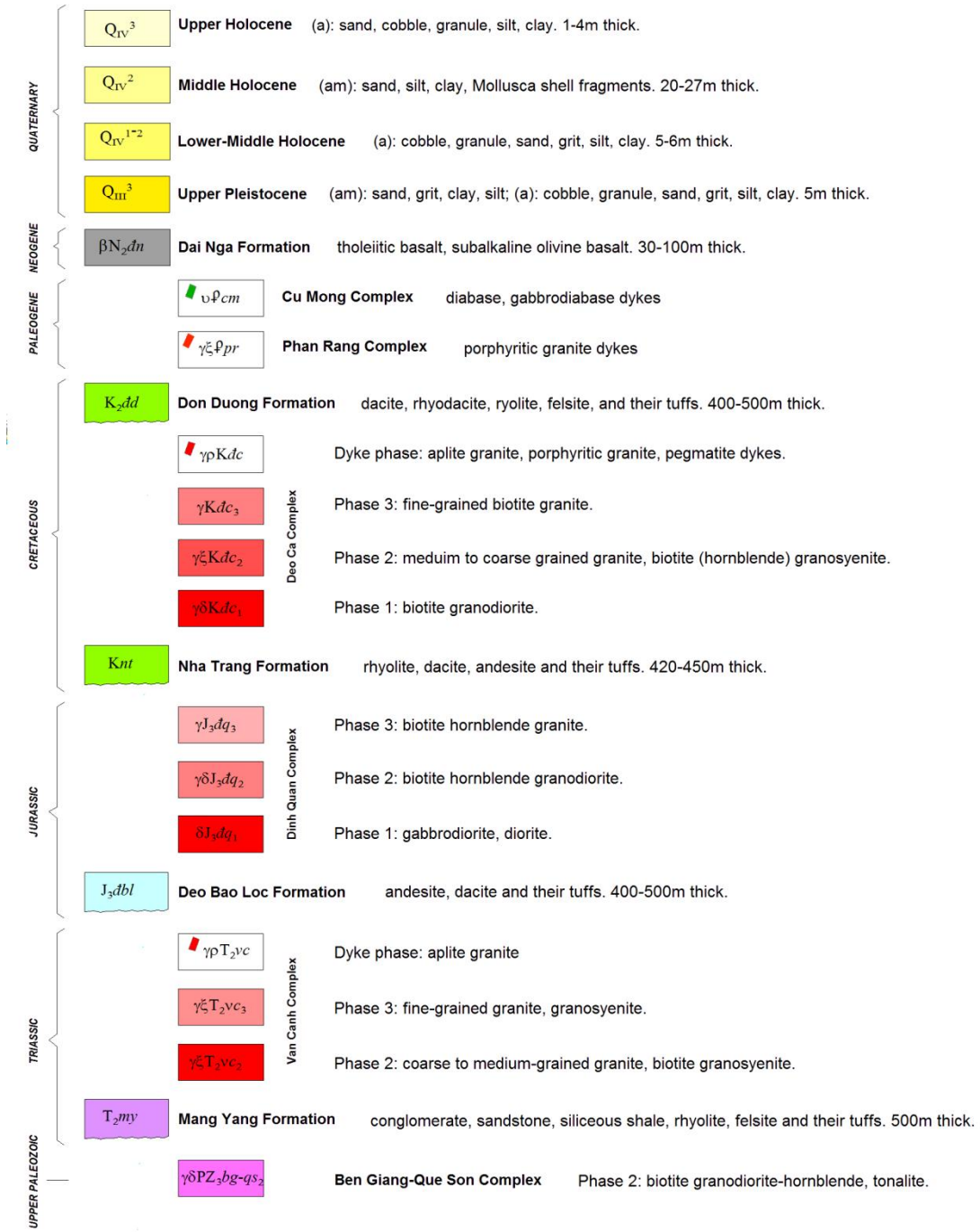
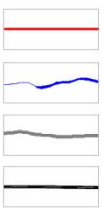


Figure 2.4: Simplified geology of Dong Xuan district. (Map modified from Ministry of Natural Resources and Environment - Department of Survey and Mapping Vietnam)

LEGEND



OTHER SYMBOLS



The Mang Yang Formation is exposed in the central coast region from Quang Nam province to areas in the north of Ninh Hoa in Khanh Hoa province. In the study area, the formation crops out in the south eastern part of Dong Xuan district and also in a small area in its north. In these areas, it consists of three members

- *Member 1:* tuffaceous conglomerate and agglomerate, tuffaceous gravelstone and gritstone, tuffaceous sandstone with interbeds of dacite, rhyodacite, rhyolite and their tuffs; 100 – 150 m thick.
- *Member 2*: arkosic sandstone, felsite and tuffolava; 300 – 400 m thick.
- *Member 3*: felsite, rhyolite intercalated with clay shale and siltstone; 200 – 300 m thick.

The Mang Yang Formation is 600 – 850 m in thickness and rests unconformably upon various older formations. In the study area, it is penetrated and contact metamorphosed to hornfels by biotite granite of the Van Canh Complex, which has been isotopically dated at 210 ± 1 Ma (Late Triassic). In other areas, such as in the Mang Yang area, it lies on Archaean crystalline schists of the KanNack Group and in the Chu Klin area it lies on Upper Paleozoic andesite of the Dak Lin Formation. According to these stratigraphic relationships and fossil evidence, the Mang Yang Formation is considered as Anisian (early Middle Triassic) in age.

Deo Bao Loc Formation ($J_3đl$)

The Deo Bao Loc Formation comprises mainly andesite and dacite and in the study area crops out in the central area of the Don Xuan district, bordering the communes of Pho Mo and Xuan Quang 1. In this area, the formation is composed of three members:

- *Member 1*: polymictic sandstone intercalated with tuffites; 150 – 200 m thick.
- *Member 2*: mainly of andesite with interbedded sandstone and tuffaceous silty sandstone; 180 – 220 m thick.
- *Member 3*: andesitodacite and its tuffs; 100 – 150 m thick.

The total thickness of the Formation reaches 430 – 570 m.

The Deo Bao Loc Formation rests unconformably upon numerous older Jurassic formations and is intruded by the Upper Jurassic igneous Dinh Quan Complex. Effusive rocks of the Nha Trang Formation cover both of these. Based on this stratigraphic relationship, and on incorporated fossils, the Deo Bao Loc Formation is considered to be Upper Jurassic in age.

Nha Trang Formation (K *nt*)

The Nha Trang Formation was originally included as a part of the Don Duong Formation when mapped at 1:500,000 scale. After subsequent mapping at 1:200,000 it has been separated as a separate unit.

The formation is exposed in the eastern part of Don Xuan district, mainly within the communes of Xuan Son Bak and Xuan Son Nam. It consists of three members:

- *Member 1*: conglomerate, tuffaceous gritstone, tuffaceous sandstone and agglomerate with the clastic component from siltstone, cherty shale, volcanic rocks and clay shale; 100 – 250 m thick.
- *Member 2*: mainly of rhyodacite, rhyolite with interbedded andesite-dacitic and dacitic tuffs and lavas; 200 – 250 m thick.
- *Member 3*: rhyolitic tuffs and lava with interbedded rhyolite and porphyritic felsite; 150 – 200 m thick.

The total thickness of the formation is 450 – 600 m.

Owing to the presence of breccias of the Upper Jurassic Dinh Quan Complex in its basal parts, and the intrusion of granites of the Cretaceous Deo Ca Complex, the age of the Nha Trang Formation is considered Late Jurassic-Early Cretaceous. However, some authors prefer to class the formation as undifferentiated Cretaceous, pending more detailed investigations (Thanh and Khúc 2006) .

Don Duong Formation ($K_2 dđ$)

The Don Duong Formation is composed mainly of felsic volcano-sedimentary rocks formed under continental conditions. In the study area it crops out over large scattered regions in the south western parts of the Dong Xuan district, where it consists of two members:

- *Member 1:* conglomerate, tuffaceous gritstone and sandstone, rhyodacitic and rhyolitic tuffs and lavas with interbeds of rhyolite; 150 – 200 m thick.
- *Member 2:* rhyodacitic and rhyolitic tuffs and lavas with interbedded rhyolite; 150 – 200 m thick.

The total thickness of the Formation is 250 – 350 m.

In the study area, the Don Duong Formation rests unconformably on the Upper Jurassic Deo Bao Formation and Dinh Quan Complex. Recent isotopic dating of rhyolite and dacite rocks has yielded a Late Cretaceous age (Thanh and Khúc 2006).

Cenozoic Stratigraphy

Dai Nga Formation ($\beta N_2 dn$)

The Dai Nga Formation is comprised mainly of tholeiitic and subalkaline olivine basalts. In the study area, the formation crops out only in a small area bordering the communes of Xuan Long and Xuan Son Bak and it is composed of three parts. The lower two consist of pyroxene and various plagioclase basalts, which are intercalated with pyroclastic tuffs or sedimentary rocks. The upper part consists of olivine and olivine-augite basalt with inclusions of spinel lherzolite and is weathered at its surface forming thin beds of lateritic bauxite or red soil bearing laterite concretions.

Quaternary Sediments

Upper Pleistocene Fluvial (aQ_{III}^{3})

This formation has been divided into three members:

- *Member 1:* cobble, pebble, granule and grit; 2.5 m thick.
- *Member 2:* sand, grey silt and clay mixed with a little grit; 4 m thick.
- *Member 3:* red-brownish clay and sand; 1.5 m thick.

Upper Pleistocene Fluvio-marine (amQ_{III}^{3})

This formation has also been divided into three members:

- *Member 1:*grit, sand and clay; 2 m thick.
- *Member 2:* greenish-grey clay; 0.8 m thick.
- *Member 3:* yellowish-grey sand and clay; 0.4 m thick.

Lower-Middle Holocene Fluvial (aQ_{IV}^{1-2})

These fluvial deposits are distributed in the form of "terrace 1". They consist of pebbles, granules grading upward to grey sand, dark-grey silty sand and silty clay; 4 m thick.

Middle Holocene Fluvio-marine (amQ_{IV}^{2})

Widely distributed deposits consisting of three members:

- *Member 1:* greenish-grey, yellowish-grey clay bearing spores and pollens and a few fragments of mollusc shell; about 10 m thick.
- *Member 2:* yellowish-grey small to medium-grained sand; 6 m thick.
- *Member 3:* brownish-yellow silty sand; 3 m thick.

Upper Holocene Fluvial (aQ_{IV}^3)

This formation exists as alluvial banks and consists of pebbles, granules, sand, silt and a little clay; 2 – 3 m thick.

Igneous Intrusions

Ben Giang – Que Son Complex ($\gamma\delta PZ_3$ *bg-qs*)

This Upper Palaeozoic intrusion is present in the far western region of Don Xuan district, where only the second ($\gamma\delta PZ_3$ *bg-qs*$_2$) of three intrusive phases crops out. This is the main component of the complex, formed essentially of biotite-hornblende granodiorite and biotite-hornblende tonalite.

Van Canh Complex ($\gamma\zeta T_2 vc$)

This complex is widely dispersed over the study area, cropping out as two main intrusive phases and a dyke phase.

- *Phase 2* ($\gamma\zeta T_2 vc_2$)*:* the main phase of the complex consisting of medium to coarse-grained biotite granosyenite and biotite granite. The rocks are generally light brown-pink, with massive structure and usually porphyritic texture with 0.5 – 2.5 cm pink K-feldspar phenocrysts.
- *Phase 3* ($\gamma\zeta T_2 vc_3$)*:* fine-grained granite and granosyenite which is light brown-pink in colour with a massive structure.
- *Dyke phase* ($\gamma\rho T_2 vc$)*:* the dykes range from decimetres to several metres in width and are up to kilometres long. They are of aplitic granite, pegmatite and porphyritic granosyenite.

Dinh Quan Complex (δ-$\gamma\delta$-$\gamma J_3 đq$)

Within the study area, this complex is exposed mainly in the Da Loc area with smaller exposures in Xuan Lanh, Xuan Long and Xuan Quang 2 communes. The complex consists of three intrusive phases.

- *Phase 1* ($\delta J_3 đq_1$)*:* fine to medium-grained quartz diorite, diorite and gabbro diorite. Green-black in colour with a massive structure.
- *Phase 2* ($\gamma\delta J_3 đq_2$)*:* medium-grained biotite-hornblende granodiorite and biotite-hornblende tonalite. White-grey in colour with black speckles and with a massive structure.
- *Phase 3* ($\gamma J_3 đq_3$)*:* fine to medium-grained biotite-hornblende granite, white-grey in colour and penetrates rocks of phase 1.

Deo Ca Complex ($\gamma\delta$-$\gamma\zeta$-$\gamma K đc$)

Exposed in most regions of the study area, this complex consists of three intrusive phases and one dyke phase.

- *Phase 1* ($\gamma\delta K đc_1$)*:* irregularly small-grained biotite-hornblende granodiorite and biotite-hornblende granomonzonite. Grey with pink spots and with a massive structure.
- *Phase 2* ($\gamma\zeta K đc_2$)*:* the main phase of the complex and consists of medium to coarse-grained biotite granosyenite and biotite (hornblende) granite. Pink-grey with a massive structure and also porphyritic in places with phenocrysts of pink orthoclase.
- *Phase 3* ($\gamma K đc_3$)*:* small-grained biotite granite and biotite granosyenite. Pink-grey with a massive structure and porphyritic in places.
- *Dyke phase* ($\gamma\rho K đc$)*:* the dykes are found in most of the massifs in this complex and range from decimetres to several metres wide and up to several

kilometres long. Composed of aplitic granite, pegmatite and porphyritic granosyenite.

Phan Rang Complex ($\gamma\zeta\wr pr$)

This is a hypabyssal complex and in the study area, it only occurs in Da Loc commune. The dykes are up to hundreds of metres long and range between decimetres to tens of metres in width. They run in a north-south direction, and have a dip from vertical to 75°. The dykes are composed of granite, granosyenite and felsite, with a massive structure and porphyritic texture. The phenocrysts are small-grained and consist of orthoclase, plagioclase and quartz. The groundmass is granophyric, felsitic or microgranular.

This complex penetrates both the Dinh Quan and the Deo Ca complexes and has been designated as Palaeogene in age.

Cu Mong Complex ($\upsilon\wr cm$)

This is another hypabyssal igneous complex, which within the study area is also exposed only in the Da Loc commune. The dykes of this complex range from decimetres to metres in width and are hundreds of metres in length. They consist of dolerite, gabbrodolerite, and porphyritic gabbrodiorite.

The complex penetrates the Van Canh, Dinh Quan and Deo Ca complexes and is also designated a Palaeogenic age.

2.2 Ninh Hoa Study Area

Ninh Hoa district belongs to Khanh Hoa province, lying to the south of Phu Yen province. The district consists of twenty-seven communes and one town, all of which were studied by Vu (2008). The present study re-sampled selected wells from four communes: Ninh Phung, Ninh Sim, Ninh Tay and Ninh Xuan.

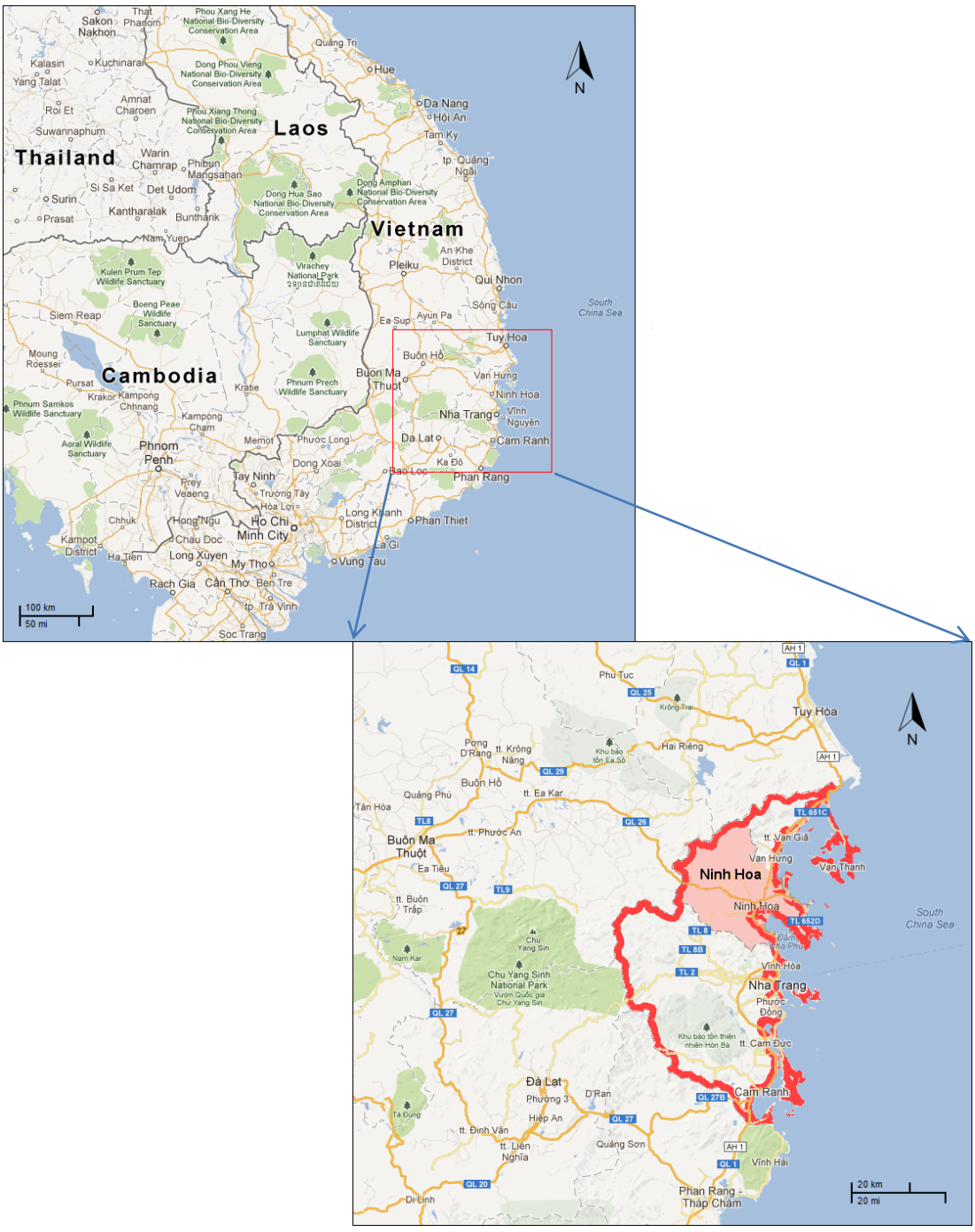


Figure 2.5: Location of Ninh Hoa district (pink shading) in Khanh Hoa province (red outline). (Google Maps)

The Ninh Hoa district lies to the north of Khanh Hoa province (Figure 2.4) and extends from latitude 12° 20′ to 12° 45′ North and from longitude 108° 50′ to 109° 20′ East.

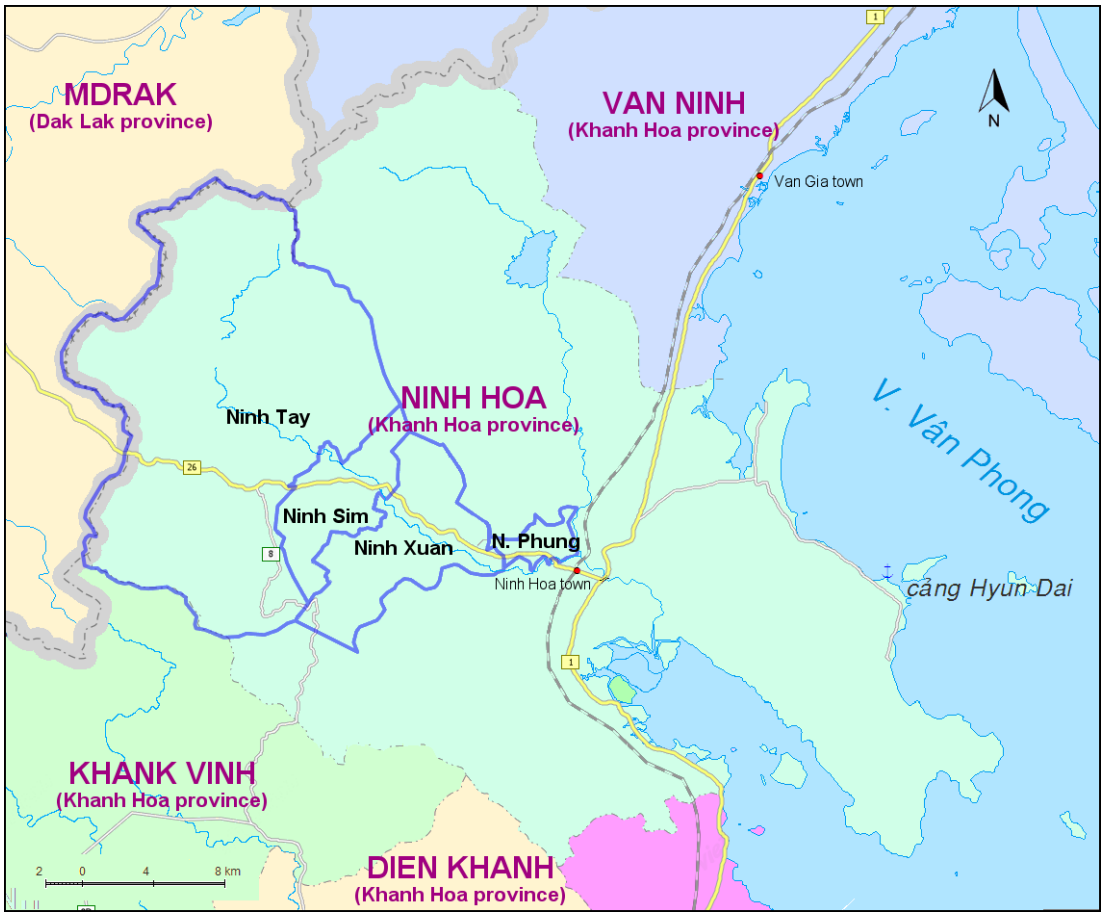


Figure 2.6: Ninh Hoa and the four re-sampled communes (named in black). (*Vietnamese electronic information portal*)

To ensure the correct wells were being re-sampled, the homeowner names, which were published in the thesis of Vu (2008), were used by commune officials to locate the individual properties. Map coordinates, which were also published in the same thesis, were used to verify the locations.

3 METHODOLOGY

3.1 Research Overview in Dong Xuan

This study consisted of a geochemical and geospatial study of the shallow groundwater composition in Dong Xuan district. Fieldwork was conducted in two periods, the first in June and July 2012, and a follow-up field visit in March 2013. Water sampling was predominantly from domestic wells; however, a number of surface waters were also sampled. Only a representative subset of wells from each commune of Dong Xuan district was sampled, due to the large number of wells present.

The study comprised essentially four distinct phases.

Phase 1: Development of an FISE method.

The development of a FISE method was performed with the use of synthetically prepared F^- standards in the EIGG laboratories at Curtin University prior to departure for Vietnam. All aspects of the FISE was investigated, including electrode performance, drift characteristics and reproducibility of results.

Phase 2: Sampling, collection and analysis of water samples in Vietnam.

The field project consisted primarily of sampling and electro-chemical analysis of groundwater from wells. The analyses were performed either directly at the sampling location, or after sample collection at a 'base station' (hotel) established in the rural area. Adequate quality control of F^- analysis was implemented by means of blanks, duplicates, in-house standards, and spiked samples.

I. Sampling location measurements

A standard suite of field parameters (pH, Eh, EC and DO) was measured at the time of the water sample being taken. Well depths and standing groundwater levels were measured using a custom-made depth gauge.

II. Base station analysis

A sample of groundwater from each sampling location was collected, kept cool in a cold-box, until a F^- determination could be performed by the FISE at the base station in the evening, using the FISE method developed in this study. An alkalinity measurement was also performed at the base station on each sample as outlined in Standard Methods for the Examination of Water and Wastewater (Eaton 2005).

Phase 3: Verification of the results of FISE analysis using HPIC, and further analyte determinations.

A subset of the suite of water samples collected and analysed in the field was transported to Perth for further analysis. This consisted of the determination of common anion and cation concentrations by HPIC, and trace metal analysis by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES). Fluoride results from the HPIC analysis were used to verify the results obtained by FISE measurement in the field in Vietnam, and to make direct comparison of the veracity of the two methods of F^- analysis. A selected number of these samples were also re-analysed by FISE in the EIGG laboratory to elucidate the stability of the F^- composition during storage of the samples and their transportation to Perth.

Phase 4: Interpretation of results and development of tools for the management of the fluoride health risk.

This included evaluation of results, modelling of F^- behaviour in groundwater with the use of geochemical speciation software (PHREEQC version 3), development of an interactive GIS using MapInfo Professional® version 10 for the Don Xuan area and construction of a fluorosis risk map.

3.2 Sampling Protocols

Both field studies were undertaken during the extensive dry season, the first trip at the end of the dry season in 2012 and the second at the beginning of the dry season in 2013. Although no sampling was undertaken during the rainy season, the earlier study of Vu (2008), thoroughly investigated seasonal variation of F^- concentrations

in groundwater and concluded that, although some significant variations were found, the overall distribution pattern remained similar.

3.2.1 Dong Xuan District

Groundwater was sampled from selected shallow dug wells to give sampling locations that were generally spaced at regular distances, although the spacing would depend on the abundance of wells in a given area. The major constraint for the sampling distribution was the locations of the wells. The residential distribution in Dong Xuan district, typical of rural Vietnamese communities, is predominantly along roads with paddy fields occupying the areas between. Therefore, sampling was not only restricted to the residential areas, but was also confined predominantly along roadways by this ribbon development. This can be seen in Figure 5.2 (page 63), where sample locations clearly define the main roads. It was for this reason that the sampling regime was not grid based but rather based on incidental sampling with a typical sample spacing of 200 – 500 metres where well availability permitted.

In some cases, where an unusually high F^- concentration was recorded, or where two samples collected from closely spaced locations showed large difference in F^- concentration, a higher density sampling regime was employed. This would serve to delineate the area of high F^- groundwater or at least give an approximation to its lateral extent. Although the present study did not focus on temporal variations, sampling during the second fieldtrip included a small number of wells that had been previously sampled during the first fieldtrip. This was done to provide a useful comparison of values between the two trips. However, as the focus was to sample as many wells as possible, only one repeat well was sampled per day. The values of the repeat analyses are presented in Table 5.1 (page 62).

All groundwater samples were obtained from the wells using either a bucket or pump, as was the practice of those using the well. Whereas it is common practice when collecting groundwater for analysis to purge the well prior to sampling, no attempt was made in the present study to purge the wells for two reasons. The first was a practical consideration: owing to the precious nature of well water during the hot dry months in Vietnam, there was a reluctance of the part of the residents to allow the wells to be purged with ensuing wastage of water. The second reason was

an academic one: since the aim of this study was to assess the human health risk, each well was sampled according to the means used to draw water (bucket or pump). As the vast majority of wells sampled were in regular use, there was little prospect that the water had stagnated or did not reasonably represent the immediate shallow groundwater composition. Certain measures were taken to ensure that the water being collected was "fresh" and represented the well water as used by the residents. Where a bucket was employed, it was first rinsed with the well water to be sampled. In wells that were serviced by a pump, the pump was first run for sufficient time to ensure a fresh sample was being collected. This would depend on the length of hose, but pumping times prior to sample collection would typically be from 1 – 2 minutes.

The water from each sampled well was collected in two plastic 500 mL bottles, which had been rinsed three times with the water to be sampled. One bottled sample was used for subsequent FISE analysis and alkalinity measurements at the base station, while the second provided a sample suite from which selected samples would be transported back to Australia for common anion and cation, and trace metal analysis. While in the field, the plastic bottles containing the water samples were stored in polystyrene cold boxes containing iced water. Once at the base station, one each of the duplicate sample bottles was prepared for storage until they could be transported to Perth. Samples to be analysed for anions and cations were filtered through a Millipore® 0.45 μm nitrocellulose membrane filter using a small hand operated vacuum pump. A 60 mL LDPE bottle was rinsed with the filtered sample three times and then filled to the top and tightly sealed with the cap. To eliminate possible cross contamination between different samples during the filtering process, the filter apparatus was pre-contaminated by flushing three times with fresh sample before the sample was filtered. A small proportion of the filtered samples were also prepared for trace metal analysis by accurately placing 9 mL of sample in an acid washed 60 mL LDPE bottle and then acidifying by addition of 1 mL of 20% nitric acid. On occasion, a sample of distilled water was filtered and prepared for trace metal analyses as a blank for quality control. Prepared sample bottles for anion and cation analysis were refrigerated until they could be transported to Perth.

Where duplicate samples were required for FISE analysis at the base station, an unfiltered portion from the second bottle was used.

Dong Xuan samples were prefixed according to the commune from which they were collected, as shown in Table 3.1. For wells that were sampled during both fieldtrips, the sample from the second collection was suffixed with "R" to designate it as a repeated well sample.

Table 3.1: Sample prefix allocation according to commune.

Commune	Sample Prefix
La Hai	LHA
Xuan Quang 1	XQA
Xuan Quang 2	XQB
Xuan Quang 3	XQC
Xuan Phuoc	XPU
Xuan Long	XLG
Xuan Lanh	XLN
Xuan Son Nam	XSN
Xuan Son Bac	XSB
Da Loc	DLC
Phu Mo	PHM

3.2.2 Ninh Hoa District

Four communes were chosen for re-sampling of wells previously studied by Vu (2008): Ninh Sim, Ninh Tay, Ninh Phung, and Ninh Xuan. Selection criteria for these communes were:

1. together they would provide a generalised cross-section of the Ninh Hoa district from highlands to lowlands;
2. each contained wells that had previous repeated samplings undertaken at different times by Vu (2008), thus providing a temporal stability profile;
3. the combination of communes would show a wide range of F^- concentration in groundwater. This would enable stability profiles to be determined on a range of F^- concentrations.

Of the four communes sampled in the first fieldtrip, one (Ninh Phung) failed to meet the second criterion. Ninh Phung was only sampled once in the previous study by Vu (2008). During the second fieldtrip, extra wells were chosen for re-sampling and many of these did not meet the second criterion as well. All samples that were

collected from Ninh Hoa in the present study were numbered the same as the samples in the original study by Vu, with different sampling date recorded.

3.3 Quality Control

To ensure the quality of analyses performed on the groundwater samples, a series of quality control procedures were employed. These included the preparation and analysis of blanks, duplicates, replicates and spiked samples. In this thesis, "duplicate results" refer to two separate water samples that were collected at the same time from the same location. These will be referred to as *field duplicates*. Laboratory replicates are simply the same water sample measured twice by the same analytical method. Quality control procedures were based on those used by the U.S. Geological Survey (*National field manual for the collection of water-quality data* n.d.).

3.3.1 Random Errors

Random errors were addressed by the following measures.

In-house Standard

During both fieldtrips, a sample was chosen from the first batch of samples that were analysed and was designated thereafter as an 'in-house' standard. The selection criterion for the in-house standard on the first fieldtrip was that its F^- concentration should be close to the recommended WHO guideline value, i.e. ~1.5 mg/L. The sample chosen was XPU08, which had a measured F^- concentration of 1.82 mg/L. The selection criterion for the second fieldtrip was to use a sample that had a value midway between the two calibration points used for the FISE method as discussed later (between 1 mg/L and 10 mg/L F^-). This would enable the collection of QC data at two different concentration values, one low and the other mid-range. XQB08R with a value of 6.64 mg/L was the sample chosen from the second fieldtrip. The in-house standards were stored in their original 500 mL plastic sample bottle and were run with every analytical session having been positioned randomly within the sample batch to be analysed. This would monitor the precision of the entire FISE method; from pipetting the sample to the drift correction measures that were applied (see section 3.4.1). Although the exact F^- concentrations in the in-house standards were

unknown, their relative concentration was used to compare the precision between batches and thereby to determine the random error. Results for the in-house standard for the first fieldtrip (XPU08) had a percent relative standard deviation (%RSD) of 1.32, while those of the in-house standard for the second fieldtrip (XQB08R) gave a %RSD value of 1.05.

Table 3.2: Values for fieldtrip "in house" standards. All values in mg/L fluoride.

	Fieldtrip 1	Fieldtrip 2
	XPU08	XQB08R
	1.82	6.64
	1.81	6.52
	1.82	6.44
	1.82	6.62
	1.84	6.59
	1.78	6.56
	1.80	6.62
	1.76	6.65
	1.77	6.54
	1.79	6.66
	1.78	
	1.78	
	1.79	
	1.79	
	1.77	
	1.75	
	1.79	
	1.77	
	1.77	
Average	1.79	6.58
Std. dev.	0.024	0.069
%RSD	1.32	1.05

Field Duplicates

Every day, a duplicate F^- determination using the FISE was performed by analysing a sample from both 500 mL containers from a well that had been sampled that day. The sampled well to be duplicated was randomly chosen and the duplicates were not analysed sequentially, and one of the duplicates was always placed at the end of the batch. The duplicate monitored any errors that were introduced into the method from field collection and preparation, to the final FISE analysis. Duplicate values from the first and second fieldtrips are listed in tables 3.3 and 3.4, respectively.

Table 3.3: Duplicate values obtained from first fieldtrip. All values in mg/L fluoride.

Sample	X_1	X_2	RPD
XPU03	1.10	1.05	4.65
XPU21	1.00	1.01	1.00
XPU14	0.84	0.84	0.00
XPU30	8.15	8.05	1.23
XQA09	0.39	0.39	0.00
XLN02	0.34	0.35	2.90
XLN12	1.77	1.74	1.71
XQB08	12.48	12.72	1.90
XLN28	1.40	1.38	1.44
XQC03	1.42	1.46	2.78
XQC18	0.64	0.75	15.83
XLG03	3.34	3.41	2.07
XQB16	11.35	11.26	0.80
LHA05	2.11	2.11	0.00
LHA17	2.87	2.89	0.69
PMH04	2.24	2.35	4.79
XSB02	1.41	1.40	0.71
XSN09	9.10	9.21	1.20
DLC03	0.88	0.90	2.25
XPU42	7.97	7.98	0.13

Table 3.4: Duplicate values obtained from second fieldtrip. All values in mg/L fluoride.

Sample	X_1	X_2	RPD
XQB23	1.50	1.45	3.39
XQA19	3.76	3.85	2.37
PM15	2.83	2.80	1.07
XSN18	6.03	5.92	1.84
LH83	0.78	0.79	1.27
XL91	0.38	0.40	5.11
XL83	3.58	3.49	2.55
XLG03R	1.13	1.16	2.62
XP85	7.92	8.01	1.13
XP97	1.20	1.17	2.53

All duplicates gave a relative percent difference (RPD) of less than 5.1% except one (XQC18).

3.3.2 Systemic Error

Systemic error, or bias, in the field measurements was determined by the use of spiked samples as outlined below. Furthermore, the standard solutions used to calibrate the FISE in the field were returned to Perth to be analysed by HPIC to assess any bias in the results of the two analytical techniques.

Sample Spikes

Sample spiking was used for the HPIC analysis to establish if any analyte was lost due to degradation of the sample, or if the water-matrix characterisation of the sample altered the analyte's concentration. The difference between the amounts of analyte measured to the actual amount spiked is referred to as the recovery, and is expressed as a percentage.

Two sample spike methods were employed in this study:

1. *Field spike samples*

The field spiked sample was to ensure that no analyte degradation had occurred from time of sampling until the time of HPIC analysis in Perth. One sample a day was spiked and due to the requirements of high precision for spiking, field spiked samples were spiked at the base station upon arrival from the field, and then stored until transported back to Perth at the end of the fieldtrip.

2. *Laboratory spike samples*

These samples were spiked immediately prior to HPIC analysis. This would determine any method performance issues caused by the water-matrix characterisation of the sample.

Method of spiking

A spike standard was prepared in the laboratory at EIGG before departure for Vietnam. A 20 mL aliquot of the sample was spiked with 1 mL of the spike standard using an Eppendorf® 1000 μL transfer pipette. The precision achieved by manual pipetting was determined prior to departure by means of multiple tests and the use of spiked blanks.

Upon return to Perth, all spiked samples analysed by HPIC obtained over 96% recovery of F^-.

3.3.3 Contamination

Potential for geochemical contamination of water samples was monitored by the use of field blanks. At the beginning of each day, a 500 mL sample container was filled with deionised water using the same protocol as for sample collection (e.g. container was rinsed three times). The sample was placed in the polystyrene cold box, and was analysed along with all other samples collected that day.

All blanks for F^- analysis by FISE were determined to contain less than 0.1 mg/L F^-.

3.4 Analytical Methods

All water samples were measured at the base station for F^- concentration using the FISE. From the first fieldtrip, approximately half of the samples were transported back to Perth and measured for major anions and cations using HPIC. From the second trip, approximately 90% of the samples that were collected were returned to Perth, giving a total number of 209 samples for major anion and cation analyses. A smaller subset of these samples (48) were analysed for selected trace elements by ICP-OES.

3.4.1 Fluoride Ion Selective Electrode

Fluoride determination by FISE requires a degree of skill on behalf of the operator so significant time was spent developing a protocol that would yield results that were consistent and reliable.

Ion-selective electrodes (ISE) enable the concentration of the ion of interest to be converted into an electrical potential difference, which is then measured by a millivolt meter. They consist essentially of a plastic tube with an ion selective membrane fitted to one end where the solution to be measured comes into contact with the outside surface only. A low noise wire is attached to the inside surface of the membrane and the interior is usually filled with a liquid or gel electrolyte. The pH electrode is the most widely used type of ISE and uses an ion selective membrane consisting of glass. Other ISEs have either a crystalline membrane or an impregnated PVC membrane. The FISE was the ISE that was used in this study, which is of the crystalline membrane type. It uses a lanthanum fluoride (LF_3) crystal, which has been doped with europium fluoride (EuF_2). The EuF_2 creates lattice vacancies, which enables the mobilisation of F^- ions within the crystal lattice, resulting in high specificity for F^-.

The FISE, like other ISEs, has an electrical potential difference response that is directly proportional to the logarithm of the ion activity (activity will be discussed later), and is described by the Nernst equation. The Nernst equation is used in electrochemistry to describe the reduction potential of a half cell or, in this case, to determine the total voltage in a full electrochemical cell, i.e. the potential difference between the FISE and its reference electrode. It must be noted that an ISE is only an electrochemical half-cell, and must be paired with a reference cell so the potential difference between the two cells can be measured. In this study, a combination FISE was used, which incorporates the reference electrode and the FISE into a single probe. Although fundamental for the understanding of the electrochemical processes, a full explanation of the Nernst equation is not necessary in this thesis. However, it is important to understand the following:

1. The response of the ion activity to the change in electrical potential (mV) is logarithmic.
2. At low concentrations, the response of potential difference to ion activity deviates from that predicted by the Nernst equation. This, and the methods used to compensate for this deviation, are discussed later.

Although the theory of operation of the pH electrode and other ISE's are similar, it must be noted that there are some very important differences between the two. For this reason, the pH electrode will be considered separately from the other ISE's in the remainder of this discussion. One notable difference between the pH electrode and ISE's is the precision with which the potential difference must be measured. pH electrodes are very forgiving, allowing several millivolts (mV) of imprecision to affect the pH by only 0.1 of a pH unit. ISE (including the FISE) require a much more precise measurement. A one millivolt difference can affect an ISE's calculated analyte concentration by several percent.

The FISE differs from other ISE's by its ion specificity. As mentioned earlier, the FISE is highly specific for F^-, whereas other ISE's are not entirely specific to the analyte ion and may be sensitive to other ions. Even though the FISE has high specificity for F^- it does, however, suffer indirectly from the presence of some interfering ions. One such interference arises from the hydroxide (OH^-) ion. This ion interferes by reacting with the lanthanum fluoride membrane, producing lanthanum hydroxide. The problem is that as lanthanum hydroxide is produced, F^- ions are released into the solution, thereby increasing the measured F^- concentration. Other major interferences are from Al^{3+} and Fe^{2+} ions, although these have nothing to do with the FISE itself, but rather their complexing ability with the F^- ion. Once these ions complex with the F^- ion, the latter is effectively incapacitated with respect to FISE sensing reactions.

To counter the various interferences, a Total Ionic Strength Adjustment Buffer (TISAB) is added to each water sample immediately before analysis. The TISAB reduces the effects of the interferences by firstly acting as a pH buffer and secondly providing a chelating agent. By maintaining a pH between 4 – 8, the hydroxide ion concentration is kept to a minimum. The chelating agent has a stronger affinity for

the Al^{3+} and Fe^{2+} ions than the F^-, and therefore acts to breakdown iron and aluminium-fluoride complexes. TISAB also adjusts the ionic strength of the measured solution, as another important difference between ISEs and pH electrodes is the vulnerably of ISEs to the ionic strength of the solution. All ISEs (pH electrodes included) actually measure the activity of the ion and not the concentration. The activity of an ion is the ion's ability to interact at the surface membrane of the ion selective electrode. In dilute solutions, the activity coefficient (the ratio of the activity to the concentration) is close to one. However, the activity coefficient reduces significantly as the ionic strength increases above 0.001 mol/L, because the more concentrated ions interact with each other more. This reduces their interaction with the surface membrane of the ISE, thereby lowering their effective concentration. Although pH electrodes experience the same effect, the pH value is not compromised since pH is already a measure of the hydrogen ion activity and not its concentration. When measuring other ions, it is the concentration of that ion that is required rather than its activity. If all the solutions being measured (samples and standards) have the same ionic strength, the problem is eliminated. The addition of TISAB, which has a high ionic strength, brings the ionic strength of all the solutions to a similar concentration.

The TISAB chosen for use in the present study was one using NaCl to adjust the ionic strength, acetic acid to buffer pH, and 1,2-cyclohexylene-dinitrilo-tetraacetic acid (CDTA) as the chelating agent. This TISAB composition was successfully trialled by Mamuse (2003). It was prepared as follows:

Into a 1 litre beaker containing approximately 500mL distilled water was added 57 mL of glacial acetic acid, 58 g of sodium chloride and 4 g of CDTA. After the solution had cooled, the pH was adjusted to 5.2 using ~6M NaOH, and then made up to one litre. Although the TISAB had a two week shelf life, it was prepared every week.

Instrumental Drift

A new Thermo Scientific Orion combination F^- electrode (model 9609BNWP) was used in this study. Instrumental drift was tested for by alternately reading 1mg/L and 10 mg/L F^- standards for two hours (approximately 25 measurements each). This exercise produced very little drift in either value. However, when the same standard was measured consecutively, an apparent drift was observed. Furthermore, when a series of standards were read in order of low to high F^- concentration, near perfect values were produced; however, when these standards were read in a random order, a strong memory or hysteresis effect was observed. Hysteresis is an effect where the measured mV potential of a sample is influenced by the analyte concentration of the sample or samples measured previously. It was noted that after a series of tests with randomly read standards, hysteresis was more likely to affect samples containing lower F^- concentrations. This is due to the logarithmic response where low concentrations of F^- are more sensitive to changes in the electrical potential difference. The difference between hysteresis and drift needs to be recognised, since their effects on the F^- measurement appear as being similar. Hysteresis is a non-systemic (random) error, which is dependent on the values of the sample, or samples, that were previously analysed, whereas drift is systemic and can be observed as a general move away from the calibrated value.

To minimise the hysteresis effect, a procedure based on the one suggested by Rundle (2000) was adopted. Rundle showed that hysteresis could be minimised by washing the electrode in distilled water between samples. This allows the measurement of all mV potentials to be 'approached' from the same direction. After initial experimentation with the procedure, a wash solution of distilled water containing the same amount of TISAB as used in the samples, i.e. a 1:1 mix, was chosen. Furthermore, if the wash solution contained 0.1 mg/L F^-, which is still low enough to reduce the hysteresis effect caused by high F^- containing samples, it could also be used as a drift indicator, if its value was recorded each time. When using the wash as a drift indicator, it is important to understand that the wash will also be affected by hysteresis. It is the overall systemic drift that is observed, not the irregular variation from sample to sample as a result of hysteresis. Using the wash solution as a very low 0.1 mg/L F^- standard also became very useful when a two-in-one calibration

method was later developed (as discussed below). It was found, however, that even after the wash, the previous sample's F^- concentration still perturbed the measured potential of the following sample. Nevertheless, this procedure of a wash between samples did minimise the hysteresis effect. Various wash times were tested and a one minute wash in TISAB containing 0.1 mg/L F^- was adopted. The procedure was to rinse the electrode with a fine stream of distilled water from a wash bottle, and then to place the electrode in a beaker containing the 0.1 ppm F^- TISAB solution for one minute. At the end of a minute, the mV potential was recorded, the electrode was rinsed with a stream of distilled water, and the next sample was analysed.

Electrode Performance

Although the standard measure of the electrode's performance is determined by the slope of its calibration curve, i.e. the mV response per decade of analyte concentration (activity), another useful measure is its zero analyte response potential and low-level linearity. "Out of the box", the electrode gave a zero analyte potential of about 200mV in a blank solution (50% TISAB, 50% distilled water) and showed good linearity down to about 0.4 mg/L F^-. However, after repeated use, the performance degraded to where a blank solution would only provide a potential of about 160mV (or even lower), with a long stabilisation time (at low F^- concentrations). Figure 3.1 illustrates the mV response of the new electrode compared to the response obtained after the electrode had been used extensively for four days. It is interesting to note that in general, the slope (measured between 1 and 10 mg/L) only changed slightly; from 59mV to about 56 mV, and the off-set (the actual mV potential) reduced moderately. However, the most significant change was its low-end linearity response, and the lower limit readability. As shown on the graph in Figure 3.1, the new FISE gave a linear response down to about 0.4 mg/L; however, this deteriorated to about 0.7 mg/L with use. Furthermore, as shown in Figure 3.2, high linearity was maintained at F^- concentrations as high as 100 mg/L.

To restore the FISE to its former condition, the mildly abrasive nature of toothpaste was used as discussed by Noh and Coetzee (2007), The lanthanum fluoride crystal was cleaned with fluoridated toothpaste by gently rotating it on a thin smear of toothpaste placed on a piece of paper. Even though this restored the electrode's performance, sometimes this would cause a noticeable drift during use, and there was

inevitably a return to the low performance state. A requirement was clearly recognised for a procedure that would allow accurate measurement of F^- in low concentrations whether the FISE had good low-level linearity or not.

Two-in-one Calibration Method

It was apparent early in the study that as the performance of the FISE degrades, the low-end linearity is reduced along with an increase of the detection limit. This poses a problem when determining samples with low F^- concentrations. To improve both the detection limit of the method and the accuracy of the results when measuring samples with low F^- concentrations, a method was developed in which two calibrations, a normal linear high-range calibration and a non-linear low-range calibration, are used together.

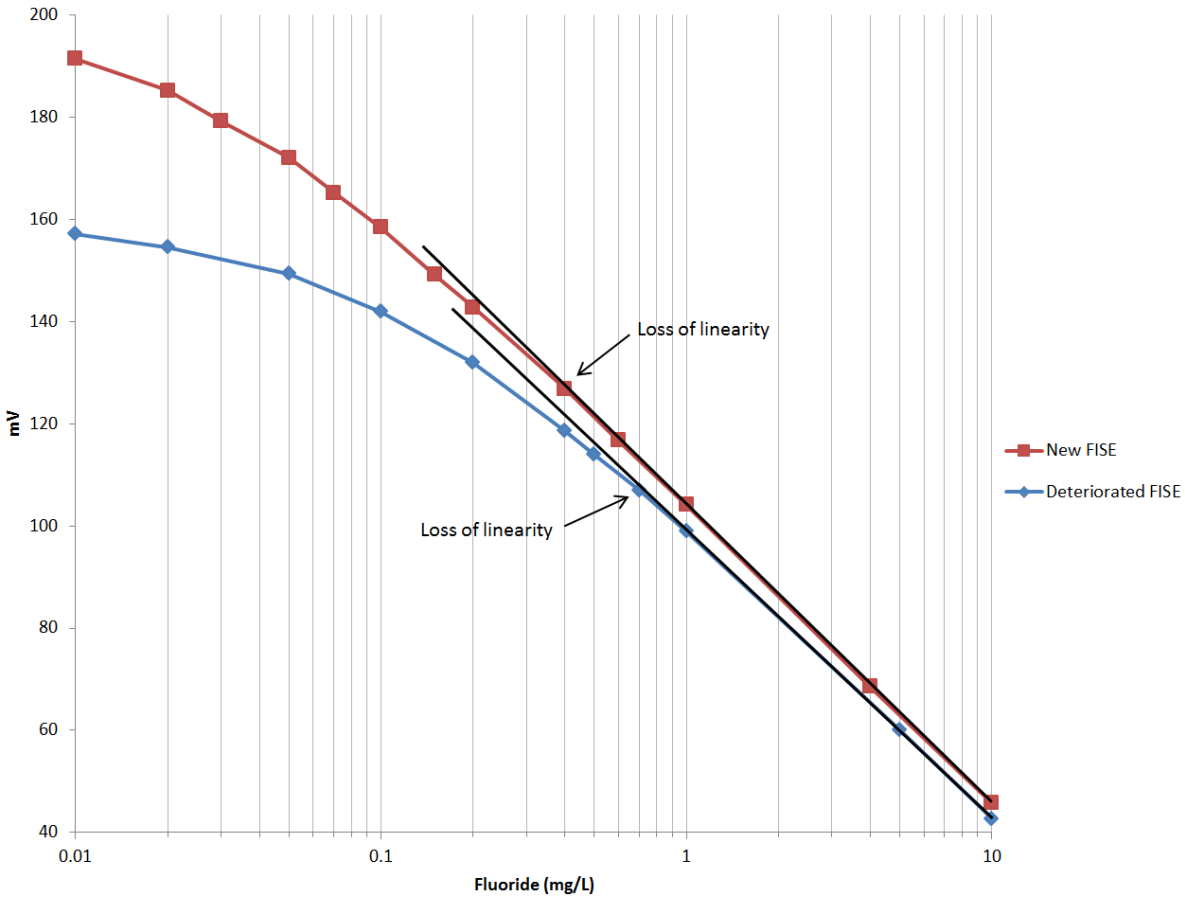


Figure 3.1: Comparison between new and deteriorated FISE.

A sample concentration of 0.5 mg/L F^- was chosen as the cut off between high and low-range calibrations. This was considered as being the "safe" lower limit of

linearity. Above this concentration, deviations from the linear calibration were small. The sole purpose of using the two-in-one calibration method is to enable accurate measurements down to 0.05 mg/L, even during low electrode performance.

However, as the electrode's performance degrades and the linearity at low concentrations reduces, the slope at these low concentrations also reduces. Even though this reduced slope is taken into account in the calibration, the low electrode response will reduce precision. It is therefore recommended to set a lower limit of determination for practical usage.

The lower limit of determination for this study was 0.1 mg/L F^-. Any measured F^- concentration lower than this was reported in this study as < 0.1 mg/L. All measurements were recorded in units of millivolt potential and a spreadsheet was developed into which the millivolt data were entered. A two point calibration (1 and 10 mg/L F^-) provided the linear high-range calibration while a three point calibration (0.1, 0.2 and 0.5 mg/L F^-) provided data for the low-range non-linear calibration. The three points of the low-range calibration indicated the differences between the measured values and the theoretical values that would be obtained if the calibration curve were completely linear at these low concentrations (Figure 3.2).

These three "difference" values enabled the calculation of an exponential curve of best fit of mV difference to concentration (Figure 3.3). This curve was then used to calculate the "ideal" millivolt potential for all the samples below 0.5 mg/L that would be obtained if the calibration curve were linear at these concentrations. The curve determined the difference that would need to be added to the measured millivolt potential, essentially enabling all samples to be read on the linear high-range calibration curve. Therefore, even if the electrode exhibited strong low-level non-linearity, the resultant large mV differences of the three low calibration standards would essentially nullify this by applying the appropriate millivolt correction to all samples below 0.5 mg/L.

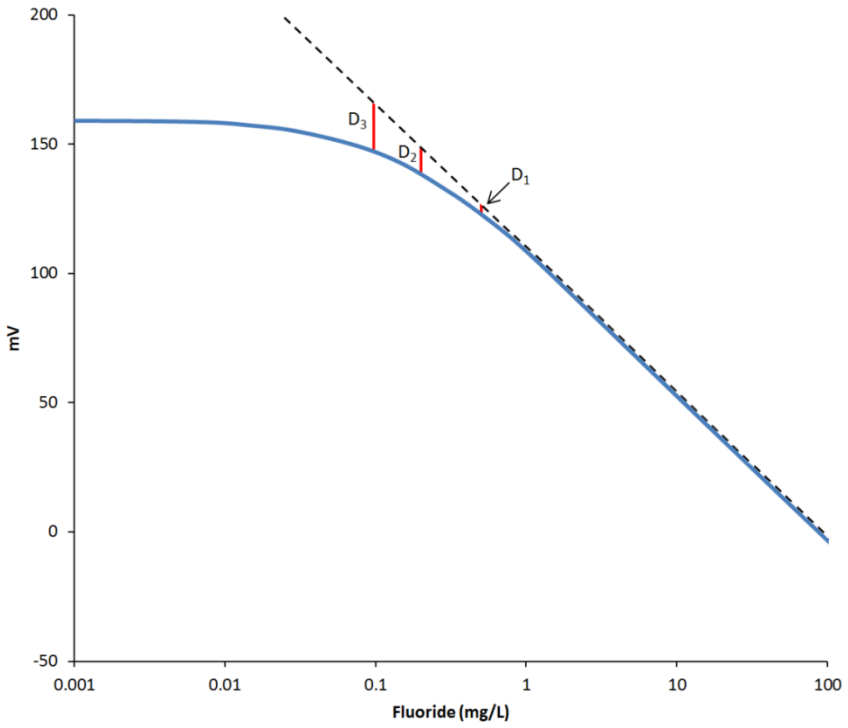


Figure 3.2: Millivolt differences of low standards between measured and theoretically linear curves.

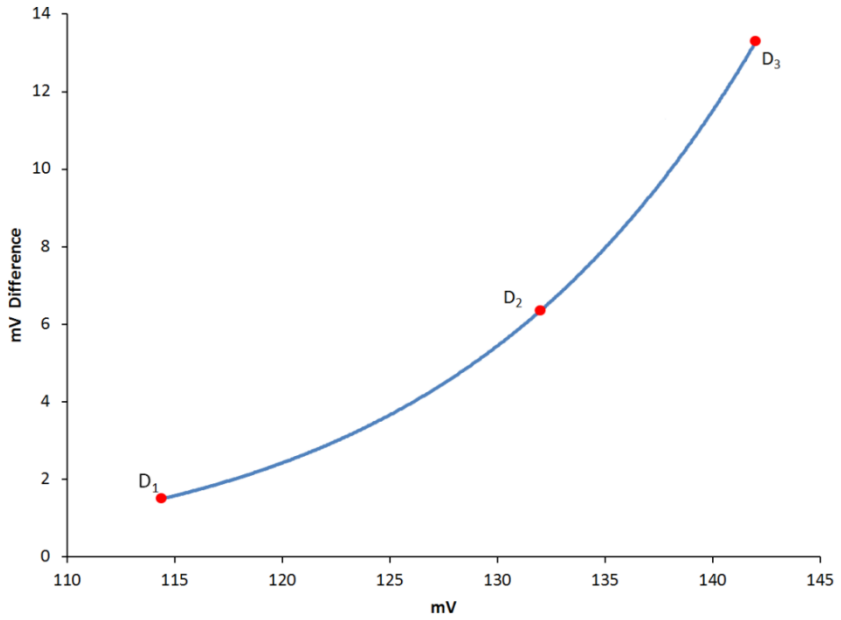


Figure 3.3: Exponential curve for millivolt differences.

Additionally, electrode drift was more severe on some occasions than others. In order to control this drift and maintain accurate readings, a modified continuous calibration method was used, as outlined by Rundle (2000). The method of Rundle

consisted of reading a sample and then a standard, alternating with a high and low standard each time a standard was measured. This would provide a continuous calibration, where each standard constantly updates the calibration. As this would add considerably to the overall analysis time, especially since there were now five standards being used, standards were run every 2 - 3 samples as deemed necessary from the results of the 0.1 mg/L F^- wash between each sample (as discussed earlier). By recording the mV potential of the electrode after a one-minute wash, any drift that was occurring could be determined. Even though individual readings of the 0.1 mg/L F^- wash solution would vary slightly depending on the concentration of the sample before it (due to hysteresis effects), the overall observed trend would indicate if drift was occurring. In practice, it was the concentrations of the measured samples that determined which standard would be run as a check. If sample concentrations were low, the low-level standards were used as the check standard; otherwise, the two high-end standards were used. Since the 0.1 mg/L F^- standard was used as the wash between samples, measures were taken to ensure this standard was not contaminated by high F^- containing samples. This was achieved by initially rinsing the electrode with a fine stream of distilled water from a wash bottle and then briefly submerging the electrode in a beaker of 50% distilled water and 50% TISAB solution. After this, the electrode was placed in the 0.1 mg/L F^- wash solution for one minute. Even if the 0.1 mg/L F^- wash solution was slightly diluted by the continual washing process, as the slope of the calibration curve at this concentration was very low, small changes in its concentration would have no effect on the calibration. Furthermore, as this standard was constantly being used and its value being recorded, it was never needed as a check standard. Only the 0.2 and 0.5 mg/L F^- standards were used for low-level check standards, and the 1.0 and 10 mg/L F^- standards for the high-level check standards. If there were a continuous amount of low samples, it was still necessary to occasionally check the higher end standards for drift, since it was the linear high-end calibration that these low samples are adjusted against.

Analytical Procedure

After initial investigatory work, an optimal procedure for analysing F^- by FISE was developed:

1. 15 mL of TISAB was added to a 60 mL glass beaker.
2. 15 mL of sample/standard was added to the beaker.
3. The sample was left for a minimum of 20 minutes to allow for breakdown of any F^- - Al^{3+} or F^- - Fe^{2+} complexes (Nicholson and Duff 1981).
4. The beaker was placed on a magnetic stirrer with the stirrer bar set to a slow speed.
5. The FISE was lowered in the solution to a depth of about 1 cm.
6. After two minutes, the millivolt reading was recorded.

After each sample had been measured, the electrode was rinsed with a fine stream of distilled water from a wash bottle, and then briefly submerged in a beaker of a 1:1 solution of distilled water and TISAB. After this, a one-minute wash was done using a 1:1 mix of distilled water and TISAB solution containing 0.1 mg/L F^- solution as discussed earlier.

3.4.2 High Performance Ion Chromatography

The major common anions and cations in water were determined using HPIC (Figure 3.4). This technique separates different ions in solution by partitioning them between a solid stationary phase (ion exchange resin packed into a separator column) and a liquid mobile phase (eluent). The sample is introduced into the eluent via an injection valve and is carried through the separator column containing the stationary phase. A high pressure pump forces the mobile phase through the packed separator column at a precise constant rate of between 1 - 2 mL/min. The partitioning of the ions between the two phases is achieved by adsorption onto the solid phase, with separation of different ionic species affected by differences in the distribution co-efficient between the liquid and solid phases. The separated ions elute from the column and pass to the detector where their concentration is measured by electrical conductivity. Chemical suppression was used to maximise peak sensitivity by reducing the background conductivity of the eluting mobile phase.

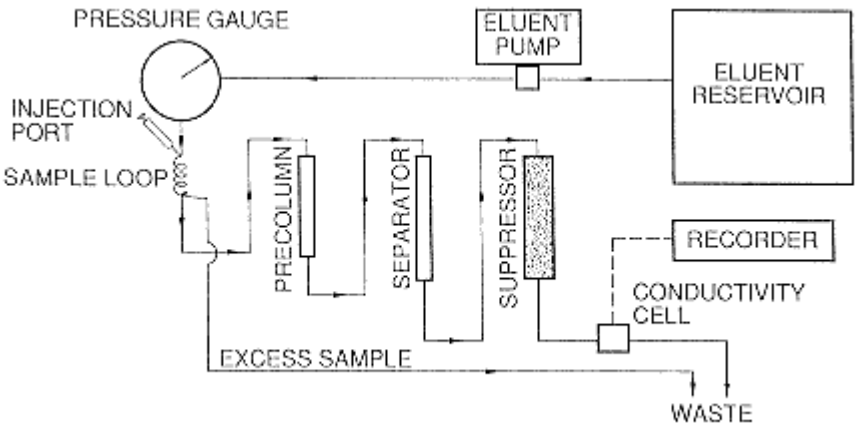


Figure 3.4: Schematic of HPIC system (Dick and Tabatabai, 1979).

The anion and cation analysis used the following equipment:

Dionex® ICS-1000 Chromatograph

Dionex® 4 mm AG-14 guard column

Dionex® 4 mm AS-14 anion separator column

Dionex® 4 mm CS-12 cation separator column

Dionex® 4 mm ASRS 300 anion suppressor

Dionex® 4 mm CSRS 300 cation suppressor

Anion eluent: 3.5 mM CO_3 / 1.0 mM HCO_3

Cation eluent: 20 mM Methane sulphonic acid

Operational parameters:

Flowrate: 1.2 mL/min (anions)

1.0 mL/min (cations)

Column temperature: 35°C

Calibration details:

Calibration standards: 2 mg/L, 5 mg/L, 10 mg/L, 20 mg/L

LOD: 0.05 mg/L

3.4.3 Alkalinity

Total alkalinity was determined by titration of the sample with standardised hydrochloric acid to an endpoint of pH 4.5. Using the determined total alkalinity and the pH of the sample, the bicarbonate and carbonate alkalinities could be determined using the following formulae:

$$HCO_3^- \text{ (mg/L)} = 0.61 \times \left(\frac{(2 \times \text{Total Alkalinity}) - (10^{-14 + pH})}{1 + 2 \times K_2 \times 10^{pH}} \right)$$

$$CO_3^{2-} \text{ (mg/L)} = K_2 \text{ x } HCO_3^- \text{ x } 10^{pH}$$

where K_2 is the second dissociation constant for carbonic acid, ($4.69 \text{ x } 10^{-11}$).

Estimation of carbonate and bicarbonate using these formulae is only practical if calcium and carbonate compounds make up the bulk of the contribution to total alkalinity. If other compounds, such as ammonia, are present then more complex formulae are required. However, in the case of the groundwater samples in this study, a reasonable assumption can be made that calcium and carbonate do contribute to the bulk of the alkalinity.

4 RESULTS OF NINH HOA STUDY

The study in Ninh Hoa district involved further sampling and analysis of a sub-set of the water sources previously studied between April 2004 and November 2006 (Vu 2008). A total of 57 water samples were collected from localities in four communes, Ninh Phung, Ninh Sim, Ninh Tay, and Ninh Xuan, originally collected by Vu (Table 4.1). Forty-seven of these samples were collected from wells, nine from hot springs and one from a bore.

Table 4.1: Fluoride concentrations of re-sampled Ninh Hoa water sources. Bold italicised results were obtained from this study. All concentrations are in mg/L. W = well, HS = hot spring, B = bore.

		Sampling Date							
Sample	Type	Apr-04	Dec-04	Jan-05	Mar-05	Nov-06	***Jun-12***	***Mar-13***	Std. dev.
NP012	W		1.12				***1.16***		0.0
NP027	W		5.10				***4.99***		0.1
NP028	W		1.00				***0.80***	***0.60***	0.2
NP028A	B		6.90				***1.27***	***1.71***	2.6
NP030	W		7.92				***5.46***		1.2
NP031	W		0.42				***0.15***		0.1
NP035	W		1.21				***1.43***		0.1
NP036	W		0.78				***1.59***		0.4
NP040	W		6.08				***6.31***		0.1
NP041	W		3.72				***2.83***	***2.14***	0.6
NP048	W		0.15				***0.27***		0.1
NP462	W		1.48				***0.81***		0.3
NS002	W	4.25					***3.35***		0.5
NS004	W	0.89					***0.71***		0.1
NS005	W	2.98	3.17			2.34	***2.30***		0.4
NS012	W	17.50	13.40			18.00	***6.57***	***6.89***	5.0
NS013	W	3.49	3.24			3.19	***3.32***		0.1
NS014	W	7.07	6.22			9.88	***5.28***		1.7
NS016	HS		5.05				***5.53***		0.2
NS036	HS			7.26			***7.63***	***5.64***	0.9
NS045	W			0.96				***1.36***	0.2
NS046	W		15.20				***3.29***	***2.93***	5.7
NS048	HS					6.56		***7.80***	0.6
NS103	W					4.79		***3.17***	0.8
NS141	W					28.10	***11.94***	***34.92***	9.6
NS142	W					0.34	***0.18***	***0.23***	0.1
NT001	HS	8.61	8.46	8.16		8.86	***8.63***	***8.70***	0.2
NT002	W	18.40	18.40					***15.21***	1.5
NT007	W	19.30					***10.80***	***12.53***	3.7
NT008	W	1.74					***1.48***		0.1

NT010	W		10.00					***6.83***	1.6
NT011	HS		6.27	6.79			***7.23***	***7.33***	0.4
NT017	W		3.69			3.48	***3.73***	***3.77***	0.1
NT018	HS		8.86		8.65	8.94	***8.44***	***8.85***	0.2
NT024	W		0.93					***1.24***	0.2
NT026	W		8.45					***8.56***	0.1
NT027	HS		7.88		7.24		***7.11***	***7.31***	0.3
NT036	W			2.48		1.36	***1.73***		0.5
NT040	W			12.70				***4.04***	4.3
NT044	HS				8.65			***8.65***	0.0
NT046	HS				8.51			***8.62***	0.1
NT047	W					0.83		***1.92***	0.5
NX001	W	11.00		10.80		11.70	***11.35***	***11.43***	0.3
NX004	W	6.50					***6.20***		0.2
NX006	W	16.50					***14.19***		1.2
NX008	W	6.39				4.53	***4.95***		0.8
NX016	W	1.00					***0.80***		0.1
NX018	W	1.54					***0.45***		0.5
NX026	W		9.39					***10.16***	0.4
NX034	W		18.90				***10.80***	***12.55***	3.5
NX086	W		0.24					***0.33***	0.0
NX096	W			5.79		5.91	***5.97***	***6.01***	0.1
NX242	W					1.04	***3.96***	***5.43***	1.8
NX243	W					16.00	***17.95***		1.0
NX244	W					2.80		***2.83***	0.0
NX313	W					2.61		***2.14***	0.2
NX314	W					0.99		***1.20***	0.1

The temporal variations in F^- concentrations results are shown in Figures 4.1 – 4.5. Note that the scale of F^- concentration depicted on the y-axes is the same on all five graphs to facilitate comparison.

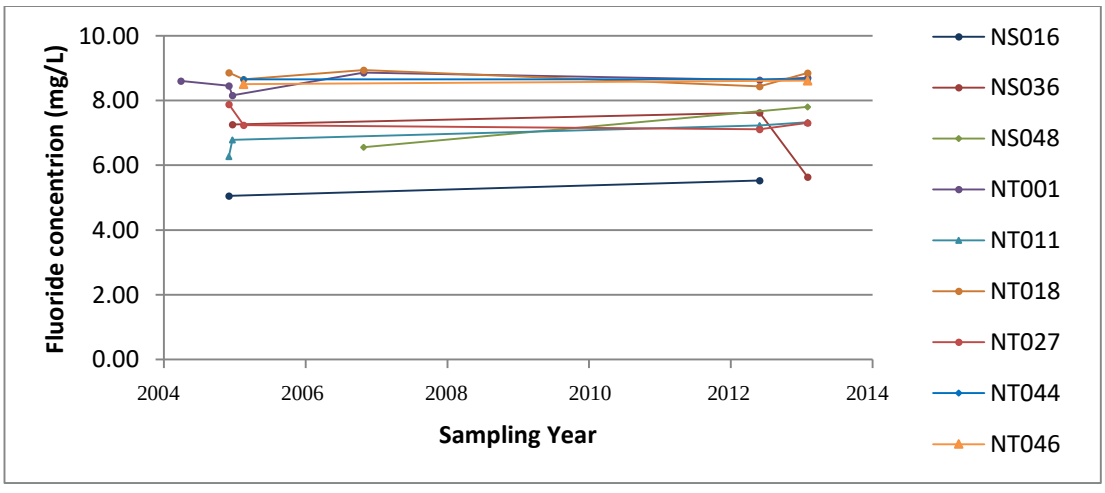


Figure 4.1: Temporal variation in F^- concentrations of hot springs in Ninh Hoa district.

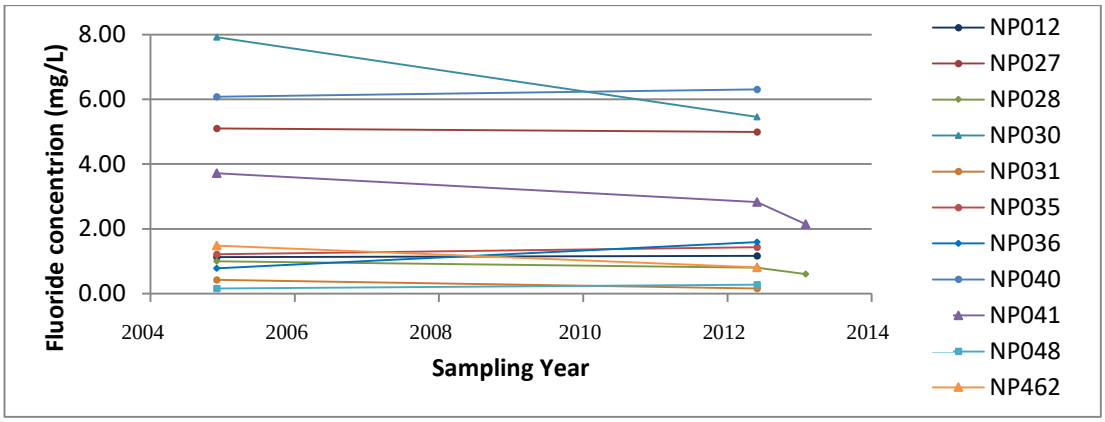


Figure 4.2: Temporal variation in F^- concentrations of selected wells in Ninh Phung commune.

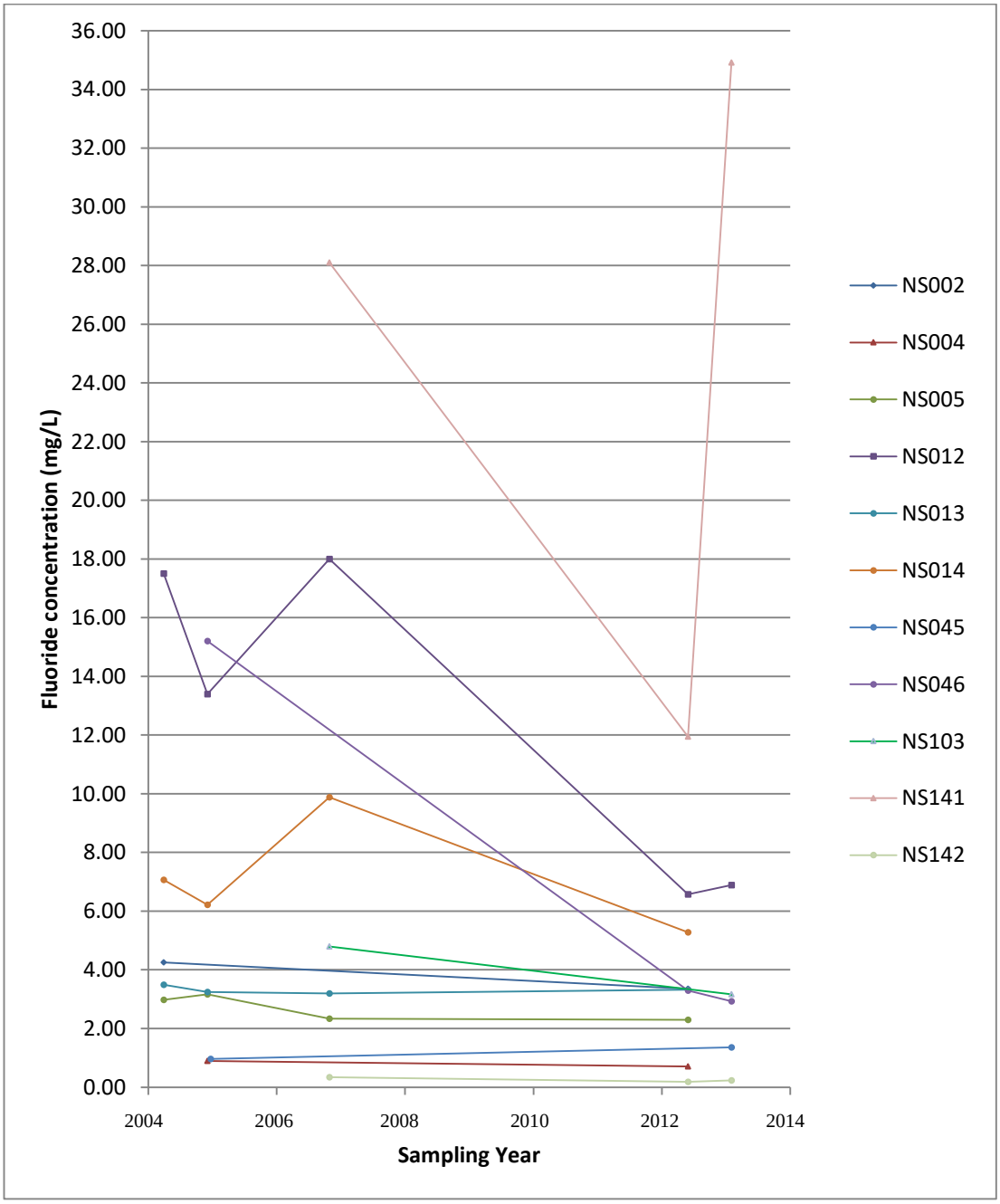


Figure 4.3: Temporal variation in F^- concentrations of selected wells in Ninh Sim commune.

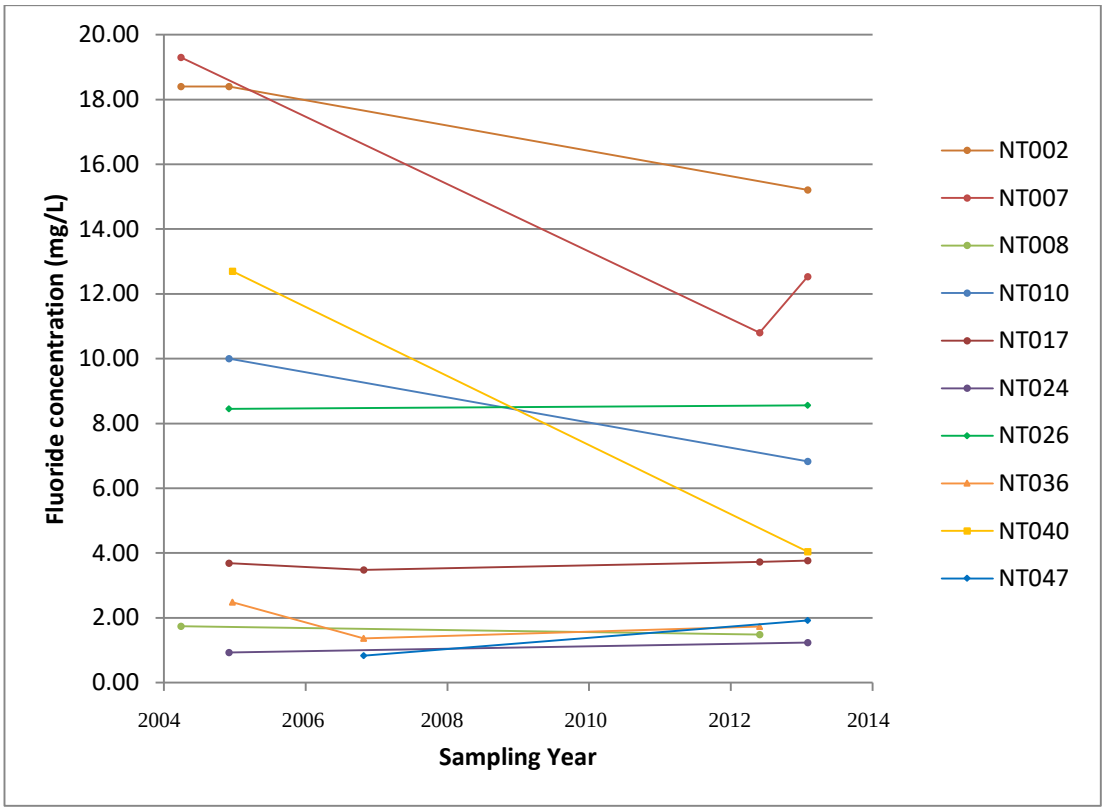


Figure 4.4: Temporal variation in F^- concentrations of selected wells in Ninh Tay commune.

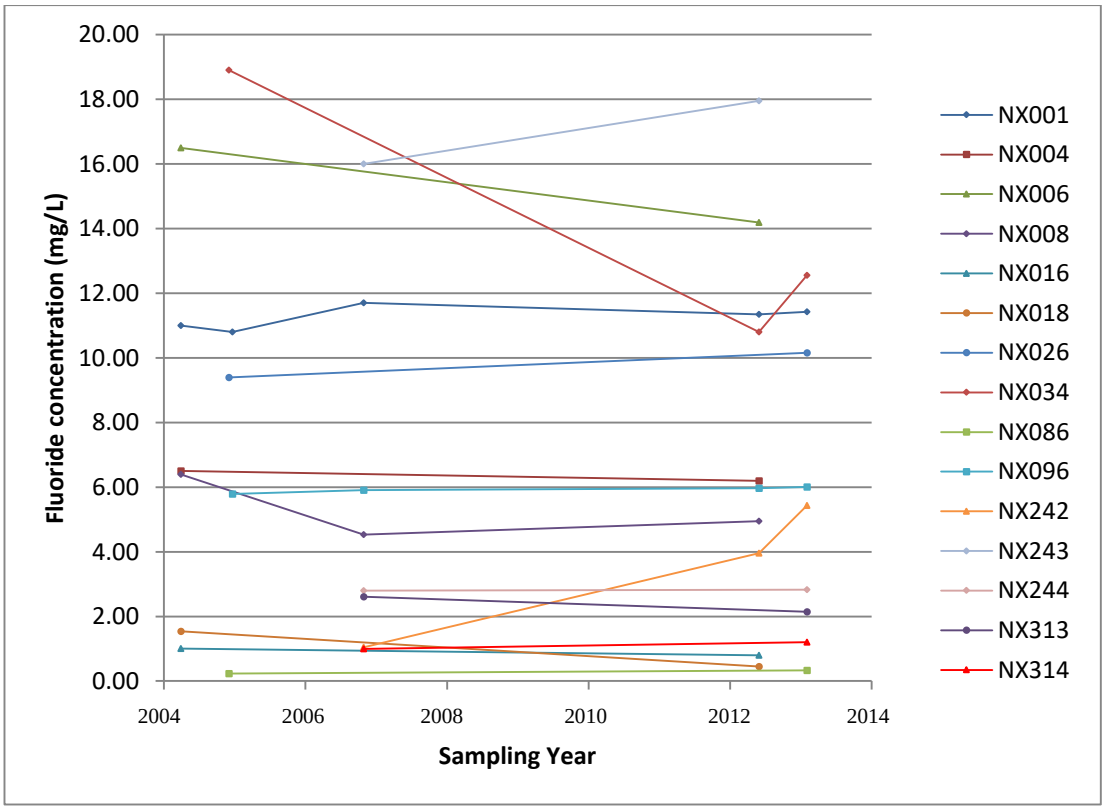


Figure 4.5: Temporal variation in F^- concentrations of selected wells in Ninh Xuan commune.

4.1 Statistical Analysis

To avoid confusion between a statistical sample, i.e. a subset of a population, and a well sample, all statistical samples will be referred to as a data set.

Before preforming statistical analyses on the results from the two studies, limitations of the data must be considered. Firstly, not all of the same wells had been sampled in each of the sampling periods, which are grouped into months in Table 4.1. Secondly, not all of the wells had been sampled at the same time of the year in the previous study, and therefore care must be taken as seasonal variation may distort the results. Even though Vu (2008) found that only a small percentage of samples underwent a significant change between different seasons, for statistical purposes possible seasonal changes need to be accounted for. Sampling in Ninh Hoa district during the present study, was restricted to two brief periods and the objective was not a detailed investigation, but rather a small opportunistic comparative study. This was made possible due to the relatively close proximity of Ninh Hoa to the main study area in Dong Xuan province.

These limitations were addressed by considering the amount of rainfall and the average monthly temperatures that were recorded in the months of sampling, and also in the months leading up to the time of sampling. Table 4.2 shows the monthly rainfall recorded in the years of the two studies. From the table, the wells that were sampled by Vu (2008) in December 2004 had experienced broadly similar rainfall in that month (48mm) to when the same wells were sampled in June 2012 in this study (24mm). Furthermore, as shown in Table 4.2 (highlighted in red), the four months leading up to both of the samplings had very similar monthly rainfalls recorded for both. These similarities of rainfall would enable a direct comparison between the data sets of these two months. As similar comparison between the other months in which sampling took place is unviable due to differing rainfall in those months, only these two months were used for comparisons. Having a tropical climate, the temperatures in Ninh Hoa varied little and as can been seen from Table 4.3 the temperature differences were approximately 5°C. It seems unlikely this small temperature difference would barely have affected infiltration rates.

Table 4.2: Ninh Hoa monthly rainfall (mm). Refer to text for red highlights.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2004	19	2	3	8	164	117	58	49	116	141	82	48
2005	6	0	38	3	0	32	42	11	258	487	355	567
2012	99	28	119	149	92	24	151	30	445	140	370	35
2013	23	5	0	8	9	139	89	58	144	60	617	5

Table 4.3: Ninh Hoa average monthly temperature (°C).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2004	24.2	23.9	25.9	28.1	28.6	28.9	28.4	29.3	28.3	25.6	26.4	24.4
2005	23.4	25.2	25.2	27.3	28.9	29.7	29.1	29.5	28.1	27.3	26.6	24.2
2012	24.0	24.6	25.0	26.5	28.5	28.8	28.1	28.6	28.7	26.9	26.4	24.4
2013	24.4	25.0	26.5	27.7	28.8	29.8	29.3	29.6	27.8	27.2	27.1	26.4

Table 4.4: Wells that were mutually sampled in December 2004 and June 2012, and used for statistical analysis.

Sample	Dec-04	Jun-12
NP012	1.12	1.16
NP027	5.10	4.99
NP028	1.00	0.80
NP028A	6.90	1.27
NP030	7.92	5.46
NP031	0.42	0.15
NP035	1.21	1.43
NP036	0.78	1.59
NP040	6.08	6.31
NP041	3.72	2.83
NP048	0.15	0.27
NP462	1.48	0.81
NS005	3.17	2.30
NS012	13.40	6.57
NS013	3.24	3.32
NS014	6.22	5.28
NS046	15.20	3.29
NT017	3.69	3.73
NT036	2.48	1.73
NX001	10.80	11.35
NX034	18.90	10.80
NX096	5.79	5.97

Table 4.4 shows the wells that used for the statistical comparison test, which were wells that were sampled in both December 2004 (Vu, 2008) and in June 2012 (this study). As already stated, even though more wells were sampled during these months, only the 22 wells that were mutually sampled were included in the comparison.

As the two data sets comprise results from the same sampled wells, a related-samples test was used. However, the differences between the two data sets were tested for normality and were found not to be normally distributed; therefore, application of the t-test was unsuitable. Instead, a non-parametric test was used and owing to the small sample size (< 25) the related-samples sign test was chosen over the Wilcoxon test (A. Darcy-Warmington *pers. comm.*).

The related-samples sign test was performed using the statistical program SPSS. If the two sets of data come from the same population then the population mean difference between the two should be zero. Testing the null hypothesis that the population mean differences of F^- in the sampled wells in December 2004 and June 2012 is equal to zero, against the alternative hypothesis that the population mean differences are different at the 5% significance level gave a p-value of 0.5235. As the p-value is greater than 0.05, the null hypothesis is not rejected as there is insufficient evidence to suggest that the population mean differences of F^- in the sampled wells are different at the 5% significance level. SPSS test summary and statistics are listed in Tables 4.5 and 4.6, respectively.

Table 4.5: Test summary as generated by SPSS.

Hypothesis Test Summary

Null Hypothesis	Test	Sig.	Decision
The median of differences between Dec 2004 and June 2012 equals 0.	Related-Samples Sign Test	0.5235	Retain the null hypothesis.

The exact p-value is computed based on the binomial distribution because there are 25 or fewer cases.

Table 4.6: Test statistics as generated by SPSS.

Total N	22
Test Statistic	9.000
Standard Error	2.345
Standardised Test Statistic	-0.640
Asymptotic Sig. (2-sided test)	0.522
Exact Sig. (2-sided test)	0.523

5 RESULTS OF DONG XUAN STUDY

5.1 Overview

A total of 384 wells in Dong Xuan district were sampled and analysed for F^-. Of these, 253 were sampled during the first field visit and the remaining 131 were collected from the second. A total of 209 samples (54%) were transported to Perth for further anion and cation analysis by HPIC. Figure 5.2 shows the sampled well locations in Dong Xuan district. The following sections in this chapter present the results from the various analytical methods performed, i.e. FISE for F^-, HPIC for major ions and ICP-OES for trace metals.

5.2 Fluoride Ion Selective Electrode

All samples were analysed for F^- by FISE and the results are presented in Appendix A. Figure 5.1 shows a detailed histogram of F^- concentration from the sampled well of Dong Xuan.

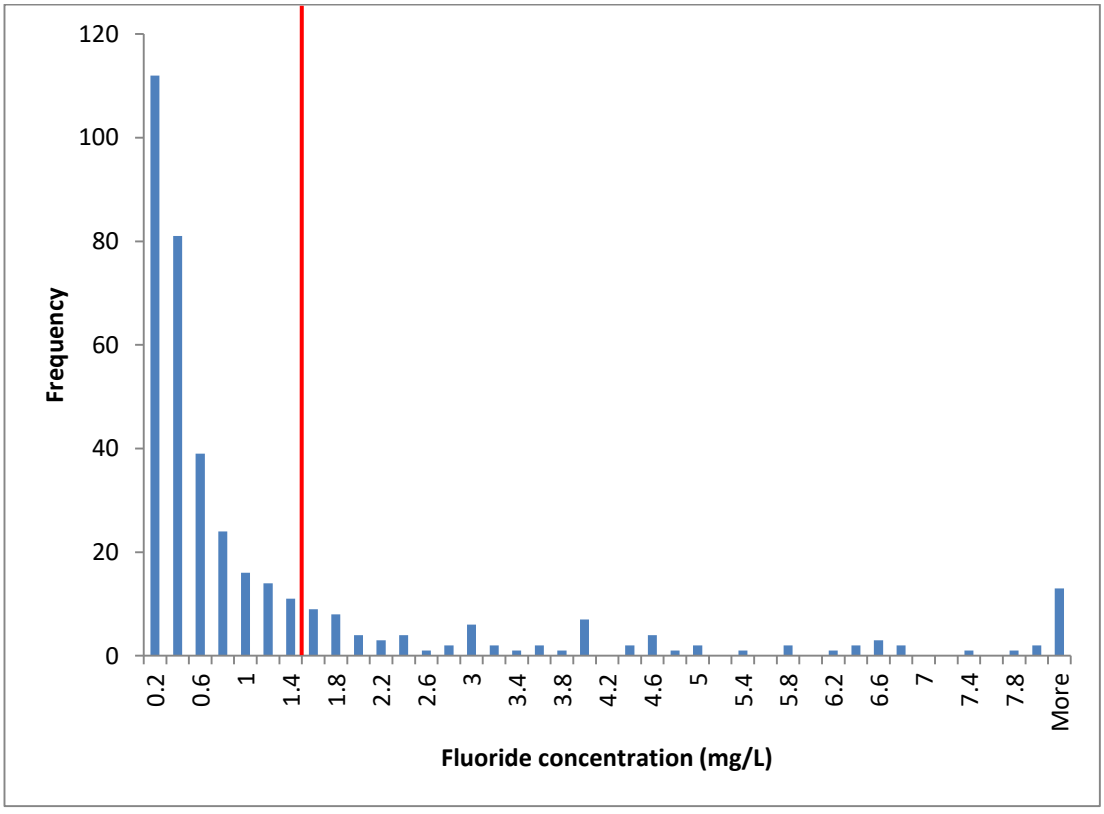


Figure 5.1: Histogram of fluoride concentrations in sampled wells of Dong Xuan district. Red line indicates WHO guideline value.

Owing to the high density sampling that was performed in some areas that had high F^- containing wells, caution must be taken when considering the overall proportion of wells that were over the WHO guideline value of 1.5 mg/L F^-. This high-density sampling would have biased the percentage towards the high F^- containing wells. When the extra wells that were sampled in the high F^- areas because of the high-density sampling are excluded, 19.5% of wells measured in Dong Xuan were over the 1.5 mg/L F^- WHO guideline value.

On each sampling day of the second fieldtrip, one well that had been sampled during the first fieldtrip was re-sampled. Usually a well bearing high F^- water was chosen, and every commune had at least one of its wells re-measured. The only exception was the commune of Da Loc, which was not sampled during the second fieldtrip having been exhaustively sampled during the first trip. Table 5.1 shows the two recorded values obtained from each well that was sampled during both fieldtrips, and their relative percent difference (RPD).

Table 5.1: Fluoride concentrations in groundwater (mg/L) recorded in 13 wells that were sampled during both fieldtrips.

Well	1st Trip	2nd Trip	RPD
LHA05	7.03	6.91	1.7
PHM04	2.24	0.30	152.8
XLN09	3.89	3.96	1.7
XLN25	3.86	7.38	62.6
XLG01	19.28	19.19	0.5
XLG03	3.34	1.13	98.9
XPU42	7.97	7.70	3.4
XQA04	4.55	4.59	0.9
XQB02	20.67	20.87	1.0
XQB08	12.48	6.64	61.1
XSB02	1.63	1.43	13.1
XSN08	4.51	4.05	10.7
XSN09	7.05	7.47	5.8

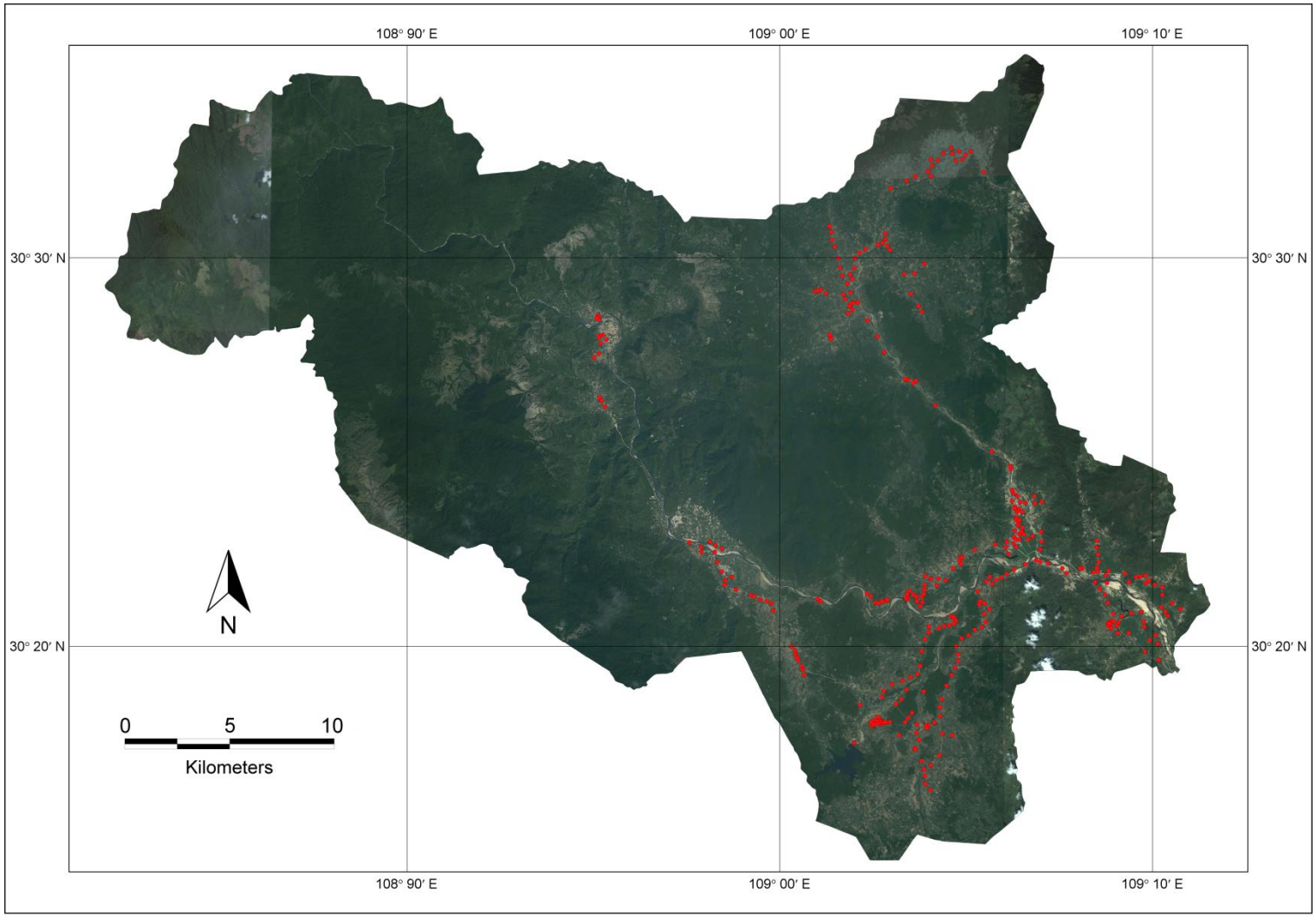


Figure 5.2: Sampled well locations in Dong Xuan district shown by red dots. (Imagery from Google Earth)

Although the study in Dong Xuan was not one of temporal comparison, it was instructive to compare the F^- concentration in water from the wells sampled six-months apart. As can be seen from Table 5.1, nine out of the thirteen re-sampled wells (69%) showed similar concentrations (RPD < 20%). The remaining wells had RPDs > 60%. These differences are discussed further in section 7.3.

5.3 High Performance Ion Chromatography

5.3.1 Quality of Analysis

Various methods can be used to measure the quality of a geochemical analysis. In the case of water, an ion balance test is usually performed. As water is electrically neutral, the anionic (-ve) and cationic (+ve) charges should balance. Other tests include comparing the measured electrical conductivity to that calculated from the sum of measured ions in solution.

Ion Balance

When determining the charge balance the sum of the anions and cations are expressed as milliequivalents per litre (meq/L), which can simply be considered as electrical charge per volume. As all aqueous solutions are electrically neutral, these charges should balance to within an accepted analytical error. The accepted method for calculating the percent difference between anions and cations is given by the formula (Eaton 2005):

$$\%\, difference = \frac{\Sigma cations\ -\ \Sigma anions}{\Sigma cations\ +\ \Sigma anions} \times 100$$

In this study, $\Sigma\, cations = [Na^+] + [K^+] + [Mg^{2+}] + [Ca^{2+}]$

$$\Sigma\, anions = [F^-] + [Cl^-] + [Br^-] + [NO_3^-] + [PO_4^{3-}] + [SO_4^{2-}] + [HCO_3^-]$$

All ionic species were determined by HPIC, except bicarbonate (HCO_3^-), which was calculated from an alkalinity titration.

Various acceptance limits of the percent difference have been suggested (Johnson *et al.* 1979; Eaton 2005). The limit of 5% suggested by Eaton (2005) was adopted for

this study. Only 60% of water sample analyses fell within this level. Johnson *et al.* (1979) encountered similar errors and suggested that high percent differences may result from limitations of the alkalinity titration, which is used to determine bicarbonate (HCO_3^-). Various forms of silica can have an effect on the titration and Johnson *et al.* concluded that alkaline waters containing measurable amounts of silica can show an excess of anions. This may be a possible explanation in the case of the Dong Xuan waters considering many of the samples are alkaline. The 49 samples that were analysed for trace elements showed that significant silica was present with an average concentration of 14.4 mg/L Si, with a standard deviation of 6.1 mg/L. In Figure 5.3, it can been seen that there is a bias towards excess anions, with sum of anions about 8% higher than the sum of cations – a clear excess of anions as discussed by Johnson *et al.* (1979).

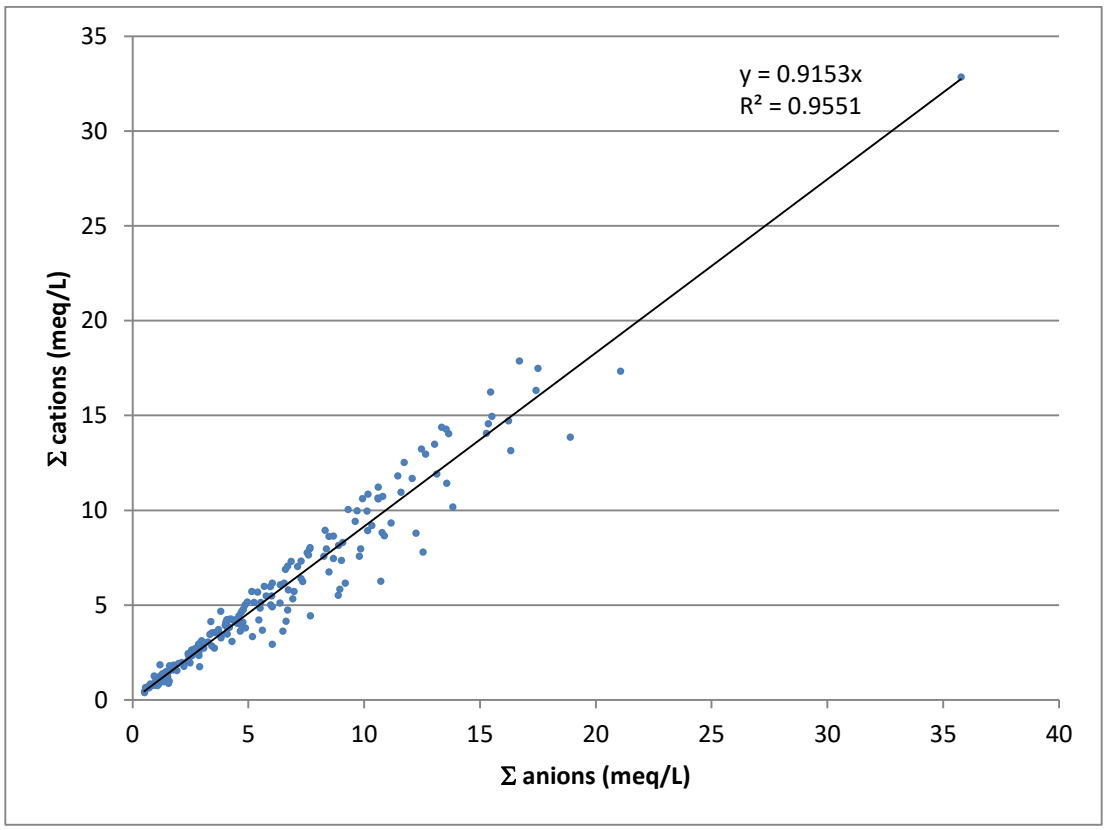


Figure 5.3: Comparison of cation and anion balances.

However, a balanced charge does not necessarily indicate that the analysis is error free and does not indicate which ion concentration is in error, if any. Electrical conductivity (EC) reflects the total charge imparted by dissolved cations and anions, and can thus provide a useful guide to the accuracy of the anion and cation analyses.

Generally, the relationship between cations, anions and electrical conductivity (EC) is expressed as follows (*Environment Testing* n.d.):

anions (meq/L) = cations (meq/L) = approx. EC (mS/m)

Figure 5.4 shows the anions to have a good correlation with the measured EC. However, when the cations are similarly plotted in Figure 5.5, there is a poorer correlation with a bias to low cations. This would suggest that apart from an alkalinity titration error, as mentioned by Johnson *et al.* (1979), another discrepancy could be due to limited number of cations (four) being analysed by HPIC. This would support the low bias seen in the correlation of cations to measured EC (Figure 5.5). Furthermore, this study is more reliant on the quality of the anion analysis, and the cation analysis is only used for general water classification and quality purposes.

Calculated Electrical Conductivity

Another method to test for analytical quality is to compare the measured and calculated electrical conductivities. There are various methods for calculating electrical conductivities in natural water based on their chemical composition. However, as discussed by McCleskey *et al.* (2012), many do not account for ion pairing, such as with divalent cations pairing with SO_4^{2-}. This is particularly pronounced at ionic concentrations above 50 mg/L. Many samples from Dong Xuan had concentrations well in excess of this. Furthermore, McCleskey *et al.* (2012) highlighted that these methods do not account for ionic speciation, to which conductivity can be very sensitive.

Furthermore, McCleskey *et al.* (2012) developed a newer method, which uses the USGS speciation program WATEQ4F version 4, to account for ion pairing and the speciation of ions. The method is applicable over wide ranges of pH, temperature, conductivity and ionic strength. Using this newer method, a good correlation of R^2 = 0.9589 is achieved for the Dong Xuan well waters as illustrated in Figure 5.6.

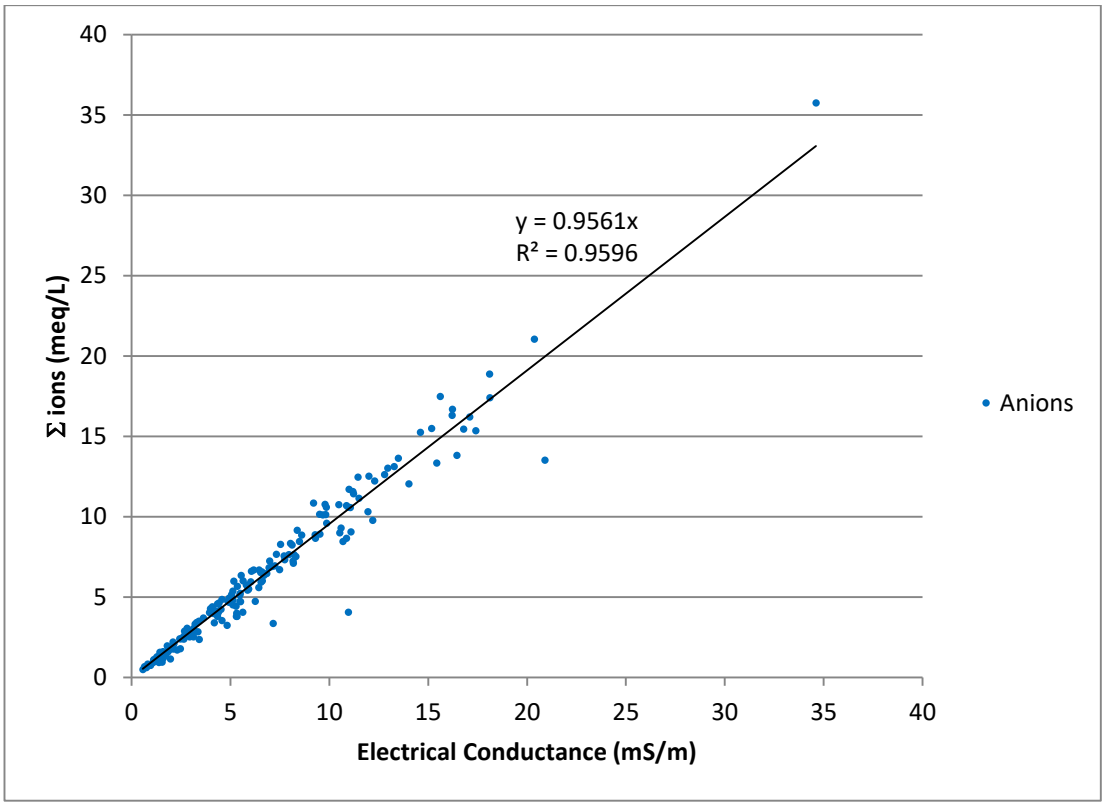


Figure 5.4: Anion balance compared to electrical conductivity.

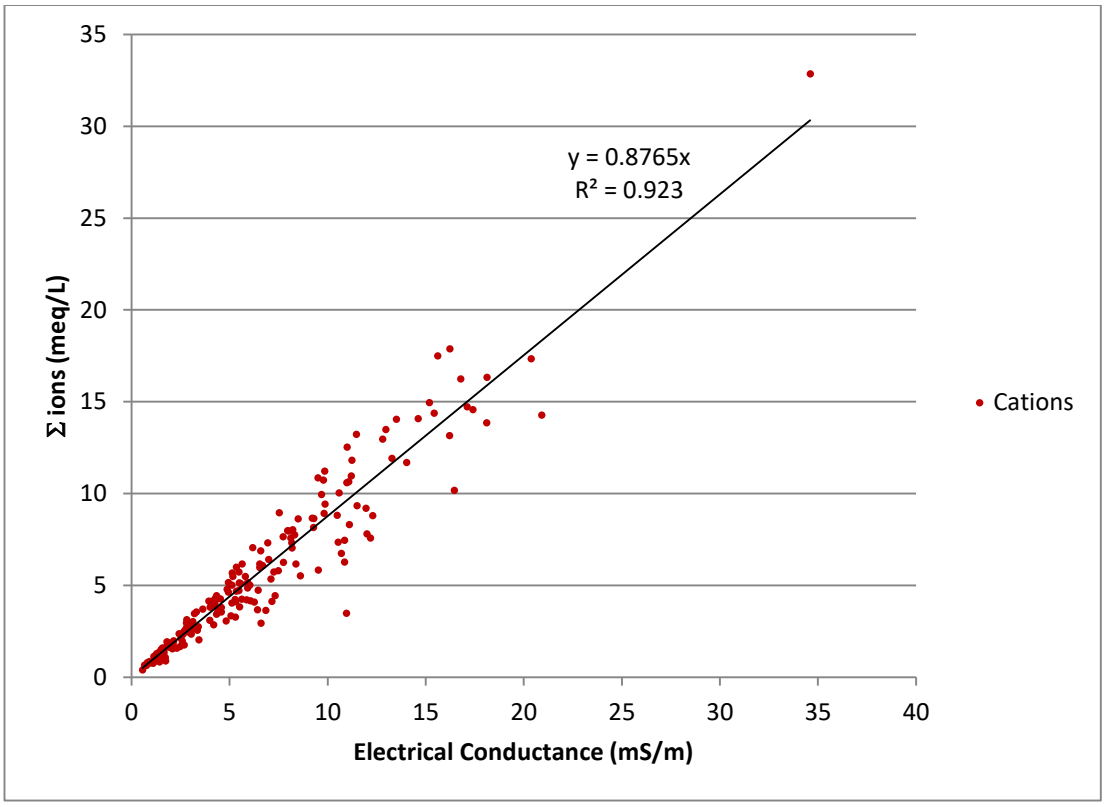


Figure 5.5: Cation balance compared to electrical conductivity.

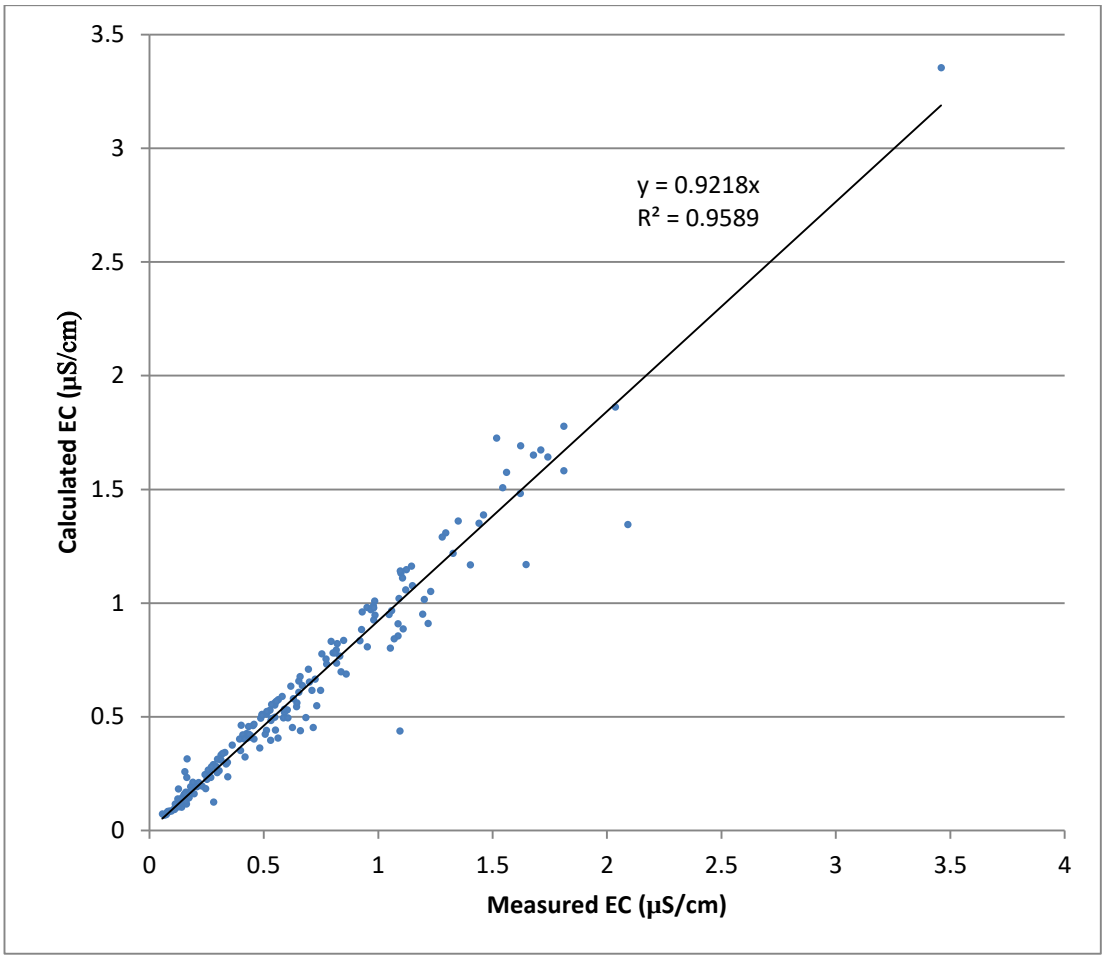


Figure 5.6: Relationship of measured EC calculated EC by method of McCleskey *et al.* (2012).

5.4 Comparison of Results between FISE and HPIC

Just over half (54%) of all samples analysed in Dong Xuan using FISE were returned to Perth for anion and cation analysis by HPIC. The F^- concentrations that were obtained from both the HPIC and FISE analyses are presented in Figure 5.7. There is a good correlation between the two methods with an R^2 value of 0.998. When compared with the results obtained by Vu (2008) (Figure 5.8), a better correlation with less outliers was obtained from this study; however, the study by Vu was a larger study and analysed 834 samples. Even though both studies used similar HPIC and FISE equipment, the FISE procedure was different. The method employed by Vu did not include a one minute wash between samples but rather a rinse of the probe with distilled water (T. Vu *pers. comm.*) As discussed earlier, this would create a significant hysteresis effect when measuring samples with marked differences in F^- concentrations, especially those with low concentrations. The

method used in the current study incorporated a one-minute TISAB wash (discussed in section 3.4.1), which was shown to reduce the hysteresis effect.

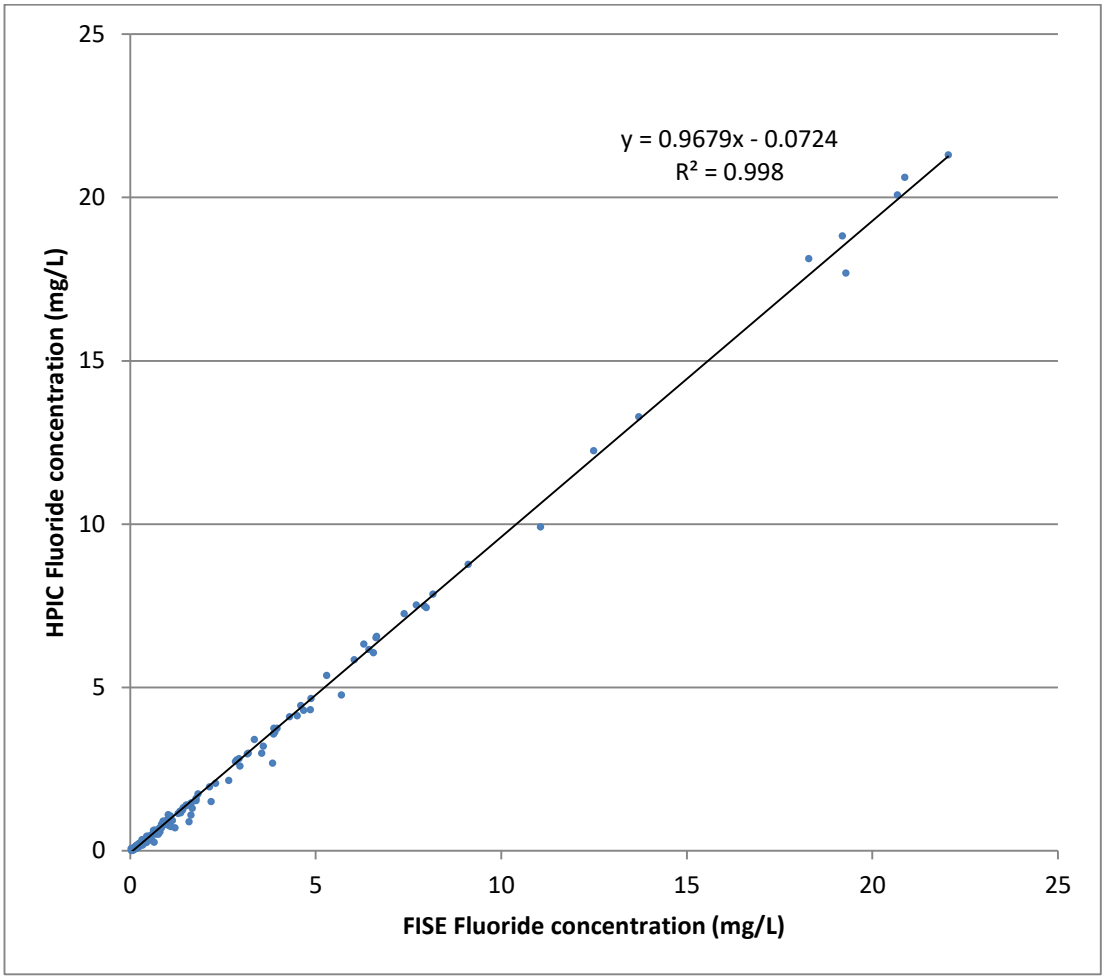


Figure 5.7: Comparison between F^- concentrations obtained by FISE and HPIC for 209 samples of Dong Xuan well waters.

The logarithmic plots of Figures 5.9 and 5.10 show the low-level response of F^- concentration to mV potential. The dispersion of plots below 0.5 mg/L F^- is clearly apparent, which is expected due to the higher percent error inherent in both FISE and HPIC methods. Importantly, it can be seen that the dispersion trends downward slightly. This could indicate a slight negative bias for the FISE analyses when compared to analyses performed using HPIC.

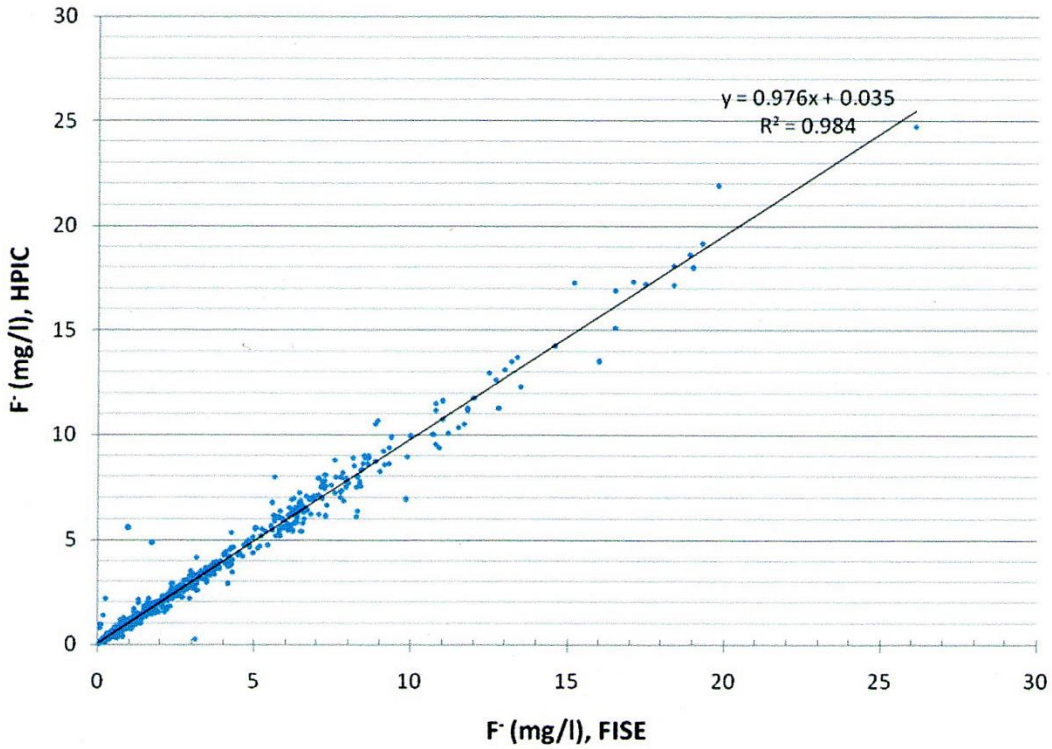


Figure 5.8: Comparison between F^- concentrations obtained by FISE and HPIC for 834 samples, Vu (2008).

When the HPIC results are compared to the FISE results where a standard calibration with just two calibration points between 1 and 10 mg/L has been used, a strong bias at low concentrations is observed (Figure 5.10). This conforms to the expected outcome, as discussed previously and shown in Figure 3.1, that at low concentrations the relationship between ion activity and mV response is non-linear. The two in one calibration employed in the present study has to a large extent, corrected low-end non-linear bias. However, due to the precision and the small differences between the concentrations at these low levels, the two in one calibration is only useful when a high importance is placed in the accuracy of low-level concentrations. For concentrations above 0.5 mg/L F^-, the standard two point calibration will suffice. Most importantly, it is the use of the TISAB wash between samples that markedly improves accuracy when analysing low and high F^- samples.

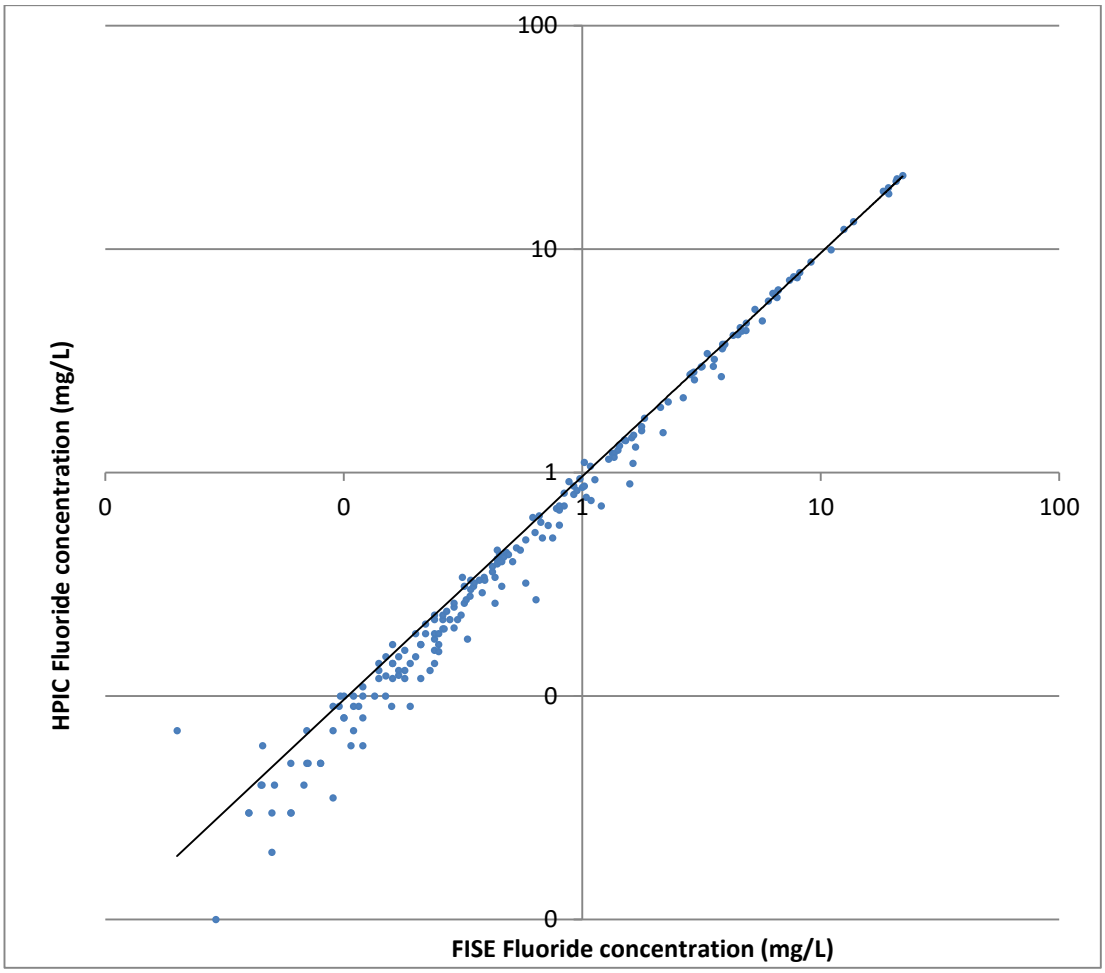


Figure 5.9: Logarithmic plot of comparison between F^- concentrations obtained by FISE and HPIC

Furthermore, as observed in this comparison, care needs to be taken when using the FISE as a tool for determining safe drinking water. Although the FISE and HPIC produced closely equivalent results, care needs to be given to their interpretation. As hysteresis has a greater effect at lower concentrations of F^-, it is this range, which is most critical for determining safe drinking water (1.0 – 1.5 mg/L), that is most likely to be affected. This makes using a TISAB wash between samples as used in this study essential, despite the increase in analysis time. Most importantly, using this new FISE method can provide a cheaper alternative than the higher costs of the HPIC instrumentation and also has the advantage that the FISE is versatile in its portability for determining F^-, while still producing results that have good accuracy.

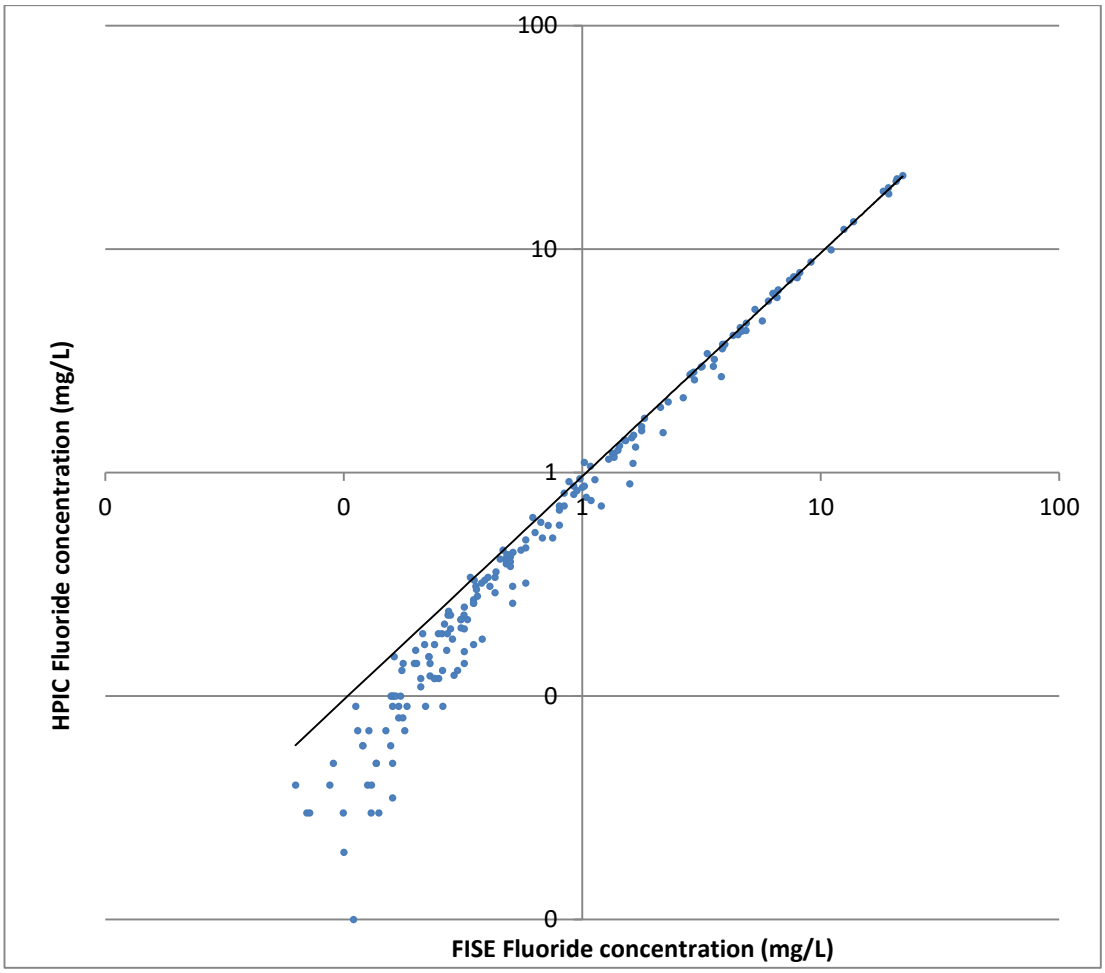


Figure 5.10: Logarithmic plot of HPIC and FISE with a standard calibration.

5.5 Chemical Modelling

Fluoride forms a number of complexes with various elements, particularly aluminium, iron and beryllium, due to its high electronegativity (Handa 1975). The USGS geochemical speciation software PHREEQC version 3 was used in this study to predict the speciation of F^- in the groundwater. The 48 water samples that were analysed for trace metals were modelled and the results are shown in Table 5.2. According to the PHREEQC modelling, an average of 96.7% of F existed in its free ion state (F^-). The maximum percentage for the free ion in individual water samples was 99.7% and the lowest was 89.4%.

Table 5.2: Speciation of fluorine in well samples as predicted by PHEEQC.

Sample	pH	% F^-	% MgF^+	% NaF	% CaF^+	% HF	% MnF^+	% FeF^+	% AlF^{+2}	% AlF_2^+	% AlF_3	% AlF_4^-
DLC03	6.55	97.27	2.33	0.08	0.27	0.04	0.00	0.00	0.00	0.00	0.00	0.00
DLC10	6.48	94.86	3.69	0.06	1.35	0.04	0.00	0.00	0.00	0.00	0.00	0.00
LHA11	6.22	97.34	1.93	0.10	0.55	0.09	0.00	0.00	0.00	0.00	0.00	0.00
LHA22	6.80	94.50	4.50	0.10	0.88	0.02	0.00	0.00	0.00	0.00	0.00	0.00
LHA28	5.62	87.25	0.17	0.02	0.08	0.33	0.00	0.00	0.30	7.81	3.99	0.06
LHA37	6.02	97.28	2.12	0.05	0.37	0.14	0.04	0.00	0.00	0.00	0.00	0.00
LHA38	6.09	99.00	0.64	0.02	0.15	0.12	0.06	0.00	0.00	0.00	0.00	0.00
PHM06	6.46	98.76	0.62	0.04	0.53	0.05	0.00	0.00	0.00	0.00	0.00	0.00
PHM11	6.69	98.64	0.48	0.04	0.81	0.03	0.00	0.00	0.00	0.00	0.00	0.00
PHM13	5.68	99.35	0.09	0.01	0.07	0.31	0.17	0.00	0.00	0.00	0.00	0.00
XLG01R	8.98	99.72	0.00	0.19	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00
XLG08	5.94	98.95	0.69	0.03	0.16	0.18	0.00	0.00	0.00	0.00	0.00	0.00
XLG15	6.06	98.99	0.65	0.04	0.15	0.13	0.04	0.00	0.00	0.00	0.00	0.00
XLN05	7.43	96.14	2.84	0.27	0.74	0.01	0.00	0.00	0.00	0.00	0.00	0.00
XLN40	7.00	91.80	5.61	0.26	1.02	0.01	1.30	0.00	0.00	0.00	0.00	0.00
XLN45	5.99	98.35	1.05	0.04	0.38	0.15	0.03	0.00	0.00	0.00	0.00	0.00
XPU01	7.35	96.23	2.70	0.28	0.77	0.01	0.00	0.00	0.00	0.00	0.00	0.00
XPU02	7.25	97.24	1.90	0.19	0.66	0.01	0.00	0.00	0.00	0.00	0.00	0.00
XPU11	6.96	96.43	2.94	0.11	0.43	0.01	0.07	0.00	0.00	0.00	0.00	0.00
XPU14	6.88	96.75	2.74	0.07	0.41	0.02	0.00	0.00	0.00	0.00	0.00	0.00
XPU19	7.03	99.15	0.07	0.01	0.30	0.01	0.00	0.00	0.16	0.28	0.01	0.00
XPU35	6.96	95.35	3.90	0.09	0.64	0.02	0.00	0.00	0.00	0.00	0.00	0.00
XPU39	6.96	93.96	5.31	0.23	0.48	0.01	0.00	0.00	0.00	0.00	0.00	0.00
XPU45	7.53	94.10	5.08	0.32	0.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00
XPU53	6.61	92.42	6.07	0.17	1.31	0.03	0.00	0.00	0.00	0.00	0.00	0.00
XPU55	7.84	97.37	1.35	0.06	0.47	0.00	0.75	0.00	0.00	0.00	0.00	0.00
XQA06	5.67	99.17	0.37	0.02	0.11	0.34	0.00	0.00	0.00	0.00	0.00	0.00
XQA23	5.15	97.75	0.30	0.03	0.11	0.94	0.87	0.00	0.00	0.00	0.00	0.00
XQA24	5.47	98.58	0.33	0.02	0.17	0.49	0.40	0.00	0.00	0.00	0.00	0.00
XQB02R	8.62	99.59	0.00	0.28	0.12	0.00	0.01	0.00	0.00	0.00	0.00	0.00
XQB08	7.72	99.10	0.53	0.19	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00
XQB08R	7.05	94.28	0.56	0.19	0.22	0.01	0.06	0.00	0.00	0.66	3.42	0.59
XQB15	7.69	99.01	0.62	0.08	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00
XQB18	7.65	96.57	2.34	0.57	0.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00
XQB30	8.24	99.09	0.37	0.35	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00
XQC12	6.59	95.38	3.57	0.31	0.72	0.03	0.00	0.00	0.00	0.00	0.00	0.00
XQC20	6.92	98.05	1.10	0.09	0.74	0.02	0.00	0.00	0.00	0.00	0.00	0.00
XQC24	6.52	97.36	0.49	0.03	0.16	0.04	0.00	0.00	0.27	1.48	0.17	0.00
XQC28	7.28	86.36	13.09	0.28	0.21	0.01	0.05	0.00	0.00	0.00	0.00	0.00
XSB06	5.90	98.56	1.03	0.05	0.17	0.19	0.00	0.00	0.00	0.00	0.00	0.00
XSB16	6.41	98.82	0.81	0.09	0.21	0.06	0.00	0.00	0.00	0.00	0.00	0.00
XSB18	5.65	98.44	0.63	0.07	0.51	0.32	0.03	0.00	0.00	0.00	0.00	0.00
XSN01	6.03	97.73	1.78	0.08	0.28	0.13	0.00	0.00	0.00	0.00	0.00	0.00
XSN08R	4.05	87.56	0.34	0.02	0.03	11.88	0.16	0.00	0.00	0.00	0.00	0.00
XSN09	7.05	98.64	0.79	0.40	0.17	0.01	0.00	0.00	0.00	0.00	0.00	0.00
XSN11	6.50	97.41	2.08	0.10	0.36	0.05	0.00	0.00	0.00	0.00	0.00	0.00
XSN20	5.20	98.04	0.20	0.02	0.02	0.91	0.81	0.00	0.00	0.00	0.00	0.00
XSN22	5.40	98.83	0.39	0.06	0.04	0.59	0.09	0.00	0.00	0.00	0.00	0.00

From the results of the speciation modelling in the presence of Al^{3+}, pH has a large influence on the availability of free F^-. Well water sample LHA28 had a pH of 5.62 and only 0.05 mg/L Al^{3+}, yet 7.8% of the F^- was locked up in the AlF^{2+} complex (Table 5.2). Sample XPU19 had an unusually high Al^{3+} concentration of 3 mg/L, yet being at neutral pH it still maintained 99.2% of F^- in its free state with very little complexing with Al^{3+}. PHREEQC showed that F^- starts complexing with Al at pH values below 6.5 - 7, depending on the concentration of F^- and Al^{3+} in the water. Although many of the samples had pH below 6.5, 94% percent of samples had Al^{3+} concentrations below 0.05 mg/L and only one (XPU19) had Al concentration above 1 mg/L.

When high Mg concentrations were present in the groundwater, the percentage of free F^- was also lowered. XQC28 had an Mg concentration of 102 mg/L (the highest recorded) and 13% of the F^- in this sample was predicted to be as the MgF^- complex. PHREEQC showed that normal pH ranges (5 - 9) did not affect the distribution of F^- into the MgF^- complex, and instead formation of the MgF^- complex is dependent on the Mg concentration. The majority of samples had low Mg concentration with only 2% of analysed wells having concentrations over 50 mg/L. It is unlikely that Mg would have an appreciable affect the speciation of fluorine.

From the results of the speciation modelling, 94% of the 48 wells that had trace metal analyses performed on them had > 90% of the F^- in solution as the free ion. If this is a true statistical representation of the water occurring in wells in Dong Xuan, it may be concluded that nearly all of the wells will have fluorine dominantly present as free, dissolved F^- ions.

5.6 Classification of Groundwater

The groundwater was chemically classified using the water analysis software Aquachem®, and its composition plotted using Piper diagrams.

5.6.1 Piper Diagrams

The chemical nature of a water sample can be graphically represented by using a Piper diagram. The cation percentages are plotted on a Ca^{2+} - Mg^{2+} - (Na^+ + K^+)

ternary plot, while the anion percentages are plotted on a HCO_3^- - SO_4^{2-} - Cl^- ternary plot. The relative percentages of the cations and anions from each ternary plot are then projected onto a common diamond plot on which the main water types or hydrochemical facies are delineated (Figure 5.11). The advantage of the Piper diagram is that many water samples can be shown on the same plot, and therefore enabling easy comparison.

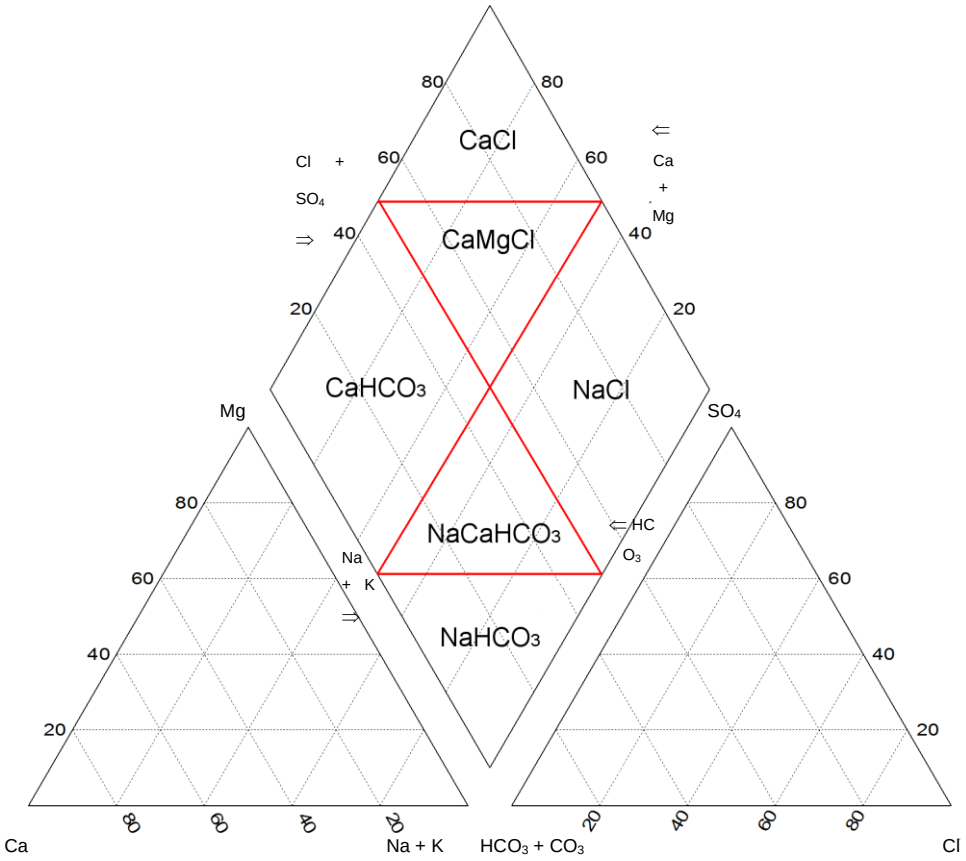


Figure 5.11: Water type classification (diamond plot) using the Piper diagram.

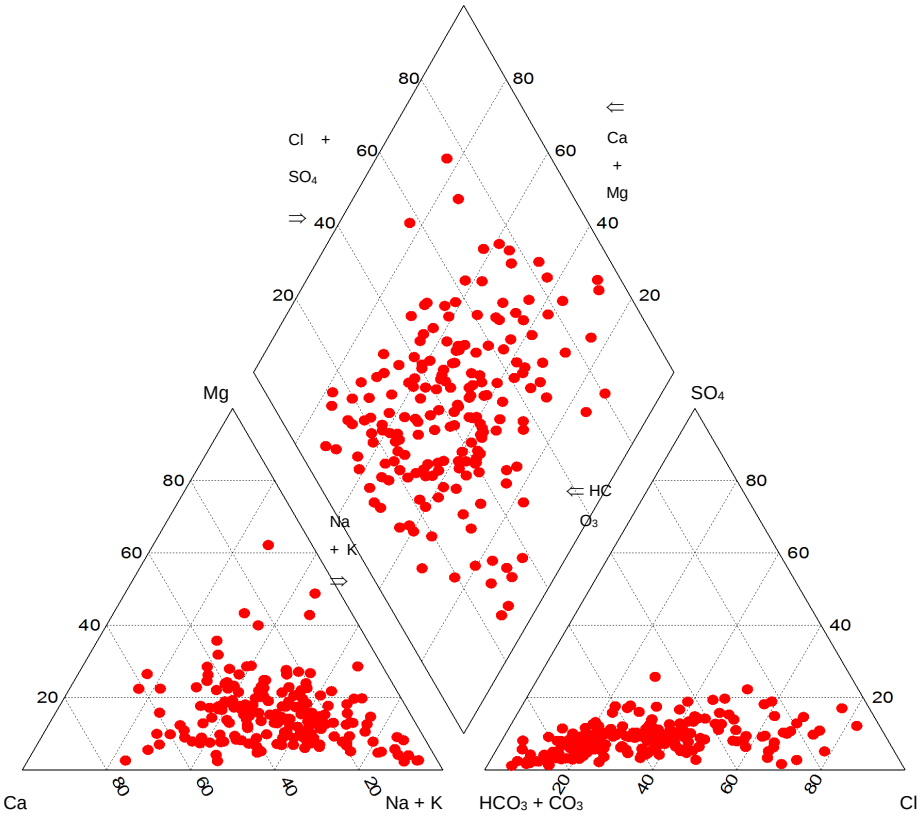


Figure 5.12: Piper diagram showing composition of all wells sampled from Dong Xuan district.

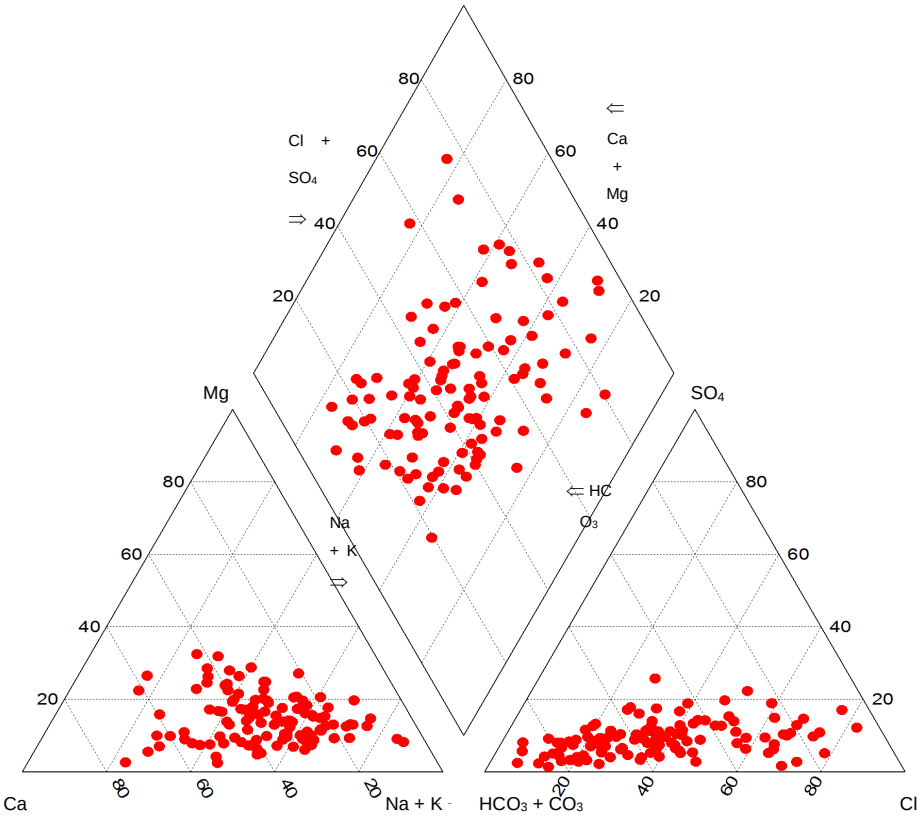


Figure 5.13: Piper diagram showing composition of wells containing 0 – 0.5 mg/L F^-

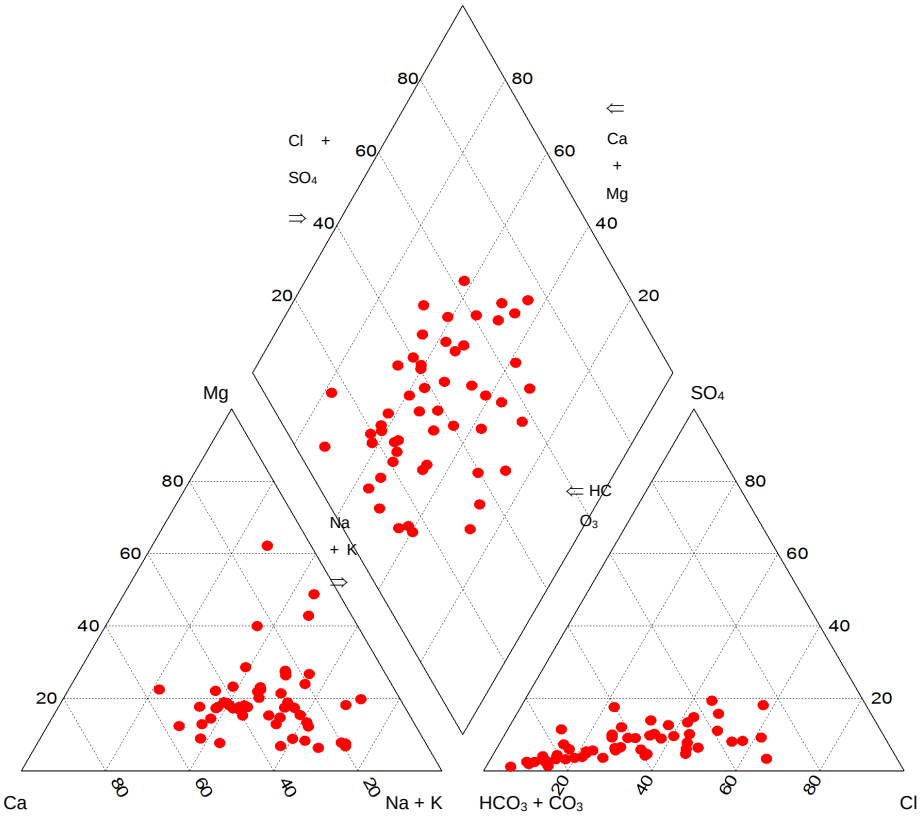


Figure 5.14: Piper diagram showing composition of wells containing 0.5 – 3.0 mg/L F^-.

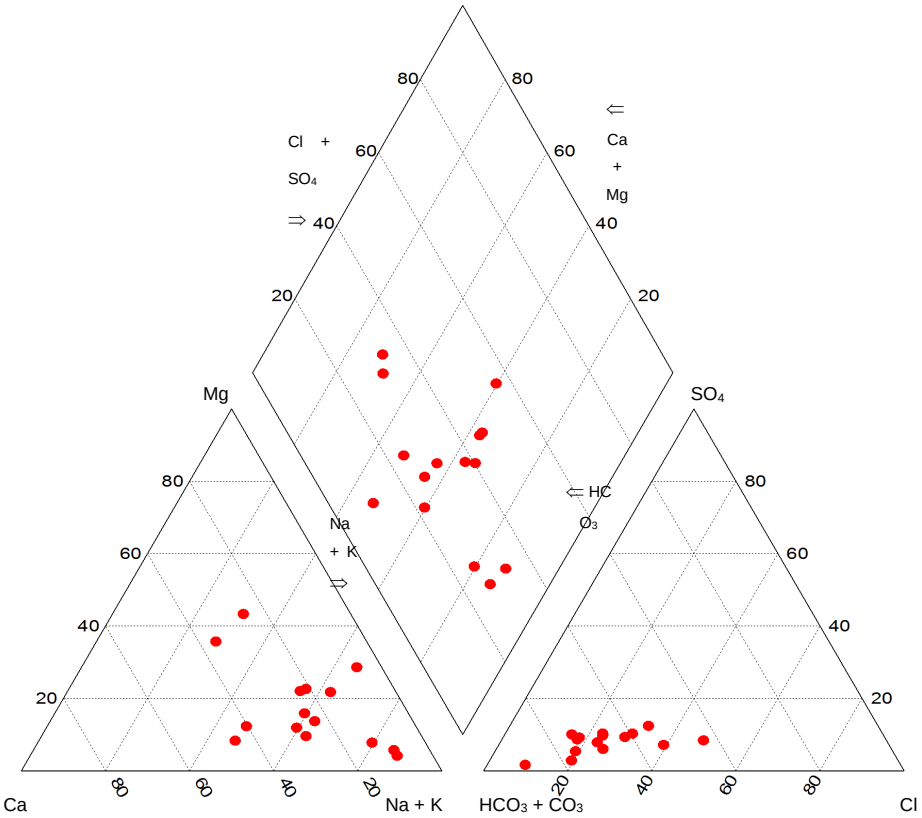


Figure 5.15: Piper diagram showing composition of wells containing 3.0 – 6.0 mg/L F^-.

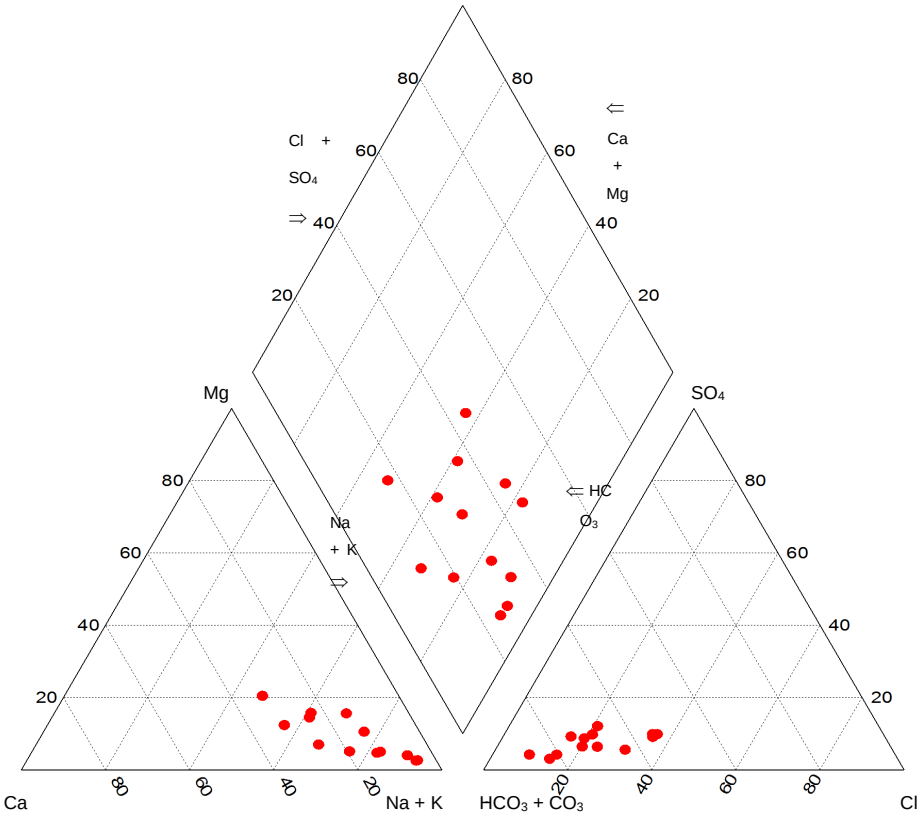


Figure 5.16: Piper diagram showing composition of wells containing 6.0 – 14.0 mg/L F^-.

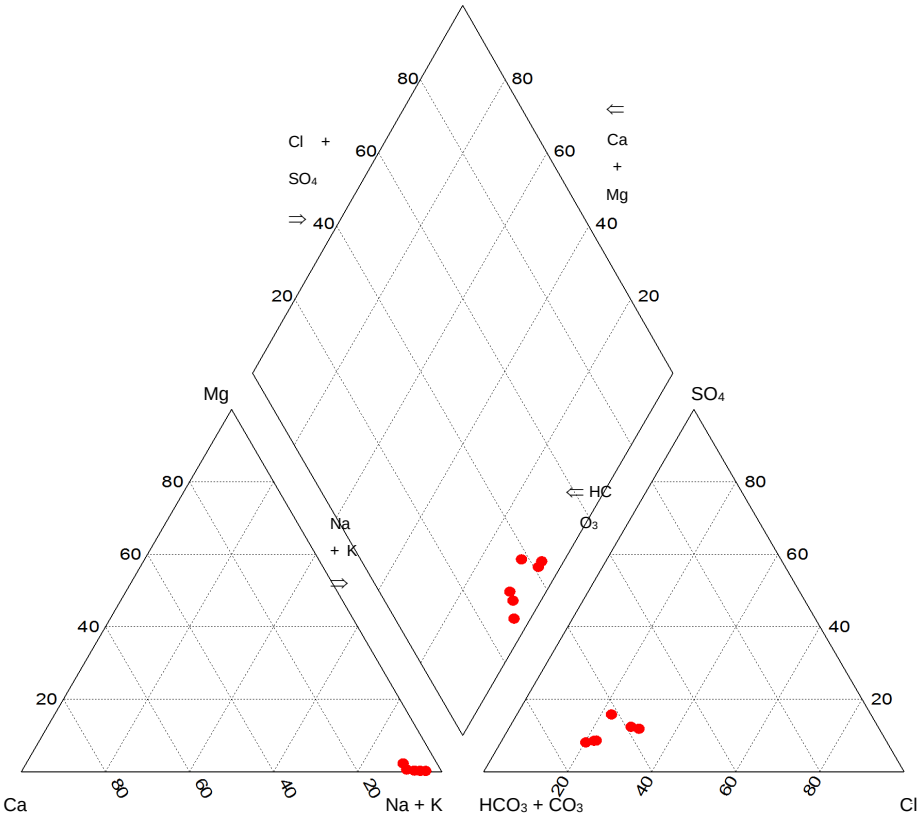


Figure 5.17: Piper diagram showing composition of hot springs.

From Figures 5.12 – 5.17, as the F^- concentration in the ground water increases, the water type becomes increasingly of the Na-Ca-HCO_3 and Na-HCO_3 types. Figure 5.17 shows the hot springs, which all had a F^- range between 19.19 and 20.67 mg/L, all plotted in the Na-HCO_3 region of the piper diagram.

5.7 Well Depth

The depth of the wells sampled from Dong Xuan district in this study ranged from 2 – 20 m. There was no correlation between well depth and F^- concentration (Figure 5.18).

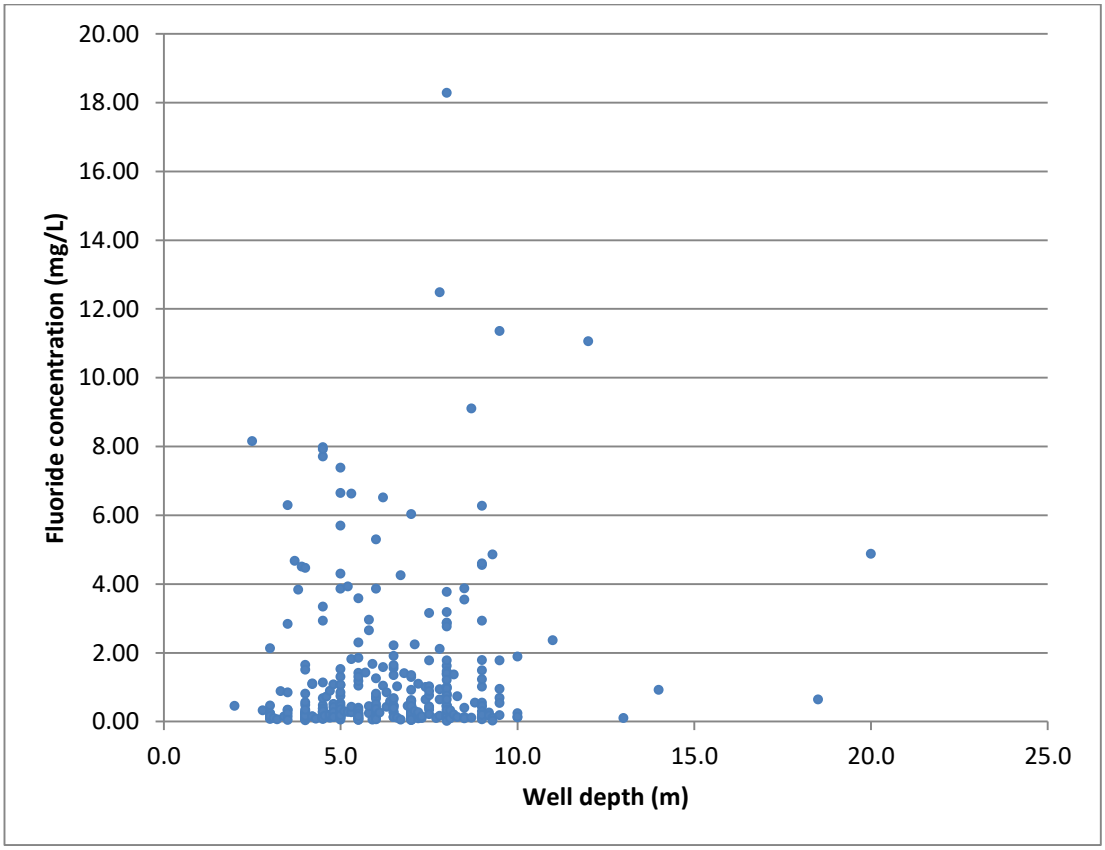


Figure 5.18: F^- concentration in relation to depth of wells in Dong Xuan district.

5.8 Major Ions and other Parameters

The WHO does not provide safe drinking water guideline values for substances that are not considered to present a health risk. However, the WHO does recognise the

importance of aesthetically pleasing water as objectionable water may discourage its use and even result in locals obtaining drinking water from other sources that may not be safe. For those substances that pose no health risk but can attribute to objectionable taste, odour and appearance, the WHO has provided values that may cause concern from consumers (Table 5.3). However, these values are only approximate and individual substances may be objectionable to some consumers at lower levels.

Table 5.3: WHO suggested limits of drinking water quality parameters (after WHO Guidelines for drinking water quality 2011) and range of concentrations found in the present study.

Parameter	Range in study (mg/L)	WHO limit (mg/L)	Objectionable limit (mg/L)	Remarks
Fluoride	< 0.05 – 22.0	1.5		Volume of water consumed and intake from other (food) sources should be considered when setting national standards.
Nitrate	< 0.05 – 172	50		Methaemoglobinaemia is the most important consideration, and the guideline derived allows for any nitrite that may also be present.
Chloride	2.50 – 728	N/A	250	No health-based guideline value is proposed for chloride in drinking water. However, chloride concentrations in excess of about 250 mg/l can give rise to objectionable taste in water.
Sulphate	0.50 – 307	N/A	250	Very high levels may cause a laxative effect in unaccustomed consumers.
Potassium	0.30 – 147	N/A		Occurs in drinking water at concentrations well below those of concern to human health.
Sodium	3.70 – 395	N/A	200	Not of health concern at levels found in drinking water. Concentrations in excess of 200 mg/l may give rise to unacceptable taste.
TDS	230 – 1920	N/A	1000	Not of a health concern, but may affect acceptability of drinking water.
Hardness	6.40 – 727	N/A	500	Not of a health concern, but may affect acceptability of drinking water.
pH	4.10 – 9.80	N/A	6.5 - 8.5	

5.8.1 Major Anions and Cations

Apart from fluoride, nitrate is the only other common groundwater ion present in the wells of Dong Xuan that has a potential health risk associated with it. While the other common ions may not be associated with health issues, they can affect the palatability of the water.

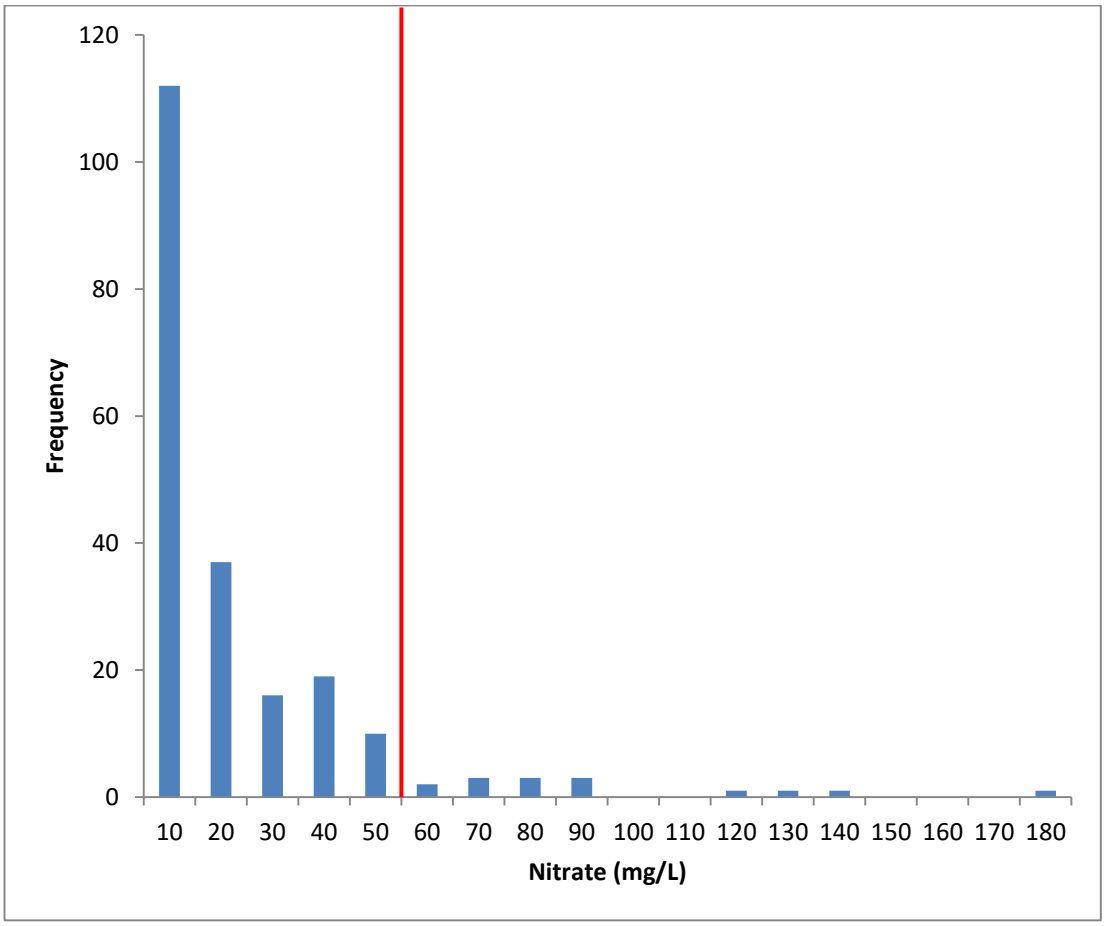


Figure 5.19: Histogram of nitrate concentrations in sampled wells of Dong Xuan district. Red line indicates WHO guideline value.

Nitrate

Elevated nitrate (NO_3^-) in groundwater is usually derived from agricultural and wastewater sources. The main health concern for NO_3^- is its presence indicates possible wastewater contamination, and its involvement in the medical condition methaemoglobinaemia. In this condition, nitrite (NO_2^-) reacts with haemoglobin to form methaemoglobin, which binds oxygen more tightly making it unavailable to the body. Although the majority of NO_2^- is oxidised to NO_3^- in the acidic conditions of the stomach, it is believed that gastrointestinal infections increase the production of

NO_2^-, and therefore high intakes of NO_3^- are reduced to NO_2^-. Methaemoglobinaemia is more likely to occur in bottle fed infants because their intake of water to body weight is higher and they have less developed repair enzymes (*Guidelines for drinking-water quality* 2011a).

Seven percent of wells (15 wells) that were sampled in Dong Xuan district had NO_3^- concentrations above the WHO guideline value of 50 mg/L. Figure 5.19 shows a histogram of the frequency of NO_3^- in sampled wells.

Chloride

Chloride (Cl^-) has no guideline value and is not recognised as a health risk in drinking water. The taste threshold is dependent on the cations present, but lies between 200 – 300 mg/L for sodium, potassium and calcium. Generally, concentrations of Cl^- over 250 mg/L give rise to a salty taste. In Dong Xuan, only four percent (nine wells) of the sampled wells had concentrations of Cl^- above 250 mg/L.

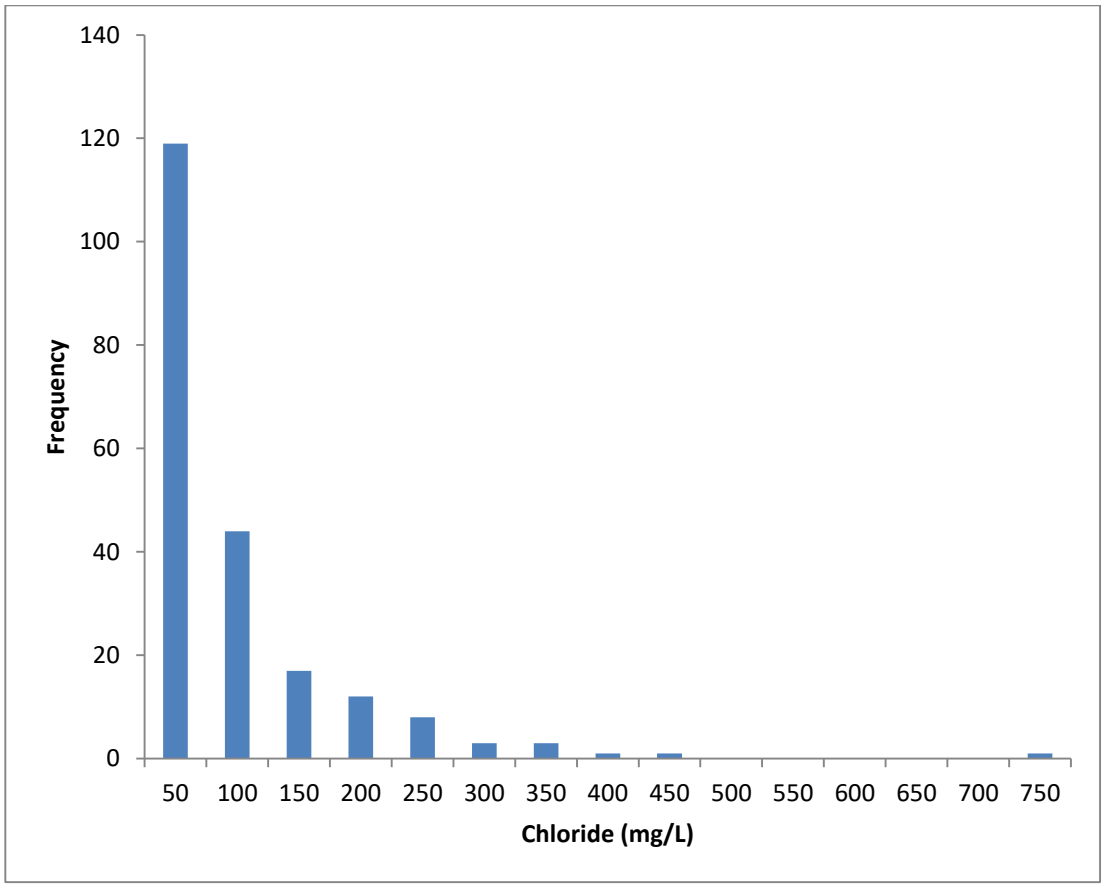


Figure 5.20: Histogram of chloride concentrations in sampled wells of Dong Xuan district.

Sulphate

No guideline value has been set of sulphate and the taste threshold for sulphate varies from approximately 250 mg/L for sodium sulphate to approximately 1000 mg/L for calcium sulphate. Less than one percent (one well) of all sampled wells in Don Xuan had sulphate concentrations above 250 mg/L (Figure 5.21).

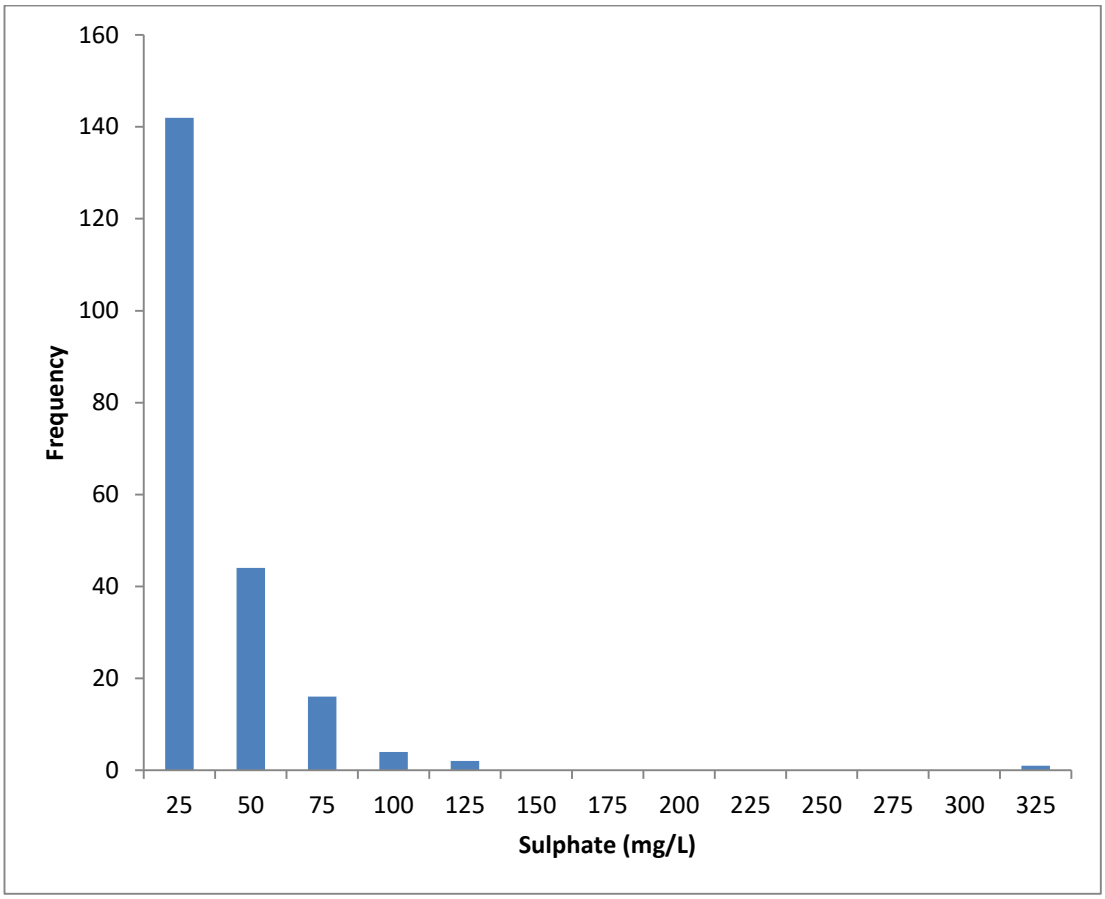


Figure 5.21: Histogram of sulphate concentrations in sampled wells of Dong Xuan district.

Calcium

Calcium has no WHO guideline value and is not considered a health risk. Its taste threshold depends on the anions present, and ranges from 100 – 300 mg/L. Of major importance in drinking water is the role it plays in water hardness (refer to total hardness in section 5.8.2). Figure 5.23, shows the general inverse relationship between calcium and F^- concentration in the Dong Xuan waters.

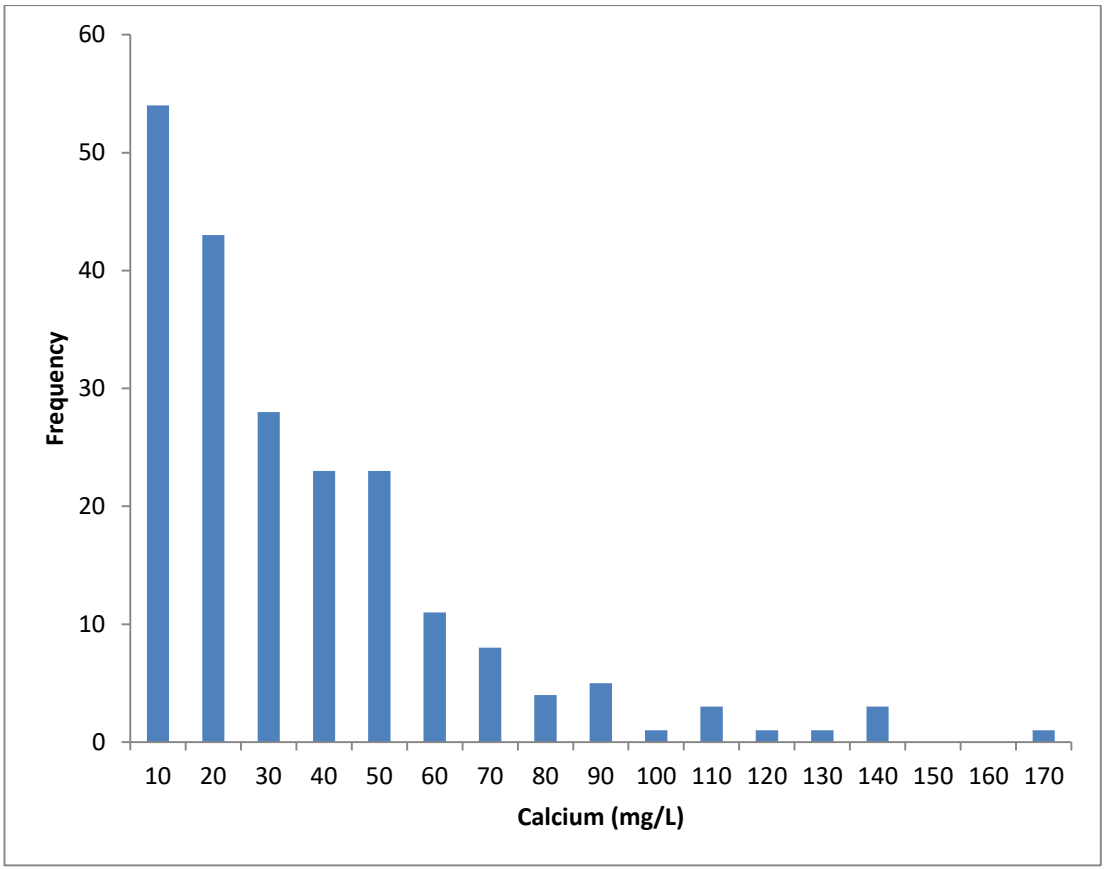


Figure 5.22: Histogram of calcium concentrations in sampled wells of Dong Xuan district.

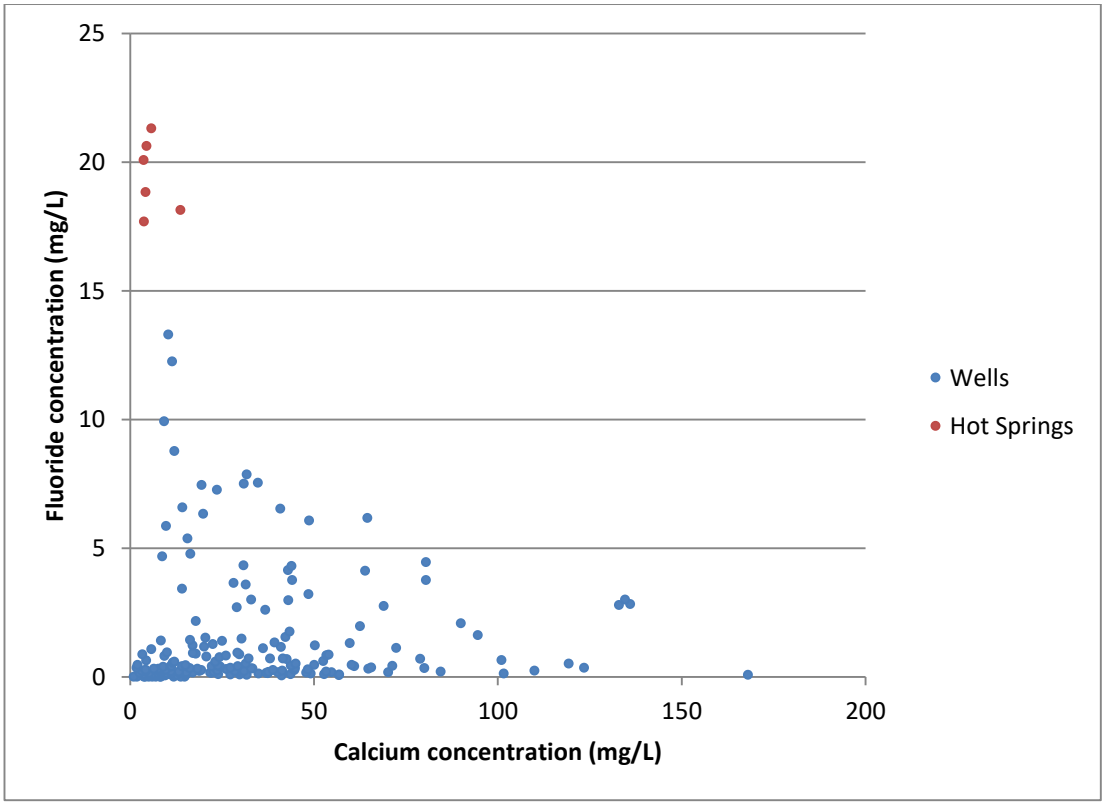


Figure 5.23: Relationship of calcium and fluoride concentration in sampled wells of Dong Xuan district.

Sodium

The WHO does not place any guideline value on sodium in drinking water. However, depending on the cations present, it can give a detectable taste at concentrations above 200 mg/L. Four percent (nine wells) of all wells sampled in Dong Xuan district had a sodium concentration above 200 mg/L (Figure 5.24). There is a slight inverse relationship between sodium and fluoride in the groundwater as shown by Figure 5.25.

Potassium

Potassium has no guideline value nor any objectionable limit as it occurs in drinking water at concentrations substantially below those of health and aesthetic concerns. Only 8% (17 wells) of sampled wells had greater than 30 mg/L potassium. Figure 5.27 shows the relationship between potassium and fluoride. Fluoride concentrations are generally low at high potassium concentration, and vice-versa. All hot springs contained very little potassium (< 5 mg/L).

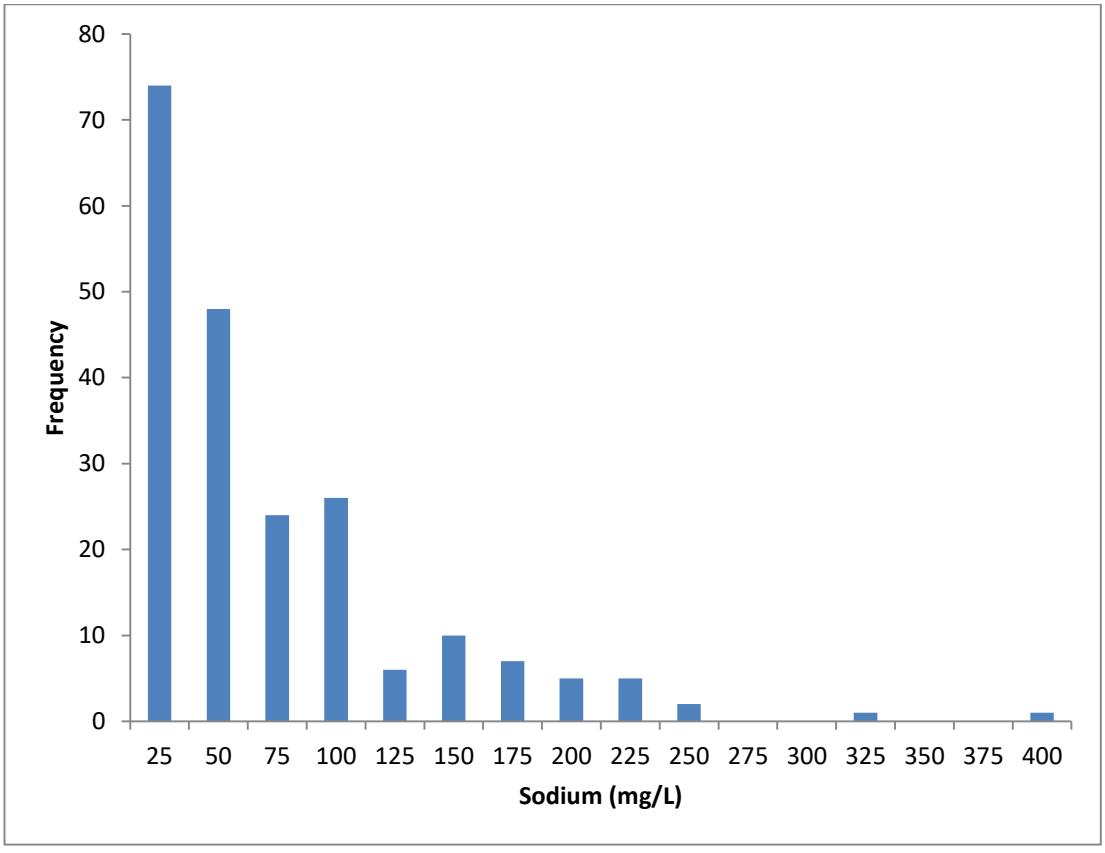


Figure 5.24: Histogram of sodium concentrations in sampled wells of Dong Xuan district.

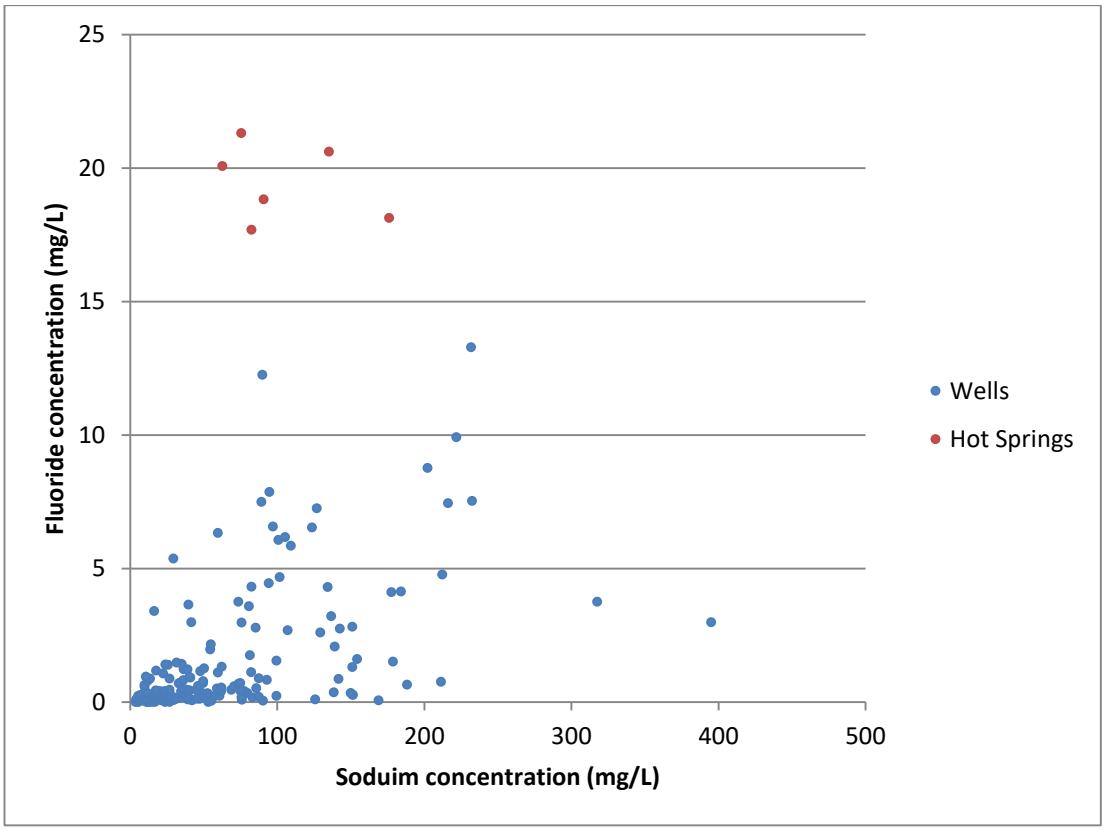


Figure 5.25: Relationship of sodium and fluoride in sampled wells of Dong Xuan district.

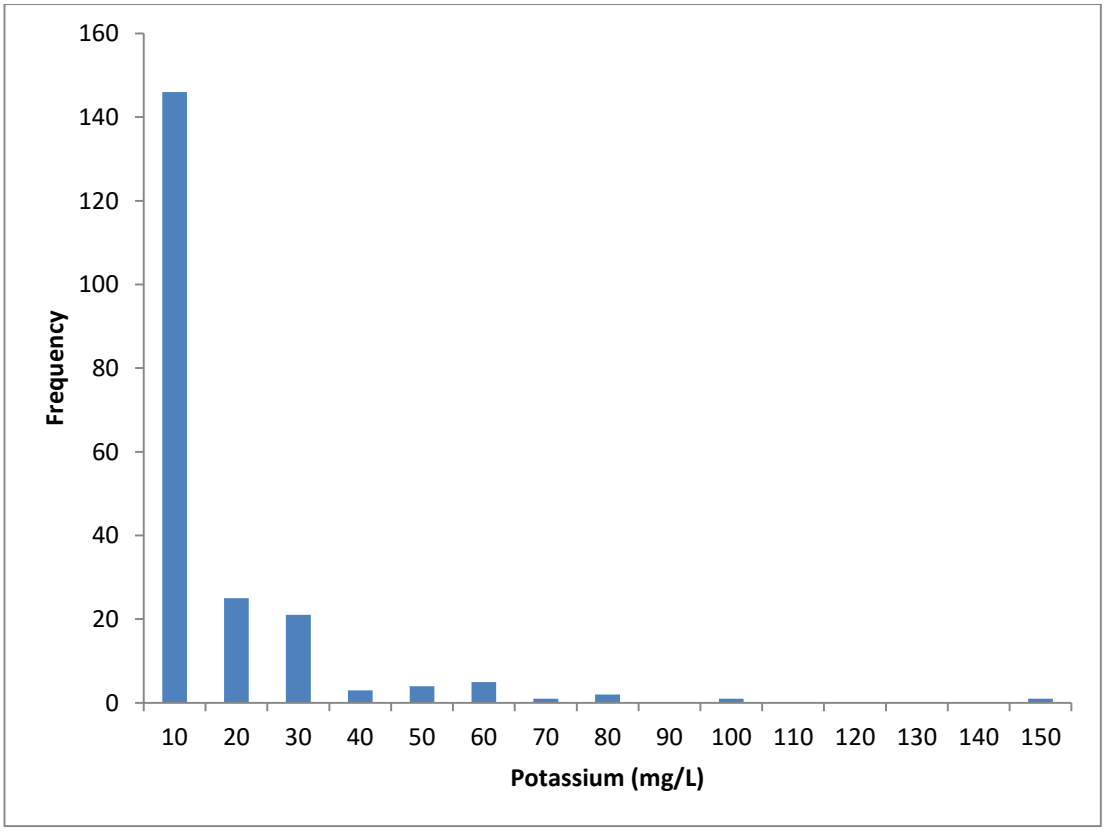


Figure 5.26: Histogram of potassium concentrations in sampled wells of Dong Xuan district.

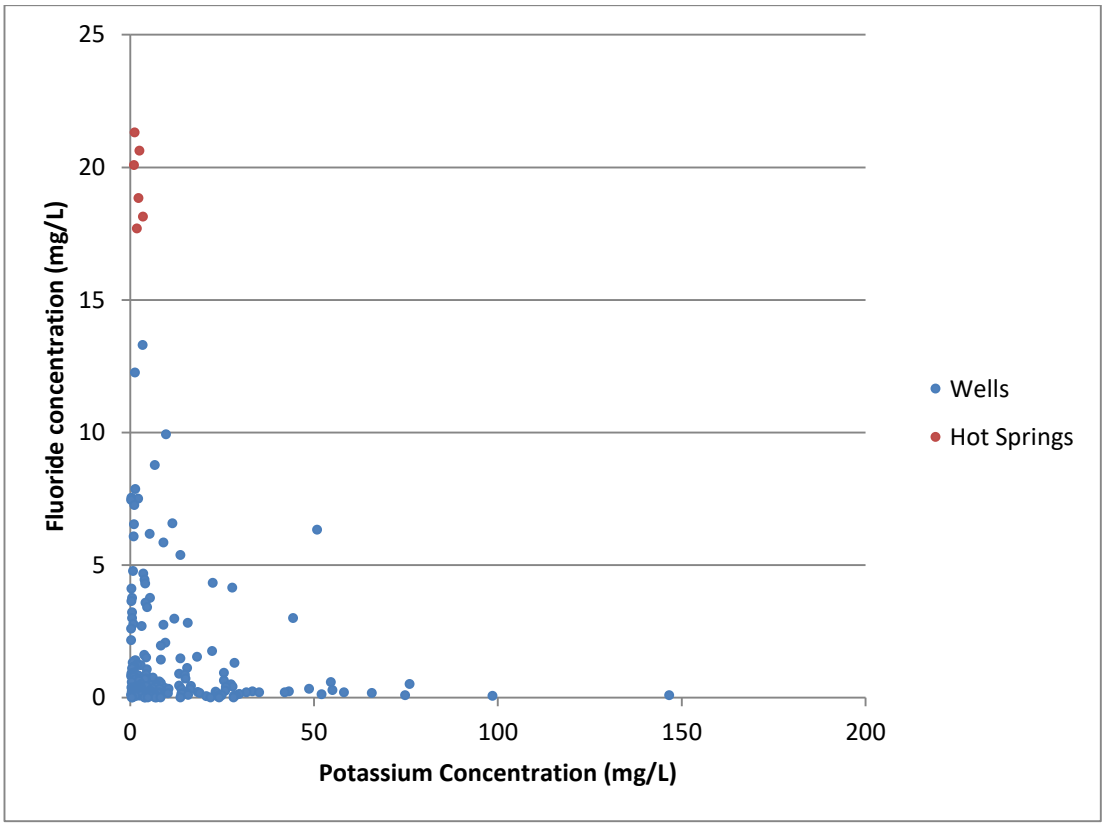


Figure 5.27: Relationship of potassium and fluoride concentrations in sampled wells of Dong Xuan district.

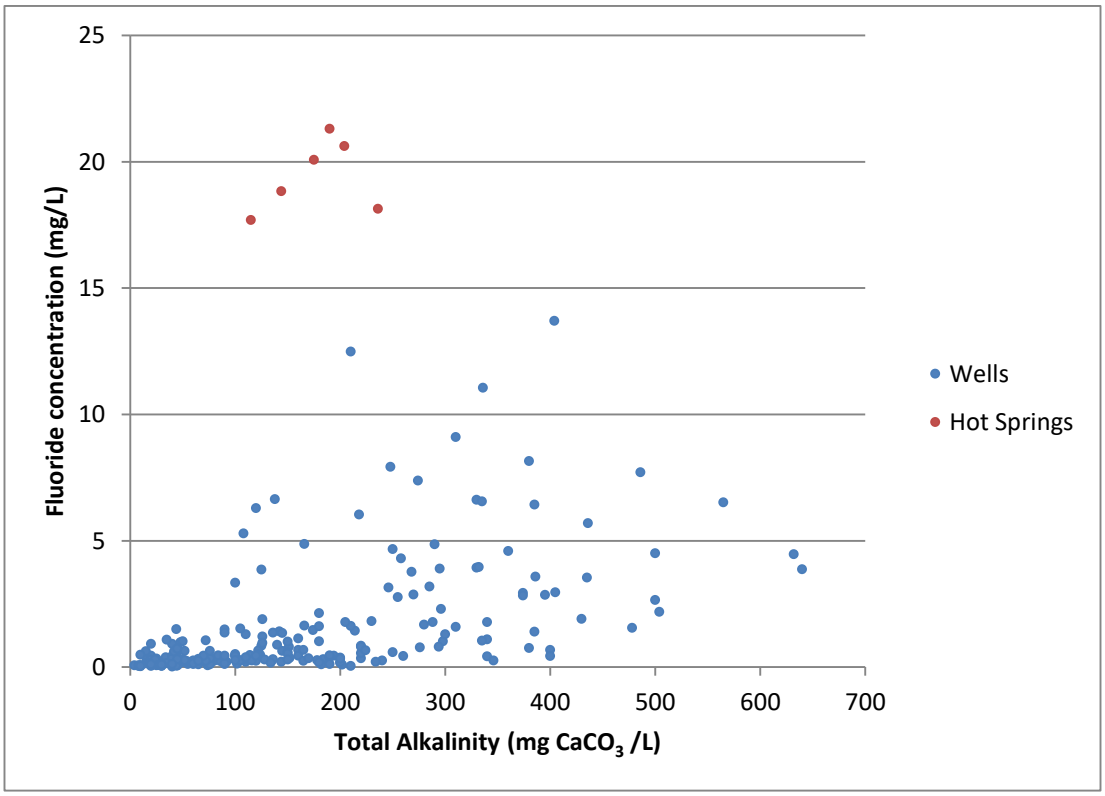


Figure 5.28: Relationship of Total Alkalinity and F^- concentration in sampled wells of Dong Xuan district.

5.8.2 Other Parameters

Total Alkalinity

As with Sodium, there was a very loose inverse relationship between total alkalinity and fluoride as shown in Figure 5.28.

Total Hardness

Hardness of water is usually caused by the divalent cations of calcium and magnesium and is expressed as mg $CaCO_3$/L. Total hardness in the present study was calculated using the following formula:

$$\text{Total Hardness as mg/L } CaCO_3 = \frac{(\text{mg } Ca^{2+})\times 100}{40.08} + \frac{(\text{mg } Mg^{2+})\times 100}{24.31}$$

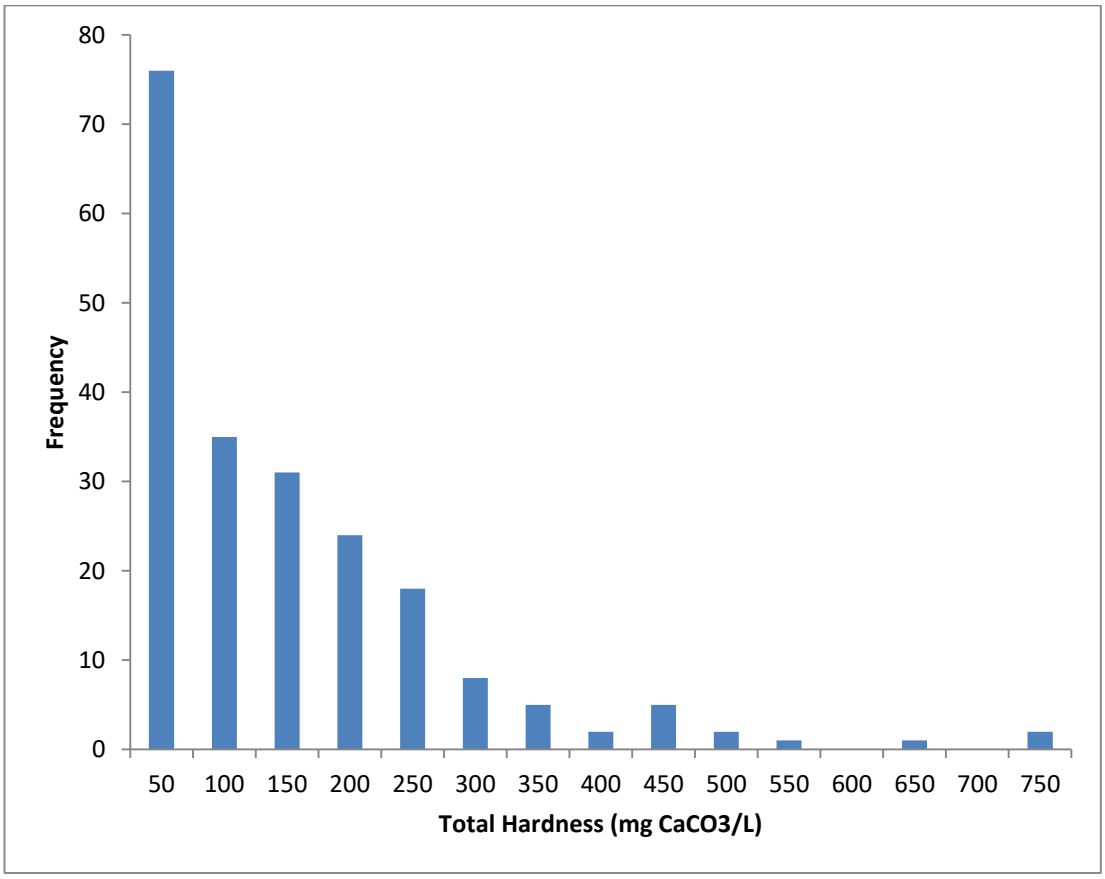


Figure 5.29: Histogram of Total Hardness in sampled wells of Dong Xuan district.

Water hardness can become objectionable at concentrations above 500 mg/L to some consumers, but the greatest issue for hardness is the formation of scale ($CaCO_3$) on

pipe work and distribution systems. In Dong Xuan district, this is a concern only for the commune of Phu Mo, which has implemented piped water. However, scum formation from soaps is another concern, where residents are using the water for washing. Only 1.5% of the 209 samples that were transported back to Perth for further analysis had a total hardness greater than 500 mg $CaCO_3$/L. Figure 5.29 shows the frequency of hard water in the sampled wells.

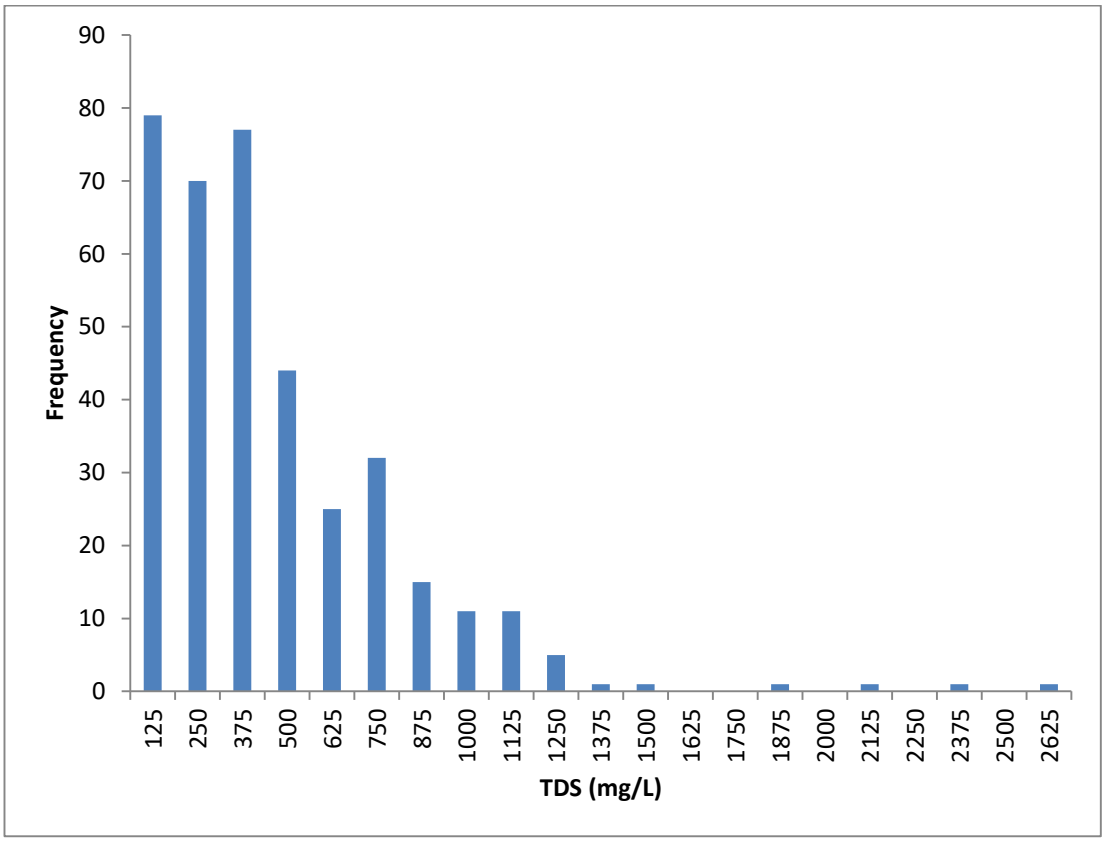


Figure 5.30: Histogram of TDS in sampled wells of Dong Xuan district.

Total Dissolved Solids

Three methods can be used to calculate total dissolved solids (TDS).

1. Gravimetric analysis
2. Chemical composition
3. Electrical conductivity

While gravimetric analysis is the most accurate, it is the most time consuming and is normally impractical for a large number of samples. Using the chemical composition of the water also produces high accuracy; however, water samples from only about

half of the wells were transported to Perth for HPIC analysis. Although the electrical conductivity method is the least accurate, it is the quickest and most practical. The electrical conductivity method uses a conversion factor to calculate the TDS directly from the electrical conductivity. This conversion factor can vary depending on the chemical composition of the water being measured. To determine the most appropriate conversion factor for the groundwater in this study, the TDS was calculated by using the known chemical composition of those samples that had HPIC analyses performed on them. An average factor of 0.66 was obtained with a minimum and maximum value of 0.58 and 0.71 respectively. Therefore, for all the TDS values in this thesis, a conversion factor of 0.66 has been used.

There is no WHO guideline value for TDS, but palatability decreases significantly above TDS values of 1000 mg/L (*Guidelines for drinking-water quality* 2011a). About 6% of the sampled wells in Dong Xuan district had a TDS greater than 1000 mg/L (Figure 5.30).

pH

Although no guideline value has been issued for pH of drinking water, it is an important parameter, especially for delivery and treatment systems. For these purposes, a value between 6.5 – 8.5 is suggested (*Guidelines for drinking-water quality* 2011a). Only 1% of the measured wells in Dong Xuan district had a pH above 8.5, while 44% had pH values less than 6.5 (Figure 5.3.1). In Dong Xuan district water is essentially untreated, and only the commune of Phu Mo has implemented piped water. Nevertheless, the low pH poses potential problems should other communes wish to follow Phu Mo in drinking water distribution.

From Figure 5.32, it can be seen at higher F^- concentrations, the pH of the samples become less variable, but there appears to be no correlation between pH and F^- concentration. All well water samples having F^- concentrations above 7 mg/L have a pH above 7, and the F^--enriched hot springs all have pH values above 8.

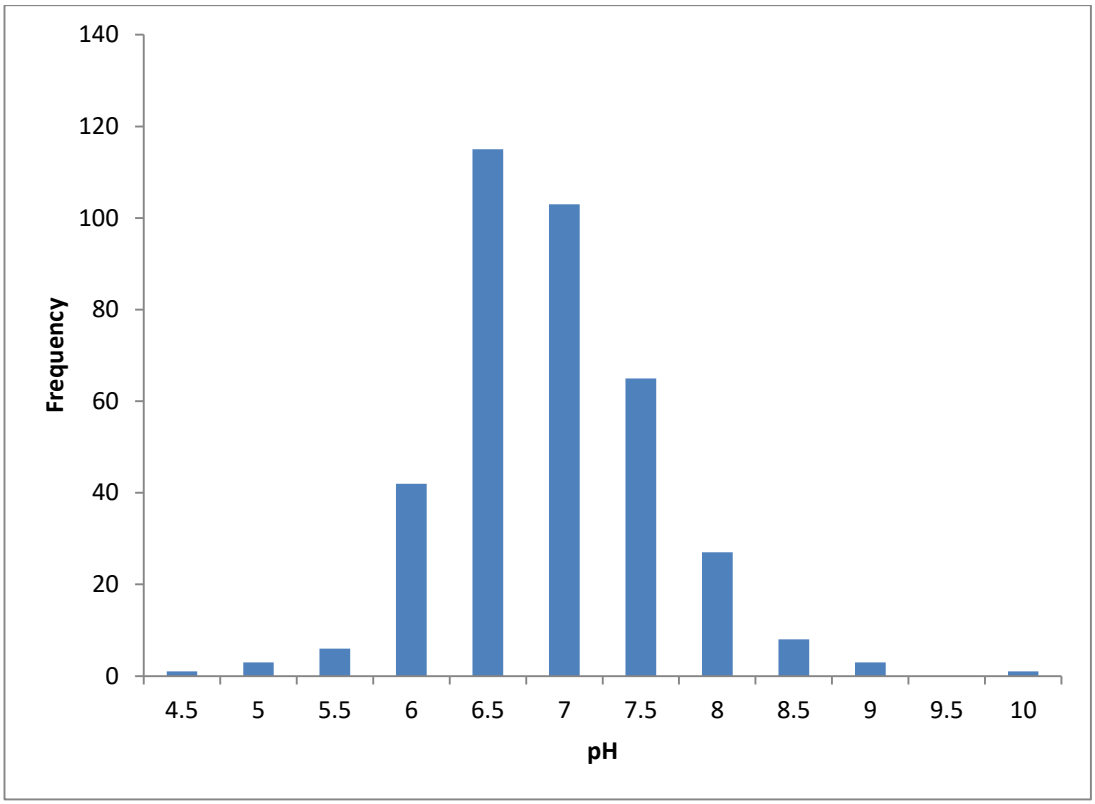


Figure 5.31: Histogram of pH in sampled wells of Dong Xuan district.

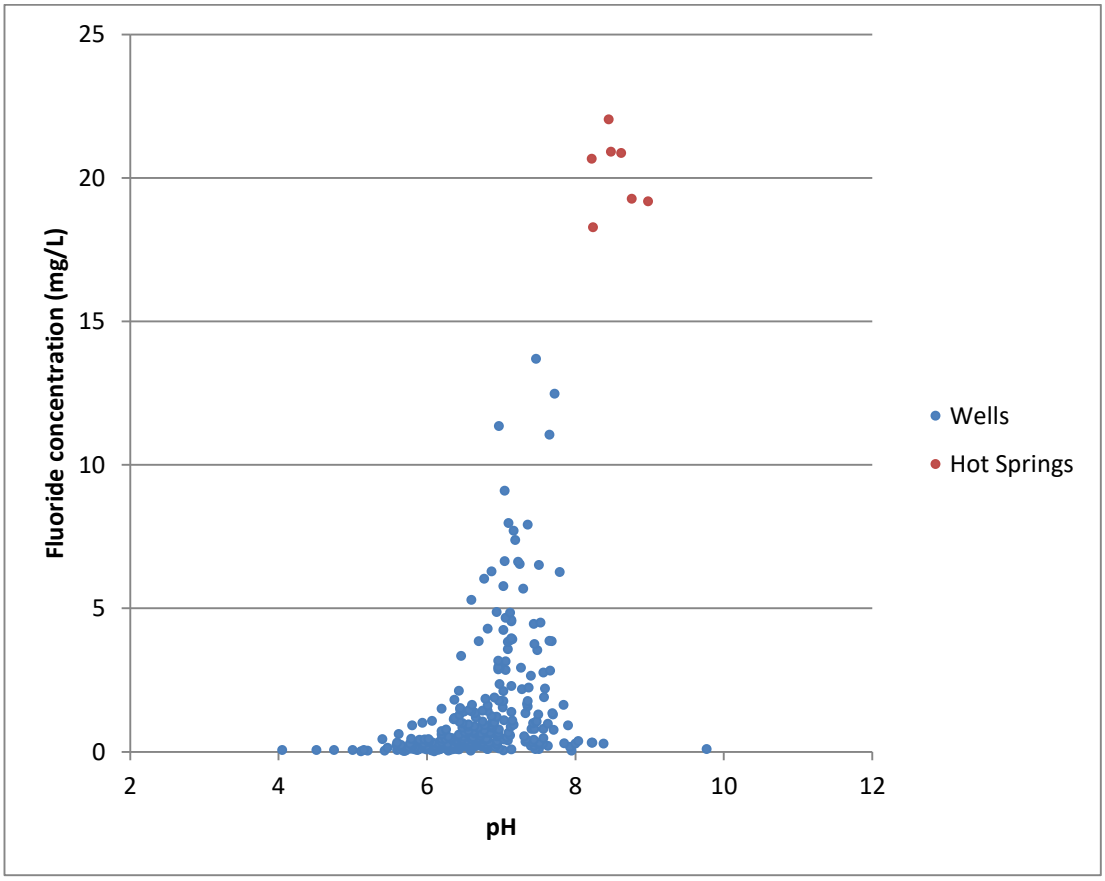


Figure 5.32: Relationship of pH and F^- in sampled wells of Dong Xuan district.

5.8.3 Trace Elements

The results of the trace element analysis are presented in Appendix B and the ranges are shown in Table 5.4. Only one sample (XPU19) out of the 48 analysed had Al^{3+} concentrations higher than 1 mg/L (3.00 mg/L) and all the samples had Fe^{2+} concentrations less than 1 mg/L. These two ions pose the greatest threat of interference in the FISE analysis, and as shown by Mamuse (2003), with the use of TISAB even in solutions containing Al^{3+} as high as 10 mg/L the F^- concentration was only reduced by 3%.

Table 5.4: Ranges of selected trace element concentrations in sampled wells.

Trace Element	Range in study (mg/L)
Aluminium	<0.01 – 383
Silicon	4.42 – 50.0
Phosphorous	<0.01 – 3.73
Sulphur	0.19 – 27.8
Manganese	0.01 – 270
Iron	<0.01 – 0.89

6 FLUORIDE DISTRIBUTION & FLUOROSIS RISK MAP

6.1 Software and Gridding Method

Surfer® version 9 was used to produce the contours for the fluorosis risk map and the map was then imported into MapInfo Professional® version 10. Owing to the spatial irregularity of the sampling that was imposed by the constraints discussed in section 3.2.1, many of the available gridding methods did not produce satisfactory results. Furthermore, many of the gridding methods' interpolations attempt to provide more detail than is inherently available in the data.

Furthermore, the F^- concentrations in waters drawn from the wells are not temporally static and seasonal fluctuations do occur. Therefore, when choosing a gridding method, it is not so critical that all the data points are honoured as these data points themselves may not exactly represent the actual concentration of F^- in the wells at any given time. After testing various gridding methods, Minimum Curvature (MC) was chosen, since its relatively simplistic rendering most appropriately reflects the approximate values of the well water. However, the limitations of MC need to be recognised. For example, whereas MC generates the smoothest surface, the data are not always honoured, i.e. the data points may not be exactly equal to the grid value on which they lay. As already mentioned, this does not pose a great concern as the F^- values also "vary" temporally to a small degree. Another, if not a more important limitation, is the way in which MC handles interpolation of sparse data points that is greater than the spacing of the gridding method. As seen in Figure 5.2, the sampling generally follows roadways, leaving extensive unsampled areas. Owing to the nature of MC plotting, when there are no data points between the points of a grid, the minimum curvature will produce a spherical surface. This effect is minimal where the space of the data points are comparable to the grid spacing but in large sparse areas this can cause large blowouts in the interpolation (Li and Götze 1999). The method of Nearest Neighbour , on the other hand, handles this better, but because it fits the data exactly, it produces more noise (Li and Götze 1999). However, as shown by Li and Götze (1999), when the density of the grid space is of a similar spatial distance to the data resolution, MC can produce acceptable results. The grid density was therefore set to 600 metres, which was at the higher end of the typical

spacing of sampled wells. To overcome the blowout limitation that would occur in the sparsely sampled areas, these areas have not been included on the fluorosis risk map, as discussed in section 6.2. Spatial delineations would not be reliable in these areas no matter what plotting method was chosen.

6.2 Map Limitations

As large areas of Dong Xuan district are unpopulated and therefore devoid of domestic wells it would be of little use to extrapolate the entire district to produce a risk map that had complete coverage. Owing to the blowouts produced by the MC plotting method in sparsely sampled areas and since the accuracy of the extrapolated data decreases proportionately with distance from the sampled wells, it would be more practical to limit how far from each sampled well to extrapolate when producing the risk map. In this study, it was shown that large changes in F^- groundwater concentrations may occur within distances as little as 30 metres (refer to discussion 7.2). However, extrapolating only 30 meters from each sampled well would produce a risk map with very limited coverage, which would be difficult to interpret. To provide a reasonable area for the risk map, an arbitrary distance of one kilometre was chosen as the maximum distance to extrapolate from each sampled well. Although it is acknowledged that this distance is well beyond the confidence limit of the extrapolated data, it does provide a map that is easier to visualise and interpret, even though the outer limits of the extrapolated data on the risk map are well outside the confidence limits.

6.3 Fluoride Distribution Map

Fluoride concentrations from sampled wells are presented in the form of a F^- distribution map (Figure 6.1). The contours of the map estimate the F^- concentration of the groundwater based on the wells that were sampled. Each contour represents a division of 1 mg/L F^-. Two areas that had undergone a high-density sampling regime (discussed in section 7.2.1) are mapped in detail in Figures 7.3 and 7.4, which is shown in Figure 6.1. The details of the contours in these areas are obscured by the numerous wells that were sampled, whose locations are shown on the map as brown dots. The inclusion of well locations is useful to determine the accuracy of the

estimated contours. Areas that contain closely spaced wells will have a higher degree of accuracy than those areas in which the wells are more sparse.

6.4 Fluorosis Risk Map

The data are also presented in the form of a fluorosis risk map (Figure 6.2). The well locations have been excluded in the risk map as well locations are provided on the fluoride distribution map for comparison, and the risk map provides an overall assessment of the fluorosis risk. The fluorosis risk assessment in this study is based upon the impact of F^- on health inferred from previous studies (Dean 1942; *Fluoride in drinking-water* 2004; Guidelines for drinking-water quality 2011b; Edmunds and Smedley 1996), and incorporates five zones of risk:

No Risk (< 0.5 mg/L F^-)
Low Risk (0.5 – 1.5 mg/L F^-)
Moderate Risk (1.5 – 4.0 mg/L F^-)
High Risk (4.0 – 8.0 mg/L F^-)
Extremely High Risk (> 8.0 mg/L F^-)

Caution needs to be exercised when interpreting fluorosis risk. Domestic water supply is the predominant exposure to F^- in most situations, where the water is used for drinking and preparation of food and beverages (Viswanathan *et al.* 2010). The map presents fluorosis risk based on F^- concentrations that the previous studies have shown to cause adverse health effects; however, there may be significant additional risk from other exposures. As discussed in section 1.5.1, the amount of exposure to other sources of F^- can vary considerably. An important contributor is tea, which has been identified as a high source of F^- exposure. This is no truer for local residents in Dong Xuan district, where it is customary to drink green tea with meals or even while waiting for coffee to be prepared.

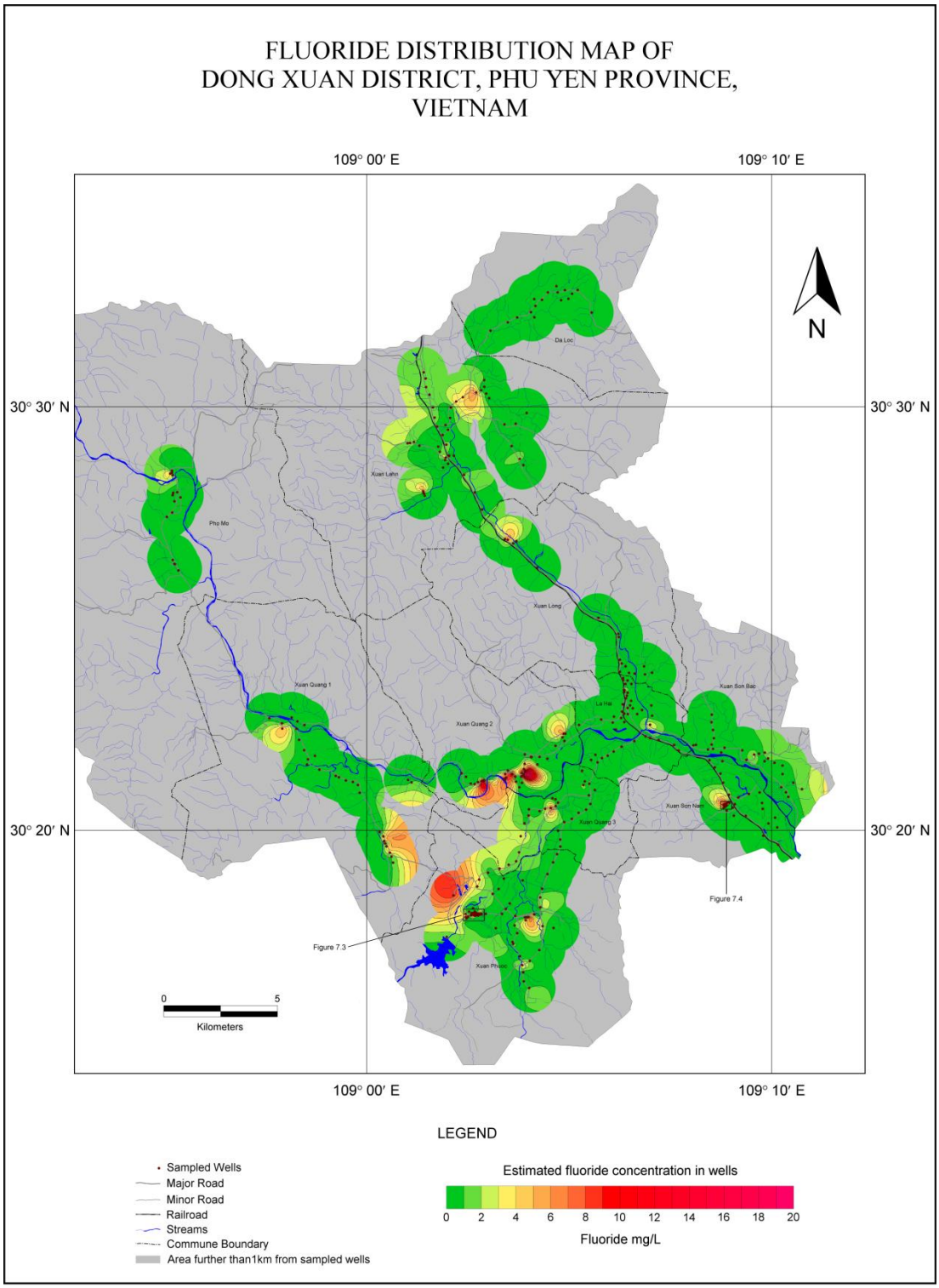


Figure 6.1: Fluoride Distribution Map of Dong Xuan district.

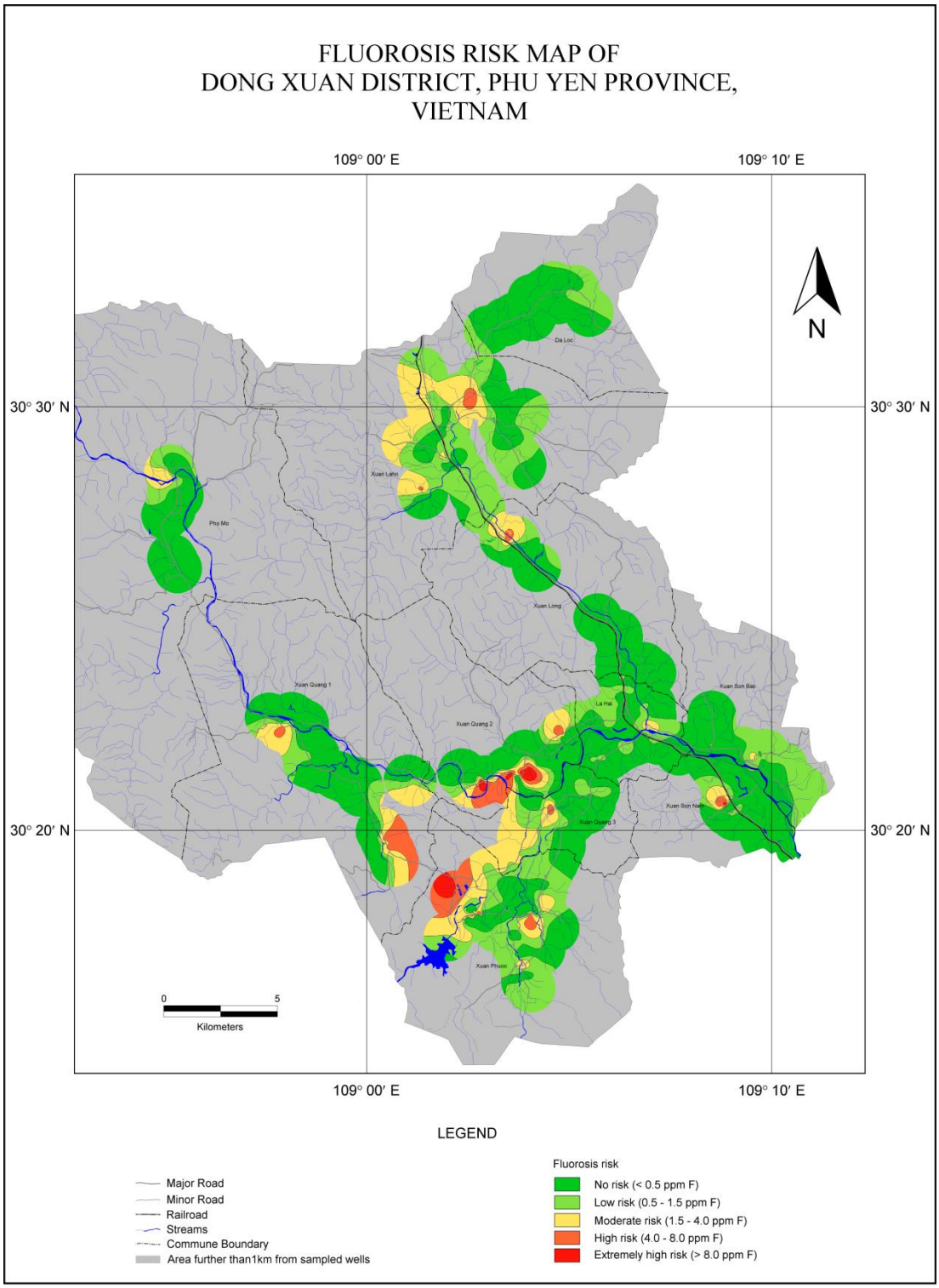


Figure 6.2: Fluorosis Risk Map of Dong Xuan district.

A further source of F^- in Dong Xuan district may even be from bottled water. During the present study, a common and locally popular brand of bottled water was tested for its F^- concentration. Although it was labelled as containing 1.7 mg/L F^-, which is just over the WHO guideline value, when analysed using FISE, the value was 2.7 mg/L F^-. The analysis was repeated with a different bottle of the same brand obtained from a different location and the result was exactly the same. The residents do not drink bottled water regularly but it is drunk often when having meals at the various restaurants and eateries.

7 DISCUSSION

7.1 Ninh Hoa District

As can be seen from the F^- concentrations in Figures 4.1 – 4.5, most samples analysed in this study gave F^- concentrations closely similar to those reported by Vu (2008). Statistical analysis of the results from wells sampled in December 2004 by Vu and June 2012, by this study, showed that the wells had similar F^- concentrations at the 5% significance level. However, due to the differences in rainfall during, and leading up to the other sampling months, further statistical comparisons were not viable. Despite this limitation, the complete data set of all the re-sampled wells can be used when considering them as a snapshot of the F^- concentrations in wells during a given time period, and then using these extra data to extend the original observation period up to that of the current study. This is discussed below.

To use all the data, averages could be taken when a well had been sampled more than once in each study (Vu's and this study) and this average value is compared with the value (averaged or not) from the other study. The limitation of this approach is the assumption that there has been a consistent change in F^- concentration, which is not the case. However, it is also important to consider the standard deviation of the wells' values, as two averaged values that are similar (or an averaged value and a single value, in some cases) does not necessary indicate little change has occurred. This can be seen with well NS141 in Figure 4.3, where the well was sampled only once during the study by Vu, but sampled during both fieldtrips of the present study. From the figure, it is clear that the F^- concentration in the well has fluctuated widely, from 28.10 mg/L to 11.94 mg/L and then up to 34.92 mg/L. When the average value of 23.43 (from this study) is compared to 28.10 (the single value of Vu's study) the difference appears relatively small. It is the standard deviation of 9.6 mg/L that indicates that large changes have occurred, rather than that suggested by the two value comparison between the two studies. Since there is clear temporal/seasonal variation in some wells, it is more useful to use the extra data obtained from this study to simply extend the observation range and assess how variable the well water compositions have been over this extended eight year period.

Care needs to be taken when interpreting the charts as there is a considerable time gap between the study by Vu and this study, and some wells have only been sampled twice (once by Vu and once in this study). This is seen in Figures 4.1 – 4.5 as two points connected by a straight line. Clearly, a horizontal line interpolated between two points cannot suggest that no change has occurred, since there is no data for approximately seven years between the two studies. However, if the F^- concentrations were fluctuating, there would have been a higher chance that the repeated sampling would have occurred when the wells had different concentrations of F^- and therefore more sloping profiles would have been produced. Although a majority of wells in this study (60%) had only been sampled twice, using the above principle of probability, the frequency of horizontal, or near horizontal, lines should be able to indicate if changes have occurred over the study period. This can be achieved by using the standard deviation of the two values to represent the gradient of the slope when plotted (standard deviations shown in Table 4.1). Statistically, the standard deviation of two samples is of little use; however, it can be of value when used in this context to provide a slope of change. Of the 29 wells that were sampled only twice, four had standard deviations greater than 1.0 mg/L F^-; the other 86% produced a relatively horizontal profile. This suggests that these wells mostly do not appear to undergo significant long term fluctuation. When the same approach is applied to wells that have been sampled more than twice, a different pattern emerges. Of the 19 wells that had been sampled more than twice, only 53% had standard deviations less than 1.0 mg/L. However, it should be noted that a further 53% of the wells that had been sampled more than twice had average F^- concentrations greater than 5 mg/L whereas only 31% of wells that were only sampled twice had average F^- concentrations above 5 mg/L. From Figures 4.2 – 4.5, it can be seen that greater fluctuations generally occur in wells with higher F^- concentrations.

Although there appeared to be relatively little fluctuation of the F^- concentration recorded in the majority of wells, there were significant fluctuations in a small percentage of wells. As already discussed, one well (NS141) showed a very high standard deviation of 9.6 mg/L. However, even its lowest value is substantially above the WHO recommended value for drinking water of 1.5 mg/L. This was the general case for wells exhibiting a high degree of fluctuation, where wells that recorded values above the WHO limit of safe drinking, remained above this limit

thereby creating no misclassification of F^- concentration in these wells. However, there was an exception, well NX242, which was of the greatest concern. This well was recorded as having a F^- concentration of 1.04 mg/L by Vu (2008) in November 2006, but was recorded as 3.96 mg/L and 5.43 mg/L in the first and second fieldtrips of this study, respectively (Table 4.1). Whether the lower value of 1.04 mg/L was an error, or the F^- concentration of the well has changed by this extent, the susceptibly of even low fluorosis risk wells becoming high risk over time should be considered.

Figure 4.1 shows that the F^- concentrations of hot springs were far more consistent over time than those recorded from wells, despite having high F^- values. Only one hot spring (NS036) showed a large change in F^- concentration, 7.63 mg/L to 5.64 mg/L. It can reasonably be suggested that the F^- concentration in hot springs are most likely to remain stable over time.

7.2 Dong Xuan District

Before proceeding with any discussion of the results from this district, and the implications that they may have, it is useful to first summarise the findings of the results for each commune. Figure 7.1 shows a thematic map indicating locations and approximate F^- concentrations of the sampled wells within each commune.

7.2.1 Individual Communes

La Hai

The capital of the district, the town of La Hai, was thoroughly sampled and no areas of fluorosis risk were found. In other areas of the commune outside of the township only one well posed any real fluorosis risk except (LHA17), which had a recorded value of 2.87 mg/L F^-. The areal extent of this high F- area is not known; however, it would appear to be limited as surrounding wells sampled approximately a couple of hundred metres away were less than 1 mg/L F^-. Nevertheless, caution must be exercised due to the possibility of high F- containing areas has discuss below.

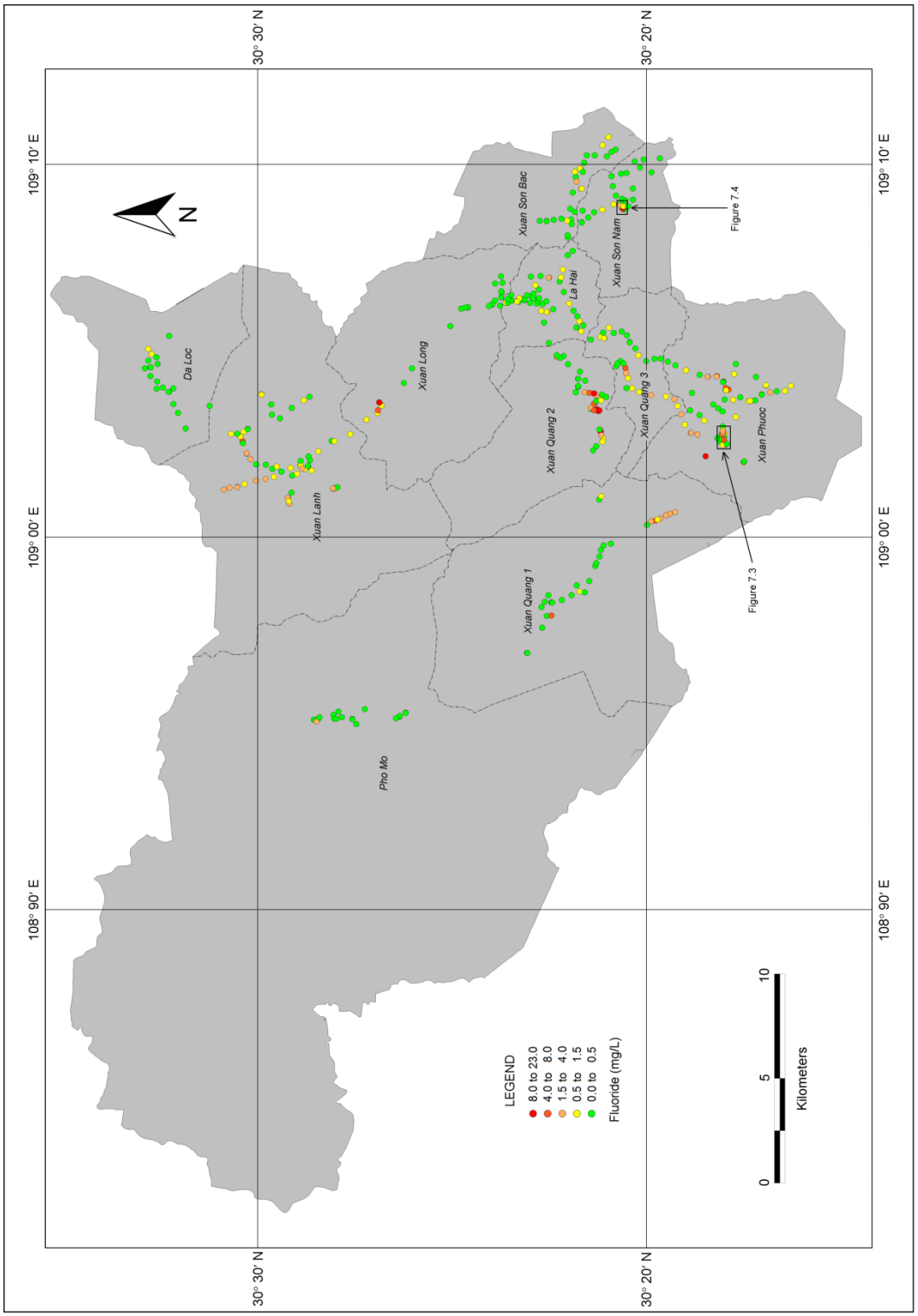


Figure 7.1: Fluoride concentration of wells in communes of Dong Xuan district.

Xuan Long

This commune is the least populated commune in Dong Xuan district and it contained one hot spring in the northern part of the commune with a F^- concentration of 19.2 mg/L. There was one nearby well that had a F^- concentration of 5.3 mg/L; however, the concentrations in other wells in close proximity to the spring were relativity low. Most of the wells sampled in this commune had low F^- and consequently the commune overall is of low fluorosis risk, despite having the presence of a hot spring.

Xuan Lanh

This commune has many wells in the north that have F^- concentrations above 1.5 mg/L and these are considered as moderate fluorosis risk areas. There is also a small area of high fluorosis risk in this region. This commune contains a fluorite deposit, which is actively mined and is located in the south of the commune in an area considered as low fluorosis risk. The fluorite mine has a river in close proximity, and in addition, there are small tributaries that flow from the mine into the river. The river was sampled during both fieldtrips (Figure 7.2), and the first fieldtrip showed that water samples taken upstream and downstream from the mine had essentially the same F^- concentration of approximately 0.35 mg/L. This initially suggested that the fluorite deposit did not influence the F^- concentration in the river. On the second fieldtrip, three samples taken upstream had similar values to that of the first fieldtrip (0.3 – 0.4 mg/L F^-). However, two samples that were taken downstream from the mine had values of almost 1 mg/L F^-. The F^- concentration in a sample taken even further downstream reduced to 0.21 mg/L, but a major tributary upstream from the sample point is likely to have contributed to this lower value.

On both fieldtrips, the F^- concentration upstream from the mine was 0.3 – 0.4 mg/L. This would appear to suggest that this is the background concentration of F^- in the river. The elevated F^- levels found downstream of the fluorite mine during the second fieldtrip would suggest the fluorite deposit could be contributing to the F^- concentration in the river during this time due to seasonal surface runoff. There is no knowledge about the hydrogeology and the current processing activity of the fluorite mine. In the absence of this information, no conclusions can be drawn on whether

the impact of the fluorite deposit on the F^- concentration in the river is dependent on the activity of the mine works, or how F^- contaminated water may be added to the river as groundwater flow. Furthermore, the extremely high river F^- concentration of 5 mg/L as found by Thang *et al* (2004) suggests that F^- concentrations are highly variable and could be a result of seasonal changes in base flow.

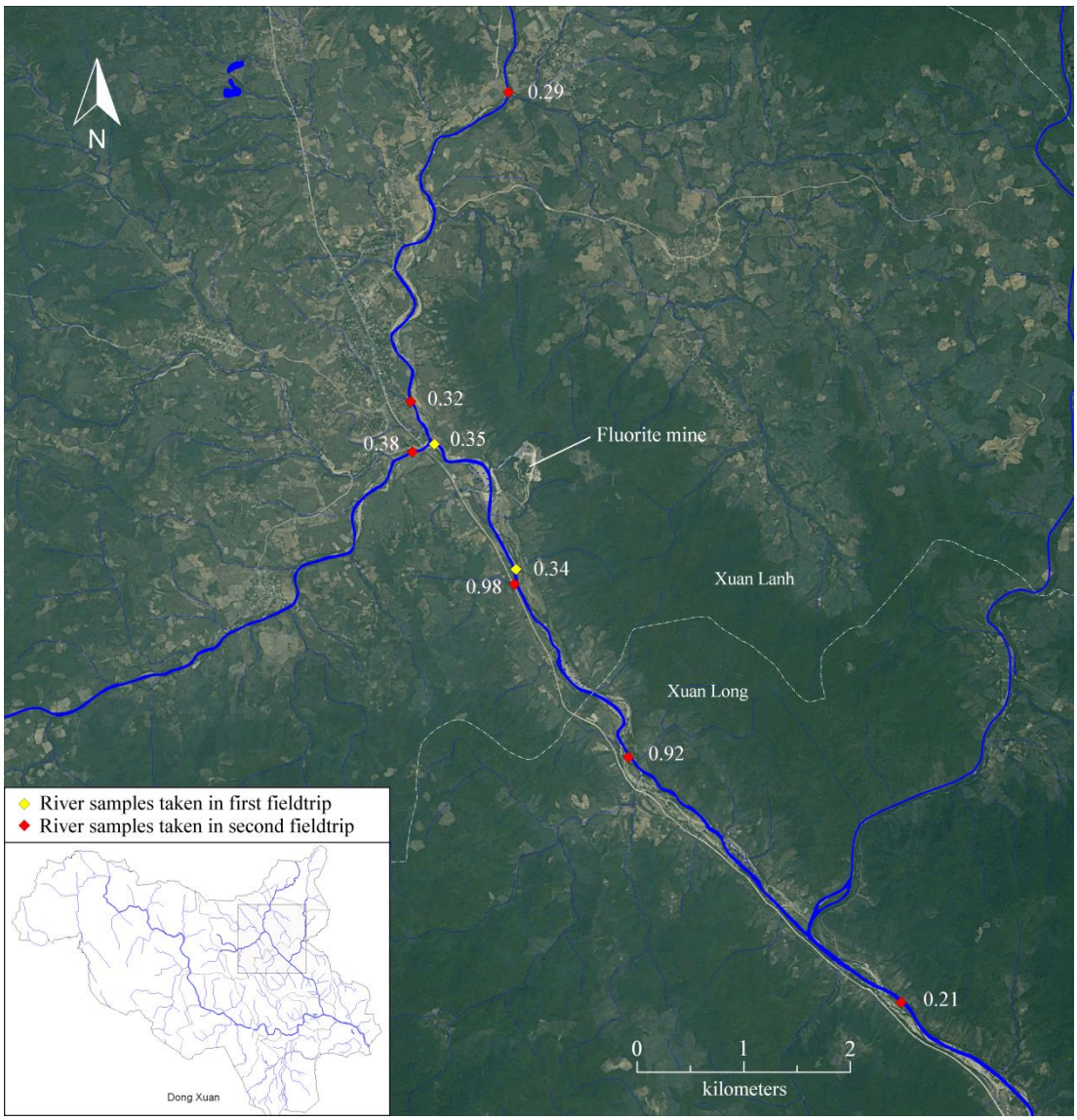


Figure 7.2: River F^- concentrations in mg/L and river sampling locations in vicinity of the fluorite mine in Xuan Lanh district (Imagery from Google Earth).

Xuan Phuoc

Xuan Phouc is the second most populous commune in Xuan Dong district, and it has areas of extremely high fluorosis risk. Many of the wells sampled contained high F^- and of particular interest in this commune are what appear to be numerous localised high F^- containing areas. The immediate area surrounding one of these localised areas was the subject of a high-density sampling regime. From the detailed sampling (Figure 7.3), the immediate area appears to enclose several localised high F^- areas. The area that Figure 7.3 encompasses is indicated on Figures 6.1 and 7.1. As can be seen in Figure 7.3, the southern edge of the right-most high F^- area is sharply delineated. Well XPU40 was sampled in both fieldtrips and both samples had similar concentrations of F^- (6.43 and 5.78 mg/L). A well (XPU47) which lies just across the road (~30 metres away) had only 0.26 mg/L F^-.

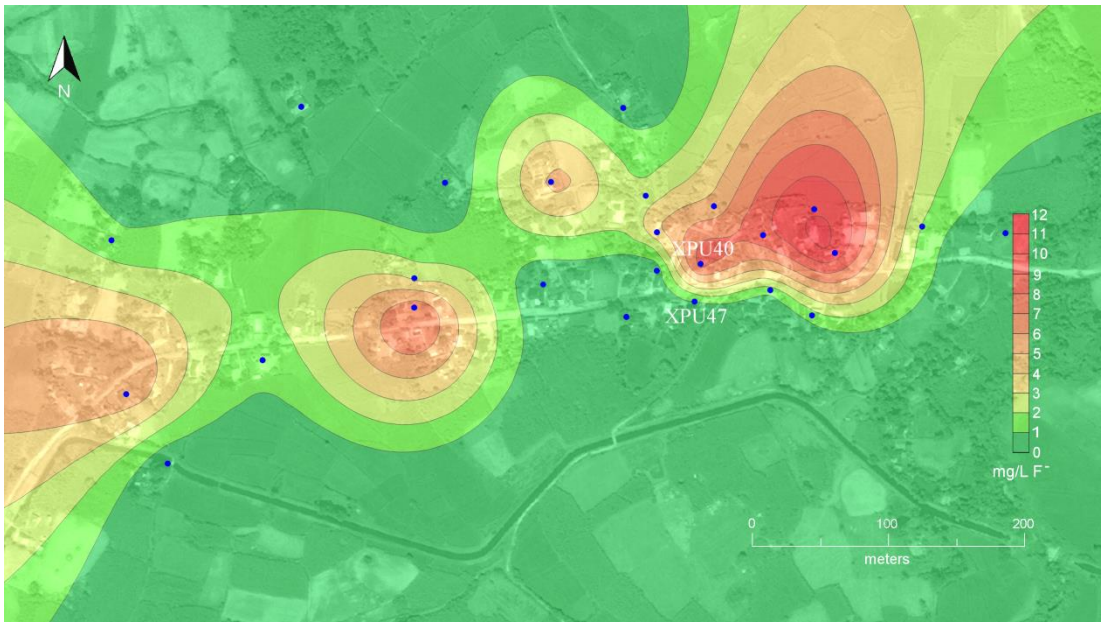


Figure 7.3: Distribution of high F^- areas in groundwater in Xuan Phuoc commune. Blue dots indicate sampled well locations. (Imagery from Google Earth)

Also noteworthy is a solitary well (XPU30, not shown), which lies close to a prison, and supplies the prison with its drinking water. It is unfortunate that this well contains ~8 mg/L F^-, thereby providing a significant health risk to those detained.

Xuan Son Bak

This commune has wells with predominately low F^- concentrations, although there are some moderately high wells (~2 mg/L F^-) towards the eastern end of the commune. Despite this, the study did not find any wells that had sufficiently high F^- concentrations and it is considered as a low fluorosis risk commune.

Xuan Son Nam

This commune provided an interesting result. Essentially, the initial results from the first fieldtrip suggested that the commune had low F^- containing groundwater with the exception of one very high F^- well, suggesting a localised area of high F^-. This high F^- area was only discovered through a chance remark of the resident of well XSN08 while it was being sampled that prompted further investigation. Otherwise, no further sampling would have been done in the area. Roughly translated from Vietnamese, the remark was "there's a man not far from here who has bad teeth". After getting the location of this man's dwelling, his well (XSN09), which was only about a hundred metres distant, was sampled and found to contain 9.1 mg/L F^-. As the surrounding wells of the commune contained water with extremely low F^-, it was decided that on the second fieldtrip, a high-density sampling regime would be conducted around this single well, with the goal of delineating the extent of the high F^- area. It was the subsequent high-density sampling of this area during the second fieldtrip that revealed the nature of the localised high F^- area, as can be seen in Figure 7.4 (refer to Figures 6.1 and 7.1 for area location). Unfortunately, there were no wells to the northwest, and the sampling regime could only be conducted on wells that were to the southeast. Owing to the absence of data points to the northeast, the high F^- area is not fully constrained. Although the actual size of this localised high F^- area cannot be determined its diameter in the northeast-southwest direction was approximately 200 metres. Even though the nature of the high F^- area to the northwest cannot be determined from the data collected, it fully illustrates how easily such a localised area of high F^- can be missed and provokes an unanswered question: are there other high F^- areas in the commune that were not detected?

This commune had in place a deep bore positioned close to the river, which allowed collection via a pumping apparatus. The natural river sediment provided basic

filtration (not fluoride removal), and this filtered river water was available to the local residents. The bore (XSN06) when measured, had a very low F^- concentration of 0.06 mg/L. Although installation of such a facility demonstrates concern for the F^- problem by the local commune authorities, apart from the aforementioned high F^- area, the commune appears essentially low in groundwater F^-.

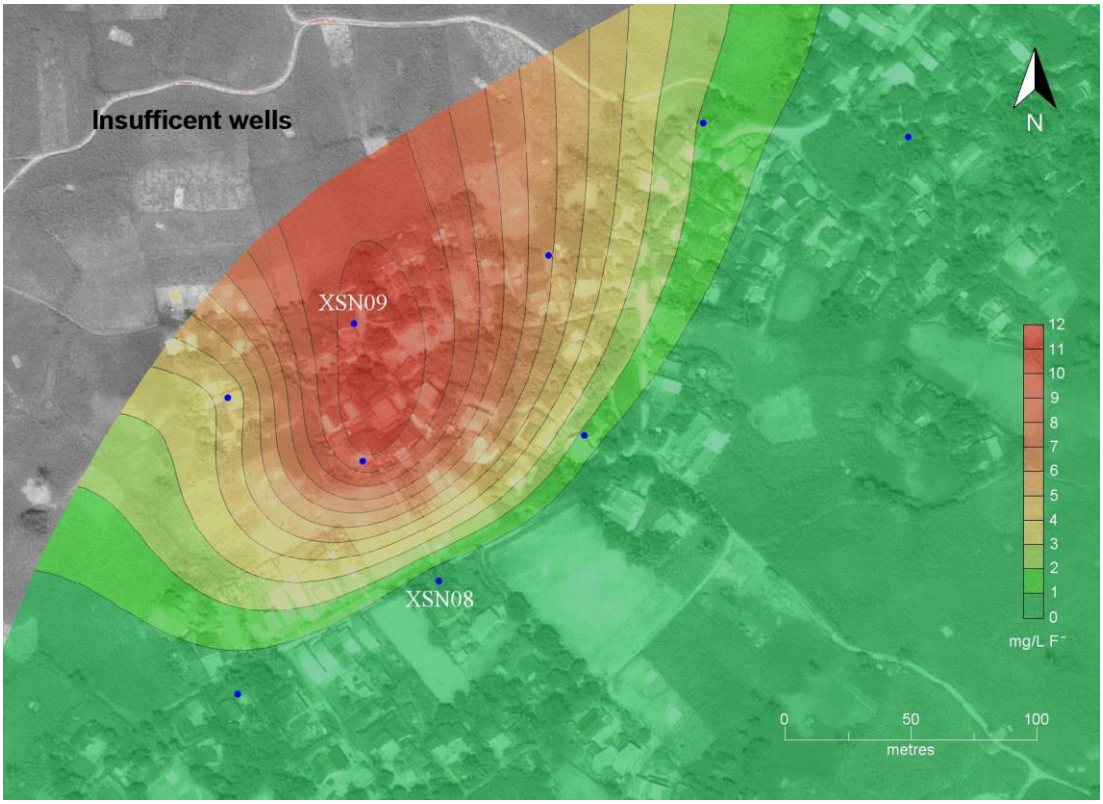


Figure 7.4: Fluoride distribution of the high F^- area in Xuan Son Nam commune. Blue dots show sampled well locations. (Imagery from Google Earth)

Xuan Quang 1

This commune has wells with predominately less than 0.5 mg/L F^-. In the northern part of the commune only one well (XQA04) had a F^- concentration of 4.57 mg/L, while the rest were below 1 mg/L. It appears that this could be a localised high F^- area, but as the well lies in a sparsely populated area, its extent is unknown. Many of the sampled wells in the extreme south of this commune had F^- concentrations in the range of 3 – 4 mg/L F^-. Groundwater in this southern most part of the commune appears to be generally high in F^-, including the adjoining region of Xuan Phuoc commune.

Xuan Quang 2

Xuan Quang 2 commune contains hot springs and some of the wells in this commune had the highest F^- concentrations found in Xuan Dong district in the present study. The hot springs contained F^- concentrations of 20 – 22 mg/L. Many of the wells near the hot springs that were sampled also had highly elevated F^- concentrations. Wells within 2 km of the hot springs had F^- concentrations in the range of 1 – 12 mg/L, with one (XQB30) having a F^- concentration of 18.28 mg/L. However, most wells further from the hot springs had very low F^- concentrations.

Xuan Quang 3

This small commune appears to have a localised high F^- area as revealed by the sampling. Well XQC09 had a F^- concentration of 6.27 mg/L and is surrounded by wells with F^- concentrations generally lower than 2 mg/L. However, this area of the commune is also close the hot springs in the adjoining commune of Xuan Quang 2, and therefore may have been contaminated by them. The majority of the wells in this commune were found to be generally low in F^-, and apart from the aforementioned localised high F^- area, the overall commune is considered as being of low fluorosis risk.

Phu Mo

The groundwater of the remote Phu Mo commune was generally found to be low in F^-. Two notable exceptions were samples PHM04 and PHM15, which had F^- concentrations of 2.24 and 2.83 mg/L respectively. However, the well that sample PHM04 was taken from was re-sampled during the second fieldtrip and was found to have a value of just 0.30 mg/L. This much lower value may have resulted from seasonal fluctuations, as discussed in section 7.2.5.

There is also an abandoned fluorite mine, which is located in an unpopulated area of the commune. Owing to this isolation, there were no wells in the vicinity of this mine and therefore no sampling could be done to determine if this deposit had any influence upon the groundwater F^- concentrations. Furthermore, all the villages in Phu Mo commune either have or are in the process of implementing piped water for

drinking purposes, so the health issues relating to this high F^- area are not considered to be of future significance.

Da Loc

This commune is of low fluorosis risk, with no sampled wells showing any sign of high F^-. The highest recorded well water sample had a F^- concentration of just 0.88 mg/L. However, caution must be laid, as there may be undetected high F^- areas, as was initially the case of Xuan Son Nam commune.

7.2.2 Hot Springs

Owing to the restricted scope of the study, a source of the high F^- containing groundwater could not be linked directly to hot springs; however, several observations are pertinent and conclusions from these can be drawn. As the study area is non-volcanic, all hot springs in Dong Xuan district are derived from deep circulating groundwater. There are two hot spring locations in the district, one in Xuan Long commune and the other in Xuan Quang 2 commune. The Xuan Long hot spring is a single fracture spring and the temperatures recorded when sampled during both fieldtrips were 51°C and 52°C. In the Xuan Quang 2 commune the thermally heated water discharges as seepages in an area of paddocks and from a fracture in a rocky outcrop. The temperature of the water issuing from these outlets ranged between 63 – 78°C. All the hot springs occurring in both communes in Dong Xuan district had a F^- concentration between 19 – 22 mg/L. Furthermore, all the wells that were sampled in Xuan Quang 2, apart from one (XQB30), had F^- concentrations that were considerably less than this. Water from well XQB30 was recorded as 18.28 mg/L F^- and comparing its composition to that of the hot spring water (Appendices 1 & 2), it appears essentially to be hot spring water that has been isolated, allowed to cool, and then slightly diluted by mixing with groundwater.

As discussed by Kim and Jeong (2005), deep circulating water is enriched with F^- from F^--rich minerals in the granitic bedrock. Although the deep circulating water becomes enriched in major cations, calcium is removed from the groundwater by precipitation of calcite at the higher pH found in deep aquifers. The relationship of

low calcium and high fluoride in Figure 5.23 shows this process. Also apparent is the elevated pH in the hot spring water as shown in Figure 5.32.

As shown on the piper diagrams (Figures 5.12 – 5.17), there is a general move towards the Na-HCO_3 type signature as the F^- concentration increases in the groundwater. The highest F^- concentrated samples, the hot springs, all lie in this Na-HCO_3 zone. As discussed by Su *et al.* (2012), conditions that lead to low calcite solubility and high F^- concentrations see this general trend.

Furthermore, high F^- areas in Dong Xuan district are more common when groundwater is in contact with particular igneous intrusions, as discussed in section 7.2.4. Owing to the deep circulating nature of the hot spring water, it is possible that this has mixed with groundwater contained in unconfined aquifers, resulting in elevated F^- concentrations of groundwater at some distances from individual hot springs. In areas to the north and south of the district, which are apparently devoid of hot springs, there is the possibility of deep percolating thermal groundwater being captured by the unconfined aquifers resulting in their contamination by fluoride.

7.2.3 Fluorite Deposits

As with the case of hot springs, the scope of this study did not include detailed assessment of the effects of fluorite deposits on the surrounding F^- groundwater concentration. The two known fluorite deposits in Dong Xuan district, an abandoned mine in the Phu Mo commune and an active mine in the Xuan Lanh commune, are in remotely populated areas. There are few wells in the vicinity of the Xuan Lanh mine and no wells close to the abandoned mine of Phu Mo commune. Owing to this remoteness, it seems unlikely that the mined fluorite deposits contribute significantly to the F^- problem in Dong Xuan district. The few wells that were sampled near the fluorite mine in Xuan Lanh commune had F^- concentrations less than 1.5 mg/L and the well that was located at the mine (XLN01) had only 1.01 mg/L F^-. It is possible, however, that other unknown fluorite deposits exist, particularly in the north of Xuan Lanh commune, which do contribute to the moderate fluorosis risk areas of this commune. This is partly supported due to the relatively high F^- background concentrations of 0.3 – 0.4 mg/L in the river that were found in this area and were

discussed earlier. Furthermore, in the areas of Xuan Quang 1 commune that are of no fluorosis risk, the river had F^- concentrations of just 0.10 mg/L.

7.2.4 Underlying Geology

To a limited extent, the underlying geology does appear to have an influence on the F^- concentration of the groundwater. Figure 7.5 shows a thematic map of F^- concentration in sampled wells compared to the underlying geology. However, owing to the limited scope of the study, no analysis was performed on the rocks to determine their F^- concentration and only observed trends are outlined here.

Medium to coarse-grained intrusions of biotite granosyenite and biotite granite, of the Van Canh Complex are widespread in the northern parts of Dong Xuan district and underlie many of the high F^- containing wells that were sampled in the district. All high F^- containing wells of Xuan Lanh commune and the northern part of the bordering Xuan Long commune (Figure 7.1) are underlain by Phase 2 ($\gamma\zeta T_2 vc_2$) of the Van Canh Complex. Although the majority of wells in the high F^- containing groundwater areas of Xuan Quang 2 rest on fluvial deposits, these are only several metres thick and the wells in this area protrude into the weathered top layers of Phase 2 of the underlying Van Canh Complex.

The high F^- areas of Xuan Phuoc, discussed in section 7.2.1, while resting on thin Upper Holocene fluvial deposits, protrude into the weathered upper layers of the finer grained granite and granosyenites of Phase 3 of the Van Canh Complex. The area in Xuan Son Nam commune containing wells with high F^- groundwater, discussed in section 7.2.1, consists of fluvio-marine deposits from the Upper Pleistocene (amQ_{III}^3). This is a relatively thin deposit of sand and clay, approximately 2 – 5 metres thick. Underlying this is the Nha Trang Formation; however, this area is also in close proximity to the Van Canh Complex and its actual lateral extent beneath the fluvio-marine deposits is uncertain.

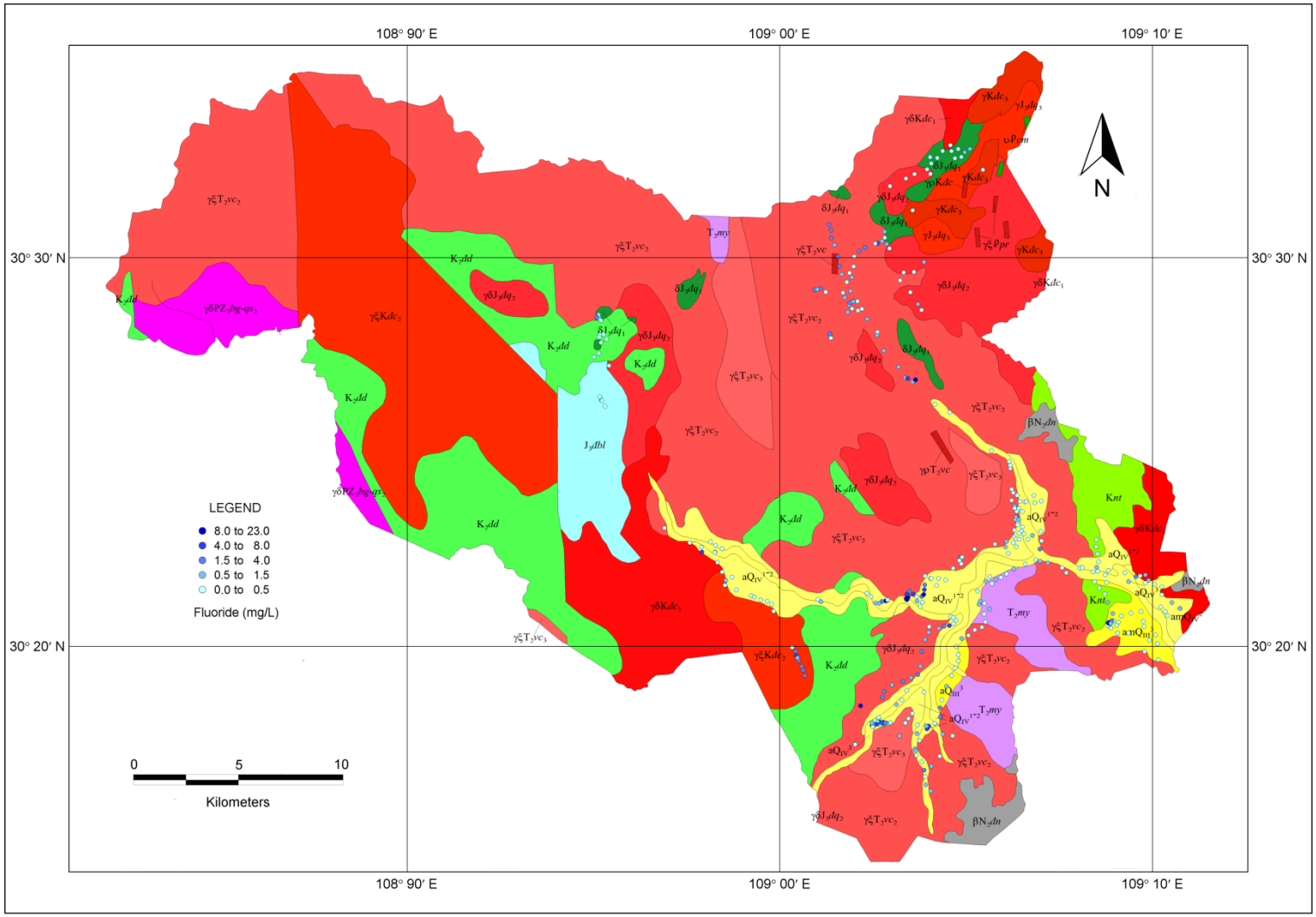


Figure 7.5: Relationship of fluoride concentration in wells and geology of Dong Xuan district. (Map modified from Ministry of Natural Resources and Environment - Department of Survey and Mapping Vietnam)

Other intrusive igneous complexes may also contribute to the elevated F^- in the groundwater of the district. The high F^- containing wells in the southern part of Xuan Quang 2 commune rest on Phase 2 of the Deo Ca Complex. Interestingly, the border between Xuan Quang 2 and Xuan Phuoc communes runs along a band of felsic volcano-sedimentary rocks of the Don Duong Formation. Across the border in Xuan Phuoc commune are several high F^- containing wells that rest in Phase 2 of the Dinh Quan Complex. It is unfortunate there were no wells in this area of the Don Duong Formation, in which subsequent sampling could have determined if this band between the two complexes also hosted high F^- groundwater. Absence of high F^- groundwater in this band could have strengthened the observation that these complexes contribute to the elevated F^- groundwater.

7.2.5 Seasonal Fluctuations in Fluoride Concentration

The majority of the wells that were re-sampled during the second fieldtrip gave values that were similar to those obtained from the first fieldtrip. However, as can be seen from Table 5.1, a small proportion of wells gave values that differed significantly from those of the first trip. For example, water from well XQB08 was recorded as containing 12.48 mg/L on the first occasion, yet 6.64 mg/L on the second time of sampling eight months later. When viewing its location on the contour map generated by the gridding program Surfer® (plotted as its average value of 9.56 mg/L F^-), it lies close to the edge of a steep concentration gradient (Figure 7.6) that exists between it and well XQB22. The figure does not attempt to distinguish between wells in the range of 8 - 20 mg/L F^- but instead emphasizes low and high F^- containing wells. The position of the well would make it more vulnerable to seasonal changes, as any slight change in the contour, such as seasonal shrinking of a high F^- area caused by a change in recharge, would produce a large change in its concentration. This principle is shown theoretically in Figure 7.7, where two samples' seasonal F^- concentrations undergo different degrees of change depending on their location. This seasonal fluctuation may result in areas of high F^- groundwater increasing then decreasing, but the overall F^- distribution pattern is maintained.

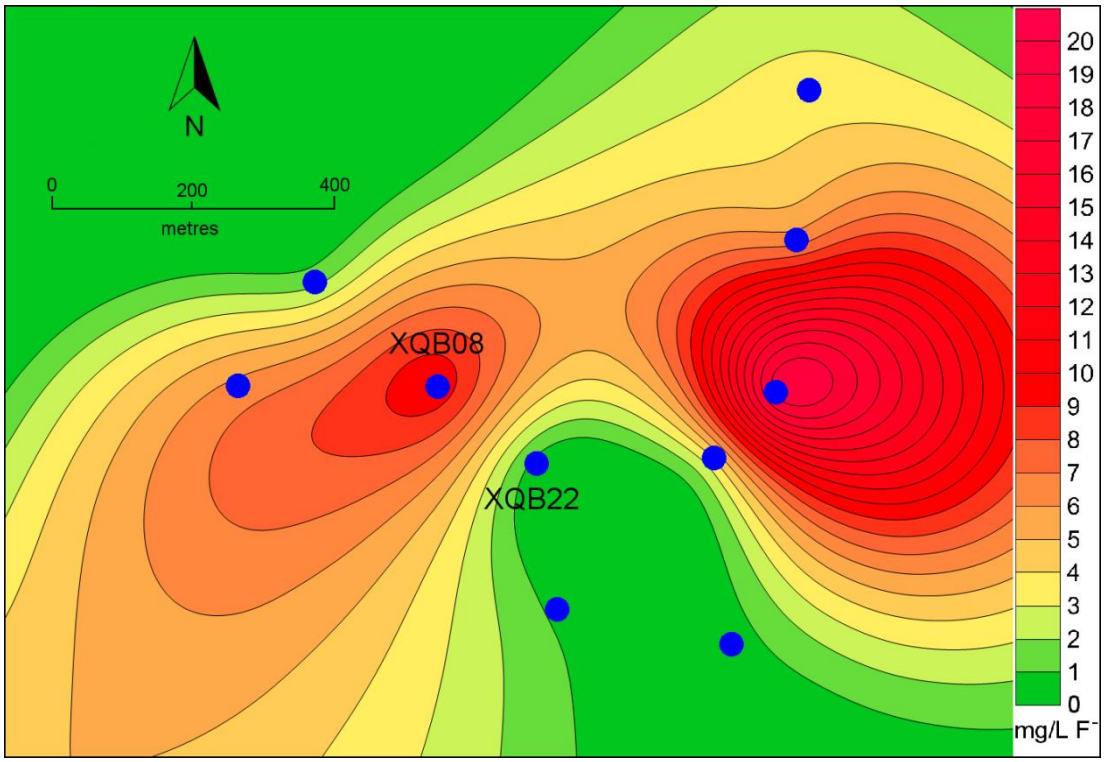


Figure 7.6: Position of well XQB08 in relation to F^- concentration contours.

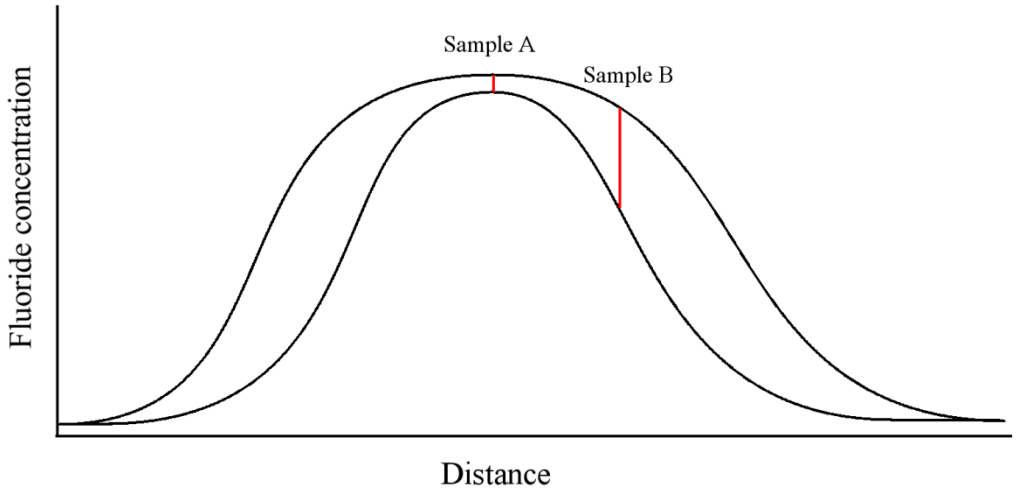


Figure 7.7: Schematic diagram showing theoretical seasonal shrinking of a high F^- area.

Also to be considered is the ribbon development of the district, i.e. the roads are flanked by housing with rice paddies filling the areas in between. Sampling can only occur generally along the roads, as few wells exist far from the roads. This can be seen from Figure 5.1 where sampling locations generally follow the roads with large

gaps signalling the regions that lie between villages where no wells exist. A low confidence level exists in those areas of the risk map without residential housing. However, this is of little direct consequence to human health risk, as these areas are not sourced for drinking water. The only concern is uptake of F^- by rice resulting in the possible assimilation of F^- into the body. Studies by Vu (2008) showed that little uptake of F^- by rice occurred in high F^- containing rice paddies and it is well known that the dominant route of F^- absorption by the body is through drinking water (Murray 1986).

7.2.6 Interpretation of the Fluorosis Risk Map

The fluoride distribution and fluorosis risk maps must be interpreted with caution. They should be regarded as a general indication of F^- groundwater concentration in shallow dug wells. Importantly, consideration must be given to possible seasonal changes to maps. Furthermore, interpolation between sampled wells can be misleading as undetected high F^- areas between sampled wells could be present. Some of the areas that had wells with an overall low F^- concentration also had the occasional well that was high in F^-, indicating possible high F^- areas such as shown in Figures 7.3 and 7.4. Owing to the time constraints on the present study, not all high F^- areas that were identified could subsequently be subject to detailed sampling. However, two high F^- areas in the communes of Xuan Son Nam and Xuan Phuoc (Figures 7.3 and 7.4), were studied in detail.

It is important to note that under the sampling regime that was employed in the current study, there is a possibility of missed high F^- areas. For example, in Xuan Son Nam commune, had we not been informed of "the man with the bad teeth", the high F^- area (Figure 7.4) would have been missed and the whole commune would have been considered as being of no fluorosis risk. It was the chance discovery of this one well that resulted in high-density sampling around this well during the second fieldtrip. Although it is not practical to sample every well during investigatory studies, an optimal spacing for the sampling may need to be determined to ensure maximum probability of detecting all high F^- areas. Before considering this any further, first compare the high F^- area in Xuan Son Nam commune with the high F^- area that was also studied in Xuan Phuoc commune (Figure 7.3). The difference with the high F^- area in Xuan Phuoc is that it was detected adequately by

the standard sampling regime. As shown in Figure 7.3, there is a very sharp demarcation at the southern edge. This could be due to a fault, fractured aquitard or some other geological feature; however, this is difficult to detect without a multidiscipline study. What is of importance in this study is that sudden changes in groundwater F^- concentrations can occur within a small distance, in this case a change from 6.1 mg/L to 0.3 mg/L within approximately 30 meters. When considering ideal sample spacing, the sudden changes in F^- concentration caused by localised high F^- areas must be accounted for. There is, however, little information of what size an average high F^- area is until more well samplings can be completed. Despite the uncertainties mentioned above, the fluoride distribution map does provide a useful generalised distribution of F^- within the shallow groundwater beneath the populated areas of the Dong Xuan district.

8 CONCLUSIONS

8.1 Ninh Hoa District

A comparative study of 57 wells from the Ninh Hoa district showed that the F^- concentration of the groundwater in the majority of wells showed little change over the maximum nine-year period between the investigations of Vu (2008) and the present study. Of the re-sampled wells, only 2 out of 13 (NT047 and NX242) that were deemed safe as drinking water sources by Vu (2008), were found in this study to exceed the WHO recommended limit of 1.5 mg/L F^-. From a practical consideration when evaluating the long-term effectiveness of a GIS in the management of human exposure to high F^- groundwater, there will be a small percentage of samples (15% in this study) that may change their status from being marginally safe to unsafe for drinking purposes. Accordingly, it is recommended that wells with water containing F^- in the range of 1 – 2 mg/L, be periodically monitored.

This study revealed that wells with higher F^- concentrations are the ones most likely to fluctuate, and this is possibly due to seasonal factors, such as variation in source and dilution. Regardless of the F^- fluctuation in these wells, the F^- concentrations has in every case remained consistently above the WHO recommended limit of 1.5 mg/L F^-. Most significantly, it is evident from the study that profound misclassification of individual drinking water sources, such as between low F^-/safe for consumption and elevated F^-/representing a high risk to health, is unlikely to arise due to temporal variations on the scale of several decades.

8.2 Dong Xuan District

The present study has provided Dong Xuan district an in-depth analysis of the F^- distribution amongst wells in all its ten communes and the risk of fluorosis within those communes. The communes at greatest risk are Xuan Phouc, Xuan Quang 1, 2 and 3, and Xuan Lanh, with a localised area in Xuan Son Nam identified as also being at risk. Although the scope of this study did not allow for a detailed study of the source of F^- in the groundwater of Dong Xuan district, it seems reasonable to

suggest that the presence of fluoride-rich hot springs and the possibility of unknown fluorite deposits in the district have contributed to the elevated concentrations of F^- detected in the groundwater.

This study has shown that it is unsatisfactory to interpolate between tested wells, as localised high F^- areas can exist. The fluorosis risk map, as presented in this thesis, should not be used as a definitive guide upon which to base decisions on well safety and care should be taken in its interpretation. Rather, it should be used as a general guide to help understand and protect groundwater resources in the more problematic areas, and these areas should be addressed first for further well testing for F^- concentration. By increasing the number of known safe wells for water consumption, the local residents will have more opportunity to obtain drinking water at a closer proximity to their home.

Despite the limitations of interpolation, there is now an extensive database of wells in each commune of Dong Xuan district, and these can provide a safe source of domestic water. Ideally, a system now needs to be developed to ensure residents can access wells with known safe F^- levels and this will involve wells being clearly identified.

This study was successful in its goal of establishing the distribution of F^- in the shallow groundwater accessed by domestic wells in Dong Xuan district, and providing reliable F^- concentration data within a GIS. However, the study is merely one component required for a management strategy that may effectively remove the human health risk of high F^- groundwater. While further scientific study can extend the database of well water compositions, for this information to be useful it must be employed effectively within social schemes for water management. It is important that the Provincial Committee of Phu Yen institutes the means to disseminate the information to the local residents, and to ensure they are knowledgeable of the risk of F^-.

9 RECOMMENDATIONS AND REMEDIATIONS

9.1 Remediations

It is easy to suggest remediation strategies by using fluoride-removing techniques that have been widely suggested and locally employed in other endemic areas of high F^- containing groundwater. Where these have been employed in certain areas of Ninh Hoa district, very limited, if any, success has been gained. With the poverty of local communes and ineffective governance, implementation of the techniques and the necessary monitoring programs required for their success, are unlikely to occur, as has been the case in Ninh Hoa district.

Using rainwater as the sole source of drinking water is also unsuitable in Dong Xuan district. With an average annual rainfall of 2000 mm and an extensive dry season, sufficient rainfall storage would be impractical, as has proved the case in Ninh Hoa district despite the use of earthenware storage jars of 2000 litre capacity. The most effective measures to mitigate the impact of high F^- containing groundwater in Dong Xuan district are:

- The use of river water: Procuring river water in Dong Xuan district has merit, as the district is industrially under-developed and there is little evidence of resultant river pollution. However, caution must be exercised in Xuan Long commune as river water with F^- concentrations as high as 5 mg/L downstream from the fluorite mine has been reported by Thang *et al.* (2004). Furthermore, the installation of a centralised plant to sterilise the water from bacterial infections would be required.

  River water could be pumped directly from the river, filtered and sterilised, and delivered via pipeline. A simpler and less expensive method of using a bore placed by the riverside and using the river sediments as a natural filtering medium could also be used, as has been done for in Xuan Son Bak commune. However, as discussed in 7.2.1, this would not remove F^-.

Piped water from uncontaminated water sources in highland areas has already been implemented in the remote commune of Phu Mo, and such an option provides an effective, but expensive, resolution to the problems in Dong Xuan and other districts in this region of Vietnam posed by high F^- groundwater.

- Well isolation: This involves little money to implement once safe wells have been identified by projects such as this study. Furthermore, marking or painting the wells that have low F^- concentrations and educating locals of the importance of using wells that are known to have safe F^- levels, will promote local awareness of the problem and help develop a persistent practice of safe well usage. The wide variation of F^- concentration occurring locally in wells, and the frequent presence of low F^- wells in close proximity to F^--rich wells, should facilitate the use of different wells for drinking supply and for only washing. Monitoring of low wells in close proximity of high wells should be done regularly.

Mitigation measures in the short to medium-term in Dong Xuan district are likely to have more success if they require little money and can be instigated at the commune level. This is due to firstly, the limited funds available and secondly, as it is the commune leaders themselves who are directly affected by the F^- problem they are more likely to support the remediative measures.

9.2 Recommendations for Future Work

The following areas of future study are suggested:

- Fluoride analysis of the various rock types to determine the relationship of the underlying geology to the identified high F^- areas.

- Study of soil profiles and groundwater conduit transportation systems.

- Oxygen isotopic analysis of groundwater and hot spring water may help to determine how hot spring water is distributed in groundwater.

- While the focus of the study was the geochemical distribution of fluoride, detailed hydrogeological studies would help establish groundwater flow patterns and improve knowledge on the distribution of high F^- risk areas.

It is acknowledged that such recommendations are expensive and beyond the financial resources of individual communes. By raising the F^- concern, it is hoped that more initiatives from the government to support and fund further analysis will occur.

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APPENDIX A

W = well, S = stream/river, L = lake, B= bore

Sample ID	Commune	Village	Name of owner	Type	Easting (UTM) (m)	Northing (UTM) (m)	Sampling Date	Well Depth (m)	Water Level (m)	F^- (FISE) (mg/L)	pH	Temp (°C)	EC (mS/cm)	DO (mg/L)	Eh (mV)	TDS (mg/L)
DLC01	Da Loc	6th village	Tran Van Hoa	W	293335	1497408	18-Jul-12	7.0	6.3	0.48	6.32	27	0.357	3.8	175	179
DLC02	Da Loc	5th village	Tran Quang Khai	W	292717	1498402	18-Jul-12	4.8	3.0	0.51	6.62	28	0.349	3.2	157	175
DLC03	Da Loc	5th village	Le Tam	W	292467	1498239	18-Jul-12	3.3	3.0	0.88	6.55	28	0.441	4.1	160	221
DLC04	Da Loc	5th village	Huynh Van Hung	W	292312	1498015	18-Jul-12	4.7	4.0	0.19	6.41	28	0.181	3.7	180	91
DLC05	Da Loc	5th village	Nguyen Thanh Cong	W	291992	1497960	18-Jul-12	3.5	3.0	0.34	6.58	28	0.734	3.2	190	367
DLC06	Da Loc	4th village	Tran Minh Tam	W	292156	1498396	18-Jul-12	8.1	7.7	0.09	5.86	28	0.109	4	170	55
DLC07	Da Loc	4th village	Nguyen Tien	W	291836	1498297	18-Jul-12	6.9	6.6	0.45	6.25	28	0.424	3.6	202	212
DLC08	Da Loc	3rd village	Huynh Van Bong	W	291785	1498572	18-Jul-12	7.5	6.3	0.34	6.45	29	0.345	2.1	188	173
DLC09	Da Loc	3rd village	Nguyen Dao Tuan	W	291414	1498300	18-Jul-12	5.5	4.5	0.14	6.35	28	0.577	3.8	186	289
DLC10	Da Loc	3rd village	Tu Tan	W	291152	1497977	18-Jul-12	6.0	5.5	0.18	6.48	28	1.109	3.1	180	555
DLC11	Da Loc	3rd village	Tran Van Ban	W	290812	1498013	18-Jul-12	7.0	6.5	0.43	7.04	29	0.624	3.2	178	312
DLC12	Da Loc	3rd village	Le Thi Mai	W	290867	1497715	18-Jul-12	3.5	2.8	0.33	6.84	28	0.879	2.9	210	440
DLC13	Da Loc	3rd village	Bui Van Khanh	W	290668	1497436	18-Jul-12	4.5	4.0	0.26	6.34	28	0.38	3.3	210	190
DLC14	Da Loc	3rd village	Bui Hac Long	W	290823	1497212	18-Jul-12	5.1	4.5	0.29	6.47	28	0.407	43	200	204
DLC15	Da Loc	2nd village	Vo Sau	W	290069	1497208	18-Jul-12	4.8	3.5	0.12	6.35	29	0.511	3.8	200	256
DLC16	Da Loc	2nd village	Pham Thi Huong	W	289654	1496997	18-Jul-12	6.0	4.5	0.11	6.81	28	1.71	2.6	210	855
DLC17	Da Loc	1st village	Doan Van Cho	W	288897	1496636	18-Jul-12	5.0	3.5	0.33	6.75	29	0.71	2.8	206	355
LHA01	La Hai	Long Binh	Trinh Thi Kim Lien	W	294818	1481402	12-Jul-12			0.68	6.85	28	0.851	2	163	426
LHA02	La Hai	Long Binh	Phan Sach	W	294822	1481302	12-Jul-12	8.3	6.0	0.12	5.88	28	0.21	3.6	200	105
LHA03	La Hai	Long Binh	Pham Thi Thanh	W	294924	1481137	12-Jul-12	4.7	3.7	0.11	5.85	28	0.323	4.6	220	162
LHA04	La Hai	Long Binh	Ho Vinh Ty	W	295189	1481136	12-Jul-12	5.8	1.0	0.24	6.38	28	0.41	2.4	202	205
LHA05	La Hai	Long Binh	Nguyen Thanh Luan	W	294889	1480876	12-Jul-12	7.8	6.7	2.11	7.03	28	1.184	4.6	202	592
LHA05R	La Hai	Long Binh	Nguyen Van Hung	W	294884	1480870	22-Mar-13	7.8	1.5	0.63	6.91	28.1	0.452	1.7	241	226
LHA06	La Hai	Long Binh	Nguyen Huu Dan	W	294992	1480628	12-Jul-12	4.5	2.7	0.09	5.88	29	0.429	3.6	210	215
LHA07	La Hai	Long Binh	no name	W	294956	1480511	12-Jul-12	4.3	2.6	0.08	6.30	30	0.58	3	210	290
LHA08	La Hai	Long Chau	Doan Thanh Ha	W	295135	1480203	12-Jul-12	5.5	2.5	0.24	6.61	29	0.59	2.9	210	295
LHA09	La Hai	Long Chau	Public well at market	W	295027	1480091	12-Jul-12	5.2	2.8	0.27	6.14	28	0.384	2	200	192
LHA10	La Hai	Long Chau		W	294783	1479933	12-Jul-12	13.0	5.5	0.10	6.04	30	0.594	5.9	195	297
LHA11	La Hai	Long Chau	Truong Van Tan	W	294886	1479844	12-Jul-12	9.0	4.0	0.14	6.22	29	0.653	4.5	190	327
LHA12	La Hai	Long Thang	Tran Bay	W	294747	1479649	12-Jul-12	6.6	6.3	0.11	6.18	30	0.39	3.1	175	195
LHA13	La Hai	Long Thang	Dinh Thi Tu	W	294381	1479448	12-Jul-12	9.5	6.0	0.68	6.64	28	0.424	2.4	175	212
LHA14	La Hai	Long Thang	Cao Van Hung	W	294512	1479148	12-Jul-12	7.0	3.5	0.19	6.80	29	0.841	5.2	170	421
LHA15	La Hai	Long Thang	Cao Tan Phuc	W	294884	1479467	12-Jul-12	5.0	1.5	0.26	6.39	29	0.816	4	176	408
LHA16	La Hai	Long Binh	Trinh Thi Yen Phuong	W	294870	1480782	13-Jul-12	7.2	2.7	0.08	6.06	28	0.332	5.8	165	166
LHA17	La Hai	Long Chau	Dang Khac Hien	W	296023	1479352	13-Jul-12	8.0	7.0	2.87	6.96	28	1.122	5.5	190	561
LHA18	La Hai	Long Ha	Ngo Son Ha	W	293722	1477710	13-Jul-12	6.3	2.5	0.42	6.40	28	0.244	2.8	190	122

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Sample ID	Commune	Village	Name of owner	Type	Easting (UTM) (m)	Northing (UTM) (m)	Sampling Date	Well Depth (m)	Water Level (m)	F^- (FISE) (mg/L)	pH	Temp (°C)	EC (mS/cm)	DO (mg/L)	Eh (mV)	TDS (mg/L)
LHA19	La Hai	Long Ha	Nguyen Van Su	W	293919	1477896	13-Jul-12	9.0	6.5	0.54	6.95	28	0.467	4.8	190	234
LHA20	La Hai	Long Ha	Le Van Cu	W	293626	1478043	13-Jul-12	5.8	3.0	0.44	6.61	28	0.414	3.5	136	207
LHA21	La Hai	Long Ha	Dang Ngoc Tan	W	293443	1477818	13-Jul-12	8.8	7.0	0.54	7.31	28	1.332	2.8	160	666
LHA22	La Hai	Long Ha	Do Thi Phu	W	294166	1478003	13-Jul-12	6.5	4.8	0.46	6.80	27	0.831	3.2	175	416
LHA23	La Hai	Long Ha	Pham Chi Cuong	W	294426	1478180	13-Jul-12	5.5	3.0	0.19	6.28	29	0.633	4.8	202	317
LHA24	La Hai	Long Ha	Pham Hong Trung	W	294774	1478392	13-Jul-12	6.0	5.5	0.72	6.20	27	0.122	2.3	212	61
LHA25	La Hai	Long Ha	Le Minh Hung	W	295328	1478636	13-Jul-12	7.0	5.5	0.45	5.79	30	0.223	5.4	200	112
LHA26	La Hai	Long An	Hoang Thi Tu	W	297285	1478219	13-Jul-12	4.8	3.2	0.30	5.96	29	0.156	2.7	215	78
LHA27	La Hai	Long An	Nguyen Van Anh	W	297084	1478456	13-Jul-12			0.24	5.65	29	0.16	2.1	211	80
LHA28	La Hai	Long An	Truong Thi Lun	W	296403	1478682	13-Jul-12	7.0	6.0	0.62	5.62	29	0.109	3.8	223	55
LHA29	La Hai	Long An	Tran Van Tuan	W	296030	1478768	13-Jul-12			0.78	6.26	29	0.292	5.6	202	146
LHA30	La Hai	Long An	Le Van Nam	W	295828	1478843	13-Jul-12	7.3	6.0	0.10	5.89	28	0.533	5	215	267
LHA31	La Hai	Long Chau	Public well	W	296106	1479742	20-Mar-13	7.0	4.5	0.27	5.80	28	0.279	2.9	304	140
LHA32	La Hai	Long Chau	Vo Thanh	W	296073	1480196	20-Mar-13	9.0	4.0	0.44	6.60	27.4	0.774	4.5	270	387
LHA33	La Hai	Long Thang	Nguyen Thi Tinh	W	292896	1479348	22-Mar-13	6.0	3.0	0.17	6.80	27.7	0.28	3.5	220	140
LHA34	La Hai	Long Thang	Huynh Cong Danh	W	293872	1479584	22-Mar-13	8.0	5.0	0.43	7.34	28.6	1.064	4.8	189	532
LHA35	La Hai	Long Thang	Phan Xuan Hoa	W	294428	1479712	22-Mar-13	8.0	4.0	0.78	6.97	27.5	0.617	3.7	215	309
LHA36	La Hai	Long Chau	Tran Van Hai	W	295036	1479817	22-Mar-13	5.0	3.5	0.21	7.40	28.1	0.516	1.7	187	258
LHA37	La Hai	Long Chau	Public well	W	294810	1480251	22-Mar-13	7.0	1.5	0.44	6.02	27.9	0.312	2.7	250	156
LHA38	La Hai	Long Binh	To Van Minh	W	295023	1481293	22-Mar-13	4.0	1.5	0.08	6.09	28	0.124	2.5	286	62
LHA39	La Hai	Long Binh	Ho Thi Nam	W	295027	1480753	22-Mar-13	6.0	1.5	0.66	6.81	27.6	1.678	4.4	235	839
LHA40	La Hai	Long Binh	Bui Van Duong	W	295183	1480399	22-Mar-13	5.0	3.5	0.10	6.82	27.1	1.149	3.5	260	575
LHA41	La Hai	Long Chau	Nguyen Thi Quy	W	295257	1480072	22-Mar-13	8.0	2.5	0.39	6.66	27.3	1.058	4	925	529
LHA42	La Hai	Long Chau	Nguyen Trung	B	295454	1479818	22-Mar-13	10.0	3.0	0.24	6.20	29.6	0.242	2.1	247	121
LHA43	La Hai	Long Chau	Nguyen Thanh Long	B	295663	1479991	22-Mar-13	18.5		0.64	6.53	27.5	0.1505	2.3	180	75
PHM01	Phu Mo	Phu Giang	commune health stations	W	275053	1489224	14-Jul-12	4.5	2.0	0.38	6.95	28	0.263	2.4	206	132
PHM02	Phu Mo	Phu Loi	La Mo Bon	W	274941	1490554	14-Jul-12	5.5	3.5	0.04	5.43	28	0.074	2.6	243	37
PHM03	Phu Mo	Phu Loi	Nguyen Van Binh	W	274940	1490471	14-Jul-12	4.8	1.1	0.41	6.54	29	0.879	3.8	225	440
PHM04	Phu Mo	Phu Loi	Ma Tam	W	274972	1490364	14-Jul-12	7.1	6.4	2.24	7.37	29	0.835	2.8	192	418
PHM04R	Phu Mo	Phu Loi	Ma Tam	W	274973	1490361	18-Mar-13	7.1	1.0	0.30	7.85	28	0.486	1.7	163	243
PHM05	Phu Mo	Phu Giang	La Thanh Hau	W	275171	1489620	14-Jul-12	4.5	1.8	0.18	6.58	28	0.266	3.9	205	133
PHM06	Phu Mo	Phu Giang	La Lan Cung	W	274996	1489592	14-Jul-12	5.3	4.5	0.26	6.46	28	0.292	3.8	196	146
PHM07	Phu Mo	Phu Giang	Ma Lui	W	274972	1489495	14-Jul-12	4.5	2.8	0.28	6.45	28	0.344	3.3	220	172
PHM08	Phu Mo		river water sample	S	275434	1488132	14-Jul-12			0.17	7.93	32	0.046	7.2	190	23
PHM09	Phu Mo	Phu Tien 2	La Mo Nut	W	275242	1486191	14-Jul-12	4.0	2.7	0.24	6.18	30	0.201	3.6	155	101
PHM10	Phu Mo	Phu Tien	La O Thi Sot	W	275072	1486481	14-Jul-12	3.5	2.3	0.14	6.38	29	0.391	3.2	185	196
PHM11	Phu Mo	Phu Giang	La O Hòa	W	274723	1488541	14-Jul-12	9.2	7.5	0.25	6.69	29	0.329	3.4	216	165
PHM12	Phu Mo	Phu Giang	La Lan Dung	W	274960	1488730	14-Jul-12	9.0	4.0	0.09	5.99	28	0.475	4.6	200	238
PHM13	Phu Mo	Phu Giang	Phu Mo Shool	W	275322	1489390	18-Mar-13	7.0	5.0	0.04	5.68	26.5	0.056	1.2	280	28
PHM14	Phu Mo	Phu Loi	A. Ma	W	274858	1490430	18-Mar-13	3.5	0.5	2.83	7.66	27.1	1.099	1	202	550

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Sample ID	Commune	Village	Name of owner	Type	Easting (UTM) (m)	Northing (UTM) (m)	Sampling Date	Well Depth (m)	Water Level (m)	F^- (FISE) (mg/L)	pH	Temp (°C)	EC (mS/cm)	DO (mg/L)	Eh (mV)	TDS (mg/L)
PHM15	Phu Mo	Phu Tien	La O My	W	275092	1486472	18-Mar-13			0.49	6.70	27.8	0.32	2.8	253	160
PHM16	Phu Mo	Phu Tien	Phu Tien Shool	W	274992	1486648	18-Mar-13	3.0	2.5	0.23	6.60	27.3	0.155	3.2	258	78
PHM17	Phu Mo	Phu Loi	River	S	275060	1490284	18-Mar-13			0.16						
XLG01	Xuan Long	Long Nguyen	hot spring	HS	290095	1487421	10-Jul-12			19.28	8.76	52	0.55		-126	275
XLG01R	Xuan Long	Long Nguyen	Tra O hot spring	HS	290093	1487414	24-Mar-13			19.19	8.98	51.2	0.585		-77	293
XLG02	Xuan Long	Long Nguyen	Phan Van Bao	W	289955	1487311	10-Jul-12	4.2	3.8	1.08	6.07	29	0.161	5.9	125	81
XLG03	Xuan Long	Long Nguyen	Dinh Thi Sau	W	289592	1487512	10-Jul-12	4.5		3.34	6.46	30	0.267	4.1	200	134
XLG03R	Xuan Long	Long Nguyen	Tran Van Lan	W	289589	1487508	24-Mar-13	4.5	2.0	1.13	6.36	27.7	0.433	3.9	256	217
XLG04	Xuan Long	Long Thach	Public well	W	294621	1483196	10-Jul-12	6.0	4.2	0.16	6.05	28	0.264	3.9	203	132
XLG05	Xuan Long	Long My	Nguyen Thanh Dung	W	294759	1482038	10-Jul-12	6.0	4.5	0.07	5.67	28	0.171	2.4	215	86
XLG06	Xuan Long	Long My	Tran Thi Muoi	W	294933	1481912	10-Jul-12	6.5	5.0	0.12	6.15	28	0.123	4.6	221	62
XLG07	Xuan Long	Long My	Vo Thi Hau	W	295083	1481623	10-Jul-12	4.0	3.5	0.06	5.60	29	0.129	4.8	225	65
XLG08	Xuan Long	Long My	Public well	W	295324	1481590	10-Jul-12	8.5	4.0	0.12	5.94	29	0.132	3.6	220	66
XLG09	Xuan Long	Long Hoa	Nguyen Khac Kiem	W	295780	1481554	10-Jul-12	4.7	4.5	0.19	6.74	28	0.404	5	200	202
XLG10	Xuan Long	Long Hoa	Hiep Thi Ba	W	295740	1481908	10-Jul-12	6.0	4.2	0.15	6.28	27	0.141	4.8	210	71
XLG11	Xuan Long	Long My	Le Tam	W	294681	1481671	10-Jul-12	7.3	3.6	0.14	6.11	28	0.172	6.4	218	86
XLG12	Xuan Long	Long Hoa	Ho Thi Tiet	W	296095	1481630	24-Mar-13	7.0	3.5	0.29	6.94	28.5	0.716	3.8	228	358
XLG13	Xuan Long		River	S	295373	1481610	24-Mar-13			0.29	8.00	33.9	0.079	6	200	40
XLG14	Xuan Long	Long My	Vo Thi Sau	W	294676	1482196	24-Mar-13	8.0	4.5	0.09	7.14	28.5	0.482	3.7	236	241
XLG15	Xuan Long	Long Thanh	Nguyen Ghi	W	294605	1483339	24-Mar-13	5.0	1.0	0.05	6.06	27.4	0.257	3.2	295	129
XLG16	Xuan Long	Long Thanh	Public well	W	293721	1484037	24-Mar-13	6.0	2.0	0.14	6.40	27.5	0.137	3.5	260	69
XLG17	Xuan Long	Long Nguyen	River	S	291719	1485867	24-Mar-13			0.21	7.63	33	0.0721	7	169	36
XLG18	Xuan Long	Long Nguyen	Tran Hoan Thien	W	289718	1487475	24-Mar-13	6.0		5.29	6.60	298	0.28	3.9	93	140
XLG19	Xuan Long			W	288578	1488801	24-Mar-13			0.61	6.20	27.5	0.411	3.2	263	206
XLG20	Xuan Long			S	289279	1488025	24-Mar-13			0.92	7.90	30.9	0.134	8.5	213	67
XLG21	Xuan Long	Long Nguyen	Public well	W	291020	1486246	24-Mar-13	3.5	1.0	0.24	6.27	27	0.108	4.1	270	54
XLG22	Xuan Long			S	294556	1483520	24-Mar-13			0.27	7.56	33	0.0777	6.3	228	39
XLN01	Xuan Lanh		well of fluorite mine	W	287777	1490322	4-Jul-12	9.0	7.5	1.01	5.94	30	0.385	3.2	140	193
XLN02	Xuan Lanh		water of Long Ba river	S	288271	1489687	4-Jul-12			0.34	7.42	35	0.112	6.4	142	56
XLN03	Xuan Lanh		water of Long Ba river	S	287538	1490793	4-Jul-12			0.35	7.33	34	0.114	6.1	165	57
XLN04	Xuan Lanh	Lanh Van	Public well	W	287102	1491175	4-Jul-12	7.5	4.0	0.76	7.71	31	0.365	7.4	145	183
XLN05	Xuan Lanh	Lanh Van	Nguyen Ngoc Phe	W	287116	1491155	4-Jul-12	8.0	5.2	1.00	7.43	30	1.106	7.1	135	553
XLN06	Xuan Lanh	Ha Rai	Dinh De	W	285999	1489535	4-Jul-12			0.70	6.51	28	0.526	5.1	102	263
XLN07	Xuan Lanh	Ha Rai	Mang Thi Cua	W	286016	1489514	4-Jul-12	8.0		0.98						
XLN08	Xuan Lanh	Ha Rai	Mang Duc	W	286051	1489419	4-Jul-12	8.2	7.0	0.21	6.13	29	0.161	5.1	175	81
XLN09	Xuan Lanh	Ha Rai	Mang Trinh	W	285982	1489623	4-Jul-12			3.89	7.12	29	0.86	4	140	430
XLN09R	Xuan Lanh	Ha Rai	Mang Trinh	W	285988	1489620	23-Mar-13			3.96	7.14	27.8	0.984		248	492
XLN10	Xuan Lanh	Xi Thoai	Mang Thi Xom	W	285287	1491713	4-Jul-12	5.3	4.0	1.81	6.37	29	0.326	2.8	152	163
XLN11	Xuan Lanh	Xi Thoai	Mang Chem	W	285563	1491776	4-Jul-12	8.0	7.2	1.61	6.82	29	0.398	4.2	167	199
XLN12	Xuan Lanh	Soi Nga	Mang Que	W	286062	1494552	5-Jul-12	9.5	7.5	1.77	7.03	29	0.927	4.3	100	464

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Sample ID	Commune	Village	Name of owner	Type	Easting (UTM) (m)	Northing (UTM) (m)	Sampling Date	Well Depth (m)	Water Level (m)	F⁻ (FISE) (mg/L)	pH	Temp (°C)	EC (mS/cm)	DO (mg/L)	Eh (mV)	TDS (mg/L)
XLN13	Xuan Lanh	Soi Nga	Mang Gia	W	285974	1494819	5-Jul-12	5.0	3.5	1.52	6.45	29	0.279	2.8	160	140
XLN14	Xuan Lanh	Soi Nga	Mang Thanh	W	286087	1494175	5-Jul-12	5.5	4.5	1.85	6.79	29	0.576	3.3	210	288
XLN15	Xuan Lanh	Lanh Truong	Nguyen Song Thanh	W	286393	1493283	5-Jul-12	6.2	5.2	1.58	7.36	28	1.229	4.9	188	615
XLN16	Xuan Lanh	Lanh Truong	Nguyen Phi Tam	W	286571	1492443	5-Jul-12	6.3	3.6	0.84	6.69	28	0.712	3.6	192	356
XLN17	Xuan Lanh	Lanh Truong	Nguyen Kiem Chu	W	286945	1492510	5-Jul-12	9.0	5.7	0.44	6.46	29	0.386	6.1	210	193
XLN18	Xuan Lanh	Lanh Truong	Nguyen Ngoc Canh	W	287147	1492819	5-Jul-12	7.0	5.8	0.34	6.02	29	0.461	4.3	212	231
XLN19	Xuan Lanh	Lanh Truong	Huynh Van Tho	W	287175	1493283	5-Jul-12	6.5	4.7	0.27	6.35	29	0.425	5.3	186	213
XLN20	Xuan Lanh	Lanh Truong	Cu Thi Khanh Van	W	287696	1493725	5-Jul-12	8.0	6.0	3.18	6.96	29	0.605	3.8	182	303
XLN21	Xuan Lanh	Lanh Cao	Tran Van Bon	W	288731	1493881	5-Jul-12	5.0	3.0	0.74	6.56	29	0.509	4.1	180	255
XLN22	Xuan Lanh	Lanh Cao	Tran Duc Han	W	288859	1493677	5-Jul-12	5.0	4.6	0.28	6.24	29	0.178	3.4	210	89
XLN23	Xuan Lanh	Lanh Cao	Nguyen Che Linh	W	288638	1494179	5-Jul-12	6.5	5.5	0.43	6.47	30	0.886	5.3	210	443
XLN24	Xuan Lanh	Lanh Cao	Nguyen Van Binh	W	288631	1494473	5-Jul-12	6.2	5.0	1.04	6.44	30	0.476	3.6	205	238
XLN25	Xuan Lanh	Lanh Cao	Nguyen Ngoc Minh	W	288286	1493927	5-Jul-12	5.0	4.0	3.86	7.68	30	0.547	6.6	150	274
XLN25R	Xuan Lanh	Lanh Cao	Nguyen Ngoc Minh	W	288285	1493925	23-Mar-13	5.0	1.5	7.38	7.19	27	0.802	4.5	239	401
XLN26	Xuan Lanh	Lanh Tu		S	289363	1492150	7-Jul-12			0.15	5.83	29	0.101	3.8	178	51
XLN27	Xuan Lanh	Lanh Tu	Tran Van Dung	W	290385	1490735	7-Jul-12	7.7	4.2	0.10	6.15	28	0.155	4.6	237	78
XLN28	Xuan Lanh	Lanh Tu	Nguyen Van Cu	W	290217	1491011	7-Jul-12	6.8	5.0	1.40	6.50	28	0.248	2.2	208	124
XLN29	Xuan Lanh	Lanh Tu	Nguyen Thi Dong Xuan	W	289856	1491583	7-Jul-12	7.8	6.3	0.16	6.07	28	0.132	4.6	214	66
XLN30	Xuan Lanh	Da Du	Public well	W	290508	1493026	7-Jul-12	8.0	5.8	0.80	7.45	30	0.668	4.4	190	334
XLN31	Xuan Lanh	Da Du	Public well	W	290030	1492555	7-Jul-12	8.0	7.8	0.45	6.82	29	0.512	5.6	175	256
XLN32	Xuan Lanh	Da Du	Doan Van Xuan	W	289537	1492524	7-Jul-12	7.2	6.0	0.19	6.08	30	0.642	3.9	200	321
XLN33	Xuan Lanh	Lanh Van	Tran Trung Trinh ?	W	286967	1491086	7-Jul-12			2.49						
XLN34	Xuan Lanh	Lanh Van	Nguyen Van Tam	W	287068	1490814	7-Jul-12	7.0	6.0	0.43	5.97	28	0.433	4.8	140	217
XLN35	Xuan Lanh	Lanh Van	Nguyen Van Trac	W	286851	1490644	7-Jul-12	9.5	9.0	0.53	6.49	28	0.724	4.2	180	362
XLN36	Xuan Lanh	Lanh Van	Hoang Ba Thong	W	286987	1491647	7-Jul-12	9.0	7.5	1.22	6.94	28	0.642	3	180	321
XLN37	Xuan Lanh	Lanh Van		W	286820	1492078	7-Jul-12	4.2	3.0	0.14	5.97	29	0.375	5.4	195	188
XLN38	Xuan Lanh	Lanh Van	Dang Sy Bao	W	287054	1492301	7-Jul-12	5.0	2.0	0.52	6.29	28	0.488	4.2	205	244
XLN39	Xuan Lanh	Lanh Truong	Nguyen Dinh Minh	W	286229	1493839	23-Mar-13	8.0	3.0	1.46	6.57	27	0.55	2	276.7	275
XLN40	Xuan Lanh	Lanh Truong	Tong Tran Duc	W	286467	1492837	23-Mar-13	7.5	3.5	1.77	7.00	27.2	1.517	2.4	258	759
XLN41	Xuan Lanh	Lanh Truong	Mr Hung	W	287411	1493541	23-Mar-13	5.5	2.0	3.58	7.09	28	0.978	3.1	247	489
XLN42	Xuan Lanh		Stream	S	288182	1493908	23-Mar-13			0.29	7.50	27.5	0.186	5.4	235	93
XLN43	Xuan Lanh	Lanh Cao	Nguyen Cu	W	288498	1494022	23-Mar-13	7.0	2.0	1.29	6.44	27.3	0.511	3.5	262	256
XLN44	Xuan Lanh	Chi Thoai	La Lan Canh	W	285391	1491728	23-Mar-13	8.0	3.0	1.36	6.65	28.3	0.492	3.2	271	246
XLN45	Xuan Lanh	Chi Thoai	La Lan Tuy	W	285805	1491605	23-Mar-13	5.0	0.5	0.15	5.99	28	0.292	4	304	146
XLN46	Xuan Lanh	Lanh Van	Nguyen Van Manh	W	286631	1491563	23-Mar-13	6.5	2.0	0.46	6.74	27.5	0.208	2.8	277	104
XLN47	Xuan Lanh	Lanh Van	Le Thi Yen	W	286934	1490982	23-Mar-13	8.0	3.0	0.95	6.56	28.3	0.794	3	281	397
XLN48	Xuan Lanh	Lanh Van	Public well	W	287325	1491165	23-Mar-13	5.0	1.2	0.32	8.23	32	0.1724	6.7	191	86
XLN49	Xuan Lanh		River	S	287342	1490718	23-Mar-13			0.38	8.04	34.1	0.0991	7	207	50
XLN50	Xuan Lanh			W	288256	1489554	23-Mar-13			0.98	7.63	35.1	0.151	6.4	210	76
XLN51	Xuan Lanh	Lanh Van	Nguyen Ngoc Do	W	286709	1491336	24-Mar-13	6.5	2.5	0.65	6.90	27.5	0.23	3.2	222	115

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Sample ID	Commune	Village	Name of owner	Type	Easting (UTM) (m)	Northing (UTM) (m)	Sampling Date	Well Depth (m)	Water Level (m)	F^- (FISE) (mg/L)	pH	Temp (°C)	EC (mS/cm)	DO (mg/L)	Eh (mV)	TDS (mg/L)
XPU01	Xuan Phuoc	Phu Xuan B	Nguyen Van Nhi	W	290653	1470935	29-Jun-12	5.9	3.2	1.67	7.35	29	1.402	4.4	120	701
XPU02	Xuan Phuoc	Phu Xuan B	Dong Tre	B	290692	1470939	29-Jun-12			6.55	7.25	29	1.2	2	66	600
XPU03	Xuan Phuoc	Phu Xuan B	Nguyen Van Nga	W	290579	1470934	29-Jun-12	4.2	2.0	1.10	7.04	29	1.621	2.1	139	811
XPU04	Xuan Phuoc	Phu Xuan B	Nguyen Minh Thai	W	290612	1470807	29-Jun-12	3.7	2.5	4.67	7.06	29	0.985	2.4	140	493
XPU05	Xuan Phuoc	group 1, Phu Xuan B	Huynh Duc Thao	W	290990	1471061	29-Jun-12	6.0	4.0	0.28	6.68	29	0.504	3.2	156	252
XPU06	Xuan Phuoc	group 1, Phu Xuan B	Phan Thi Nhi	W	291969	1473698	29-Jun-12	4.5	1.0	0.12	6.34	27	0.143	3	100	72
XPU07	Xuan Phuoc	group 2, Phuoc Hoang	Nguyen Thi Tien	W	291550	1472829	29-Jun-12	9.5	5.0	0.94	7.17	28	1.36	2.4	109	680
XPU08	Xuan Phuoc	group 5, Phuoc Hoang	Cao Thi Thieu	W	291235	1471800	29-Jun-12	9.0	4.0	1.82	6.97	28	1.218	2.2	165	609
XPU09	Xuan Phuoc	group 2, Phu Xuan B	Luong Van Tinh	W	290120	1470587	29-Jun-12	6.0	4.0	1.25	6.87	29	0.351		155	176
XPU10	Xuan Phuoc	group 2, Phu Xuan B	Pham Thi Nui	W	290241	1470248	29-Jun-12	9.3	6.1	0.11	6.19	28	0.342	1.9	175	171
XPU11	Xuan Phuoc	group 3, Phu Xuan B	Nguyen Trung	W	290036	1469859	29-Jun-12	6.4	4.8	0.58	6.96	28	1.086	3.2	190	543
XPU12	Xuan Phuoc	group 8, Phuoc Hoa	Tran Thi Xuan	W	291351	1470547	30-Jun-12	8.0	6.0	1.39	7.14	28	1.441	2.6	122	721
XPU13	Xuan Phuoc	group 8, Phu Hoi	Phan Van Trang	W	291211	1469504	30-Jun-12	4.5	2.0	0.46	6.66	29	1.112	2.4	146	556
XPU14	Xuan Phuoc	group 2, Phu Hoi	Le Van Chien	W	290803	1469027	30-Jun-12	5.0	2.0	0.84	6.88	28	0.511	3.1	150	256
XPU15	Xuan Phuoc	group 2, Phu Hoi	Nguyen Manh Hung	W	290467	1468839	30-Jun-12	4.5	3.0	2.93	7.27	29	1.181	2.1	129	591
XPU16	Xuan Phuoc	group 3, Phu Hoi	Nguyen Thi Kim Bich	W	290518	1468524	30-Jun-12	5.0	3.0	0.24	6.81	27	0.415	3.4	142	208
XPU17	Xuan Phuoc	group 3, Phu Hoi	Huynh Vinh	W	290539	1468136	30-Jun-12	7.0	5.5	0.60	6.43	28	2.667	1.6	168	1334
XPU18	Xuan Phuoc	group 3, Phu Hoi	Nguyen Thang	W	290780	1467844	30-Jun-12	5.5	3.0	1.04	7.47	28	0.731	3.5	145	366
XPU19	Xuan Phuoc	group 2, Phu Hoa	Nguyen Thi Giao	W	290365	1469236	30-Jun-12	5.9	1.8	0.05	7.03	29	0.126	6.5	190	63
XPU20	Xuan Phuoc	Phu Xuan B	Tia stream	S	290088	1469543	30-Jun-12	3.1	0.3	0.10	7.51	30	0.1093	8.6	206	55
XPU21	Xuan Phuoc	group 3, Phu Xuan B	Ngo Hoang	W	290067	1469779	30-Jun-12	7.4	5.2	1.00	6.48	28	1.692	2.4	170	846
XPU22	Xuan Phuoc	group 9, Phu Xuan B	Ngo Dinh Chung	W	290145	1470994	30-Jun-12	4.5	3.5	0.28	6.55	29	0.142	2.5	195	71
XPU23	Xuan Phuoc	group 9, Phuoc Hoa	Huynh Son	W	291833	1470466	30-Jun-12	7.0	5.0	0.04	6.29	28	0.195	4.4	256	98
XPU24	Xuan Phuoc	group 6, Phuoc Hoa	Nguyen Tran Yen	W	291252	1471373	30-Jun-12	6.5	4.5	2.21	7.59	29	1.133	3.9	216	567
XPU25	Xuan Phuoc	group 6, Phuoc Hoa	Nguyen Thanh Duy	W	291248	1471375	30-Jun-12	6.5	2.0	1.90	7.58	30	1.242	3.9	166	621
XPU26	Xuan Phuoc	group 3, Phuoc Hoa	Pham Ngoc Chau	W	290467	1472553	30-Jun-12	6.0	5.0	0.42	6.34	29	0.46	1.1	165	230
XPU27	Xuan Phuoc	group 1, Phu Xuan A	Nguyen Van Dong	W	289449	1473073	1-Jul-12	11.0	4.5	2.36	6.98	28	0.331	2.6	182	166
XPU28	Xuan Phuoc	group 1, Phu Xuan A	Nguyen Bao Duy	W	288939	1472898	1-Jul-12	7.0	3.0	0.58	7.12	29	0.625	3.7	183	313
XPU29	Xuan Phuoc	group 2, Phu Xuan A	Phung Thi Yen	W	288556	1472593	1-Jul-12	8.0	6.5	2.85	7.06	29	0.954	3.4	185	477
XPU30	Xuan Phuoc		Public well	W	287424	1471908	1-Jul-12	2.5	1.0	8.15		29	0.837	4.7	167	419
XPU31	Xuan Phuoc	Phu Xuan A	near Suoi Trau lake	W	287139	1470092	1-Jul-12	8.2	4.0	1.36	6.64	28	0.251	2.3	61	126
XPU32	Xuan Phuoc		Suoi Trau lake	L	287168	1470072	1-Jul-12			0.10	9.77	30	0.085	7.4	148	43
XPU33	Xuan Phuoc	group 2, Phu Xuan A	Tran Tan Tai	W	288468	1472295	1-Jul-12	8.0	6.0	2.76	7.57	29	1.212	3.6	154	606
XPU34	Xuan Phuoc	group 4, Phu Xuan A	Nguyen Thi Kim Hoang	W	289145	1471970	1-Jul-12	7.0	5.0	0.92	6.87	30	0.62	3.3	162	310
XPU35	Xuan Phuoc	group 7, Phu Xuan B	Huynh Ngoc Minh	W	289723	1471303	1-Jul-12	4.5	1.5	0.37	6.96	29	1.086	2.3	156	543
XPU36	Xuan Phuoc	group 8, Phu Xuan B	Nguyen Van Tam	W	289567	1471092	1-Jul-12	4.5	1.1	0.22	7.45	30	0.357	3.6	186	179
XPU37	Xuan Phuoc	group 3, Phu Xuan A	Nguyen Tri Phuong	W	288853	1471097	1-Jul-12	3.5	2.3	0.04	7.95	30	0.185	6.5	195	93
XPU38	Xuan Phuoc	group 3, Phu Xuan A	Truong Thi Ai	W	288395	1471057	1-Jul-12	4.5	3.0	0.67	7.10	30	0.952	5.5	185	476
XPU38_R	Xuan Phuoc	group 3, Phu Xuan A	Truong Thi Ai	W	288399	1471057	19-Jul-12	4.6	1.6	0.72						
XPU39	Xuan Phuoc		Ho Van Xuan	W	288202	1471053	1-Jul-12	5.8	5.2	2.95	6.96	30	1.645	4.3	166	823

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Sample ID	Commune	Village	Name of owner	Type	Easting (UTM) (m)	Northing (UTM) (m)	Sampling Date	Well Depth (m)	Water Level (m)	F- (FISE) (mg/L)	pH	Temp (°C)	EC (mS/cm)	DO (mg/L)	Eh (mV)	TDS (mg/L)
XPU40	Xuan Phuoc	group 3, Phu Xuan A	Nguyen Viet Quyet	W	288425	1471061	1-Jul-12			6.43						
XPU40_R	Xuan Phuoc	group 3, Phu Xuan A	Nguyen Viet Quyet	W	288431	1471059	19-Jul-12			5.78	7.03	31	0.909	3	150	455
XPU41	Xuan Phuoc	group 2, Phu Xuan A	Tran Minh Hoan	W	288674	1471085	19-Jul-12	2.0	1.0	0.51	6.48	29	0.304	2	160	152
XPU42	Xuan Phuoc	group 3, Phu Xuan A	Nguyen Do	W	288527	1471108	19-Jul-12	4.5	3.0	7.97	7.10	29	1.133	3.5	160	567
XPU42R	Xuan Phuoc	Phu Xuan A	Nguyen Van Do	W	288516	1471103	25-Mar-13	4.5	2.5	7.70	7.17	28.2	1.145	3.3	238	573
XPU43	Xuan Phuoc	group 3, Phu Xuan A	Nguyễn Thanh	W	288482	1471084	19-Jul-12	5.3	3.3	6.62	7.23	28	1.047	3	172	524
XPU44	Xuan Phuoc	group 3, Phu Xuan A	Vo Minh	W	288397	1471090	19-Jul-12	3.8	1.4	3.83	7.09	29	1.658	3.7	176	829
XPU45	Xuan Phuoc	group 3, Phu Xuan A	Pham Thi Nhung	W	288441	1471111	19-Jul-12	3.9	2.1	4.50	7.53	29	1.81	4.3	150	905
XPU46	Xuan Phuoc	group 3, Phu Xuan A	Nguyen Viet Quang	W	288486	1471039	19-Jul-12	4.8	2.5	1.07						
XPU47	Xuan Phuoc	group 3, Phu Xuan A	Tran Van Phoi	W	288425	1471031	19-Jul-12	4.8	0.2	0.26						
XPU48	Xuan Phuoc	group 3, Phu Xuan A	Le Trung Hien	W	288370	1471018	19-Jul-12	3.0	0.8	0.46	6.66	30	0.457	5.8	150	229
XPU49	Xuan Phuoc	group 3, Phu Xuan A	Tran Van Vinh	W	288521	1471017	19-Jul-12	5.0	2.0	1.05	6.75	30	1.038	3.3	152	519
XPU50	Xuan Phuoc	Phuoc Hoa	Nguyen Ky	W	291791	1473335	25-Mar-13	7.0	3.0	0.34	6.67	27.7	0.214	4	265	107
XPU51	Xuan Phuoc	Phuoc Hoa	Vo Hong Thai	W	291323	1472183	25-Mar-13	6.0	4.0	0.25	6.42	28.1	0.492	4	265	246
XPU52	Xuan Phuoc	Phu Xuan B	Pham Van Phong	W	289294	1470467	25-Mar-13	6.0	3.0	0.80	7.41	28.7	0.98	2.7	228	490
XPU53	Xuan Phuoc	Phu Xuan B	Huynh Binh	W	289904	1471540	25-Mar-13	6.5	4.0	0.26	6.61	28	1.349	1.9	172	675
XPU54	Xuan Phuoc	Phu Xuan A	Le Thi Kim	W	288536	1471068	25-Mar-13	4.5	2.5	7.92	7.36	29.4	0.698	4	244	349
XPU55	Xuan Phuoc	Phu Xuan A	Ho Hong Cong	W	288608	1471088	25-Mar-13	4.0	2.0	1.64	7.84	28.5	0.4	3.8	195	200
XPU56	Xuan Phuoc	Phu Xuan A	Huynh Quy	W	288290	1471343	25-Mar-13	6.0	3.0	0.10	6.13	28	0.125	2.1	276	63
XPU57	Xuan Phuoc	Phu Xuan A	Ho Thi Hoa	W	288113	1471197	25-Mar-13	4.5	3.0	0.10	6.43	28.3	0.197	3.8	276	99
XPU58	Xuan Phuoc	Phu Xuan A	Nguyen Van Thin	W	287974	1470960	25-Mar-13	4.0	2.5	4.46	7.44	28.3	3.08	2.4	191	1540
XPU59	Xuan Phuoc	Phu Xuan A	Tran Thi Chung	W	288371	1471193	25-Mar-13	4.0	2.0	0.30	6.63	28	0.565	3.7	256	283
XPU60	Xuan Phuoc	Phu Xuan A	Nguyen Duc Huy	W	288387	1471120	25-Mar-13	5.5	3.0	2.29	7.14	28.3	1.295	2.9	215	648
XPU61	Xuan Phuoc	Phu Xuan A	Tran Van Tam	W	288312	1471131	25-Mar-13	5.0	1.0	4.29	6.82	29	1.279	2.1	261	640
XPU62	Xuan Phuoc	Phu Xuan A	Phan Thi Phuoc	W	288305	1471046	25-Mar-13	6.5	3.0	0.39	6.50	29	1.811	2.9	249	906
XPU63	Xuan Phuoc	Phu Xuan A	Pham Thi Thuong	W	289400	1472187	25-Mar-13	7.0	3.5	0.42	7.44	28.5	0.95	1.5	215	475
XPU64	Xuan Phuoc	Phu Xuan A	Nguyen Khac Trung	W	289636	1472634	25-Mar-13	7.0	3.5	0.19	6.66	28.2	0.799	2.9	252	400
XPU65	Xuan Phuoc	Phu Xuan A	Huynh Minh	W	288229	1471131	26-Mar-13	4.0	3.0	0.23	6.69	27.8	0.675	4.3	269	338
XPU66	Xuan Phuoc	Phu Xuan A		W	287963	1471087	26-Mar-13	8.0	4.0	1.20	6.66	27.8	1.069	2.4	266	535
XPU67	Xuan Phuoc	Phu Xuan A	Nguyen Thi Mo	W	288005	1470900	26-Mar-13	7.2	7.0	0.26	6.94	26.7	0.153	2.2	222	77
XPU68	Xuan Phuoc	Phu Xuan A	Nguyen Thanh Xuan	W	288202	1471028	26-Mar-13	5.0	3.5	5.69	7.30	27.9	1.46	2.9	235	730
XPU69	Xuan Phuoc	Phu Xuan A	No name	W	288083	1470985	26-Mar-13	5.0	3.5	1.30	7.50	28.2	0.704	2.4	216	352
XPU70	Xuan Phuoc	Phu Xuan B	Huynh Duc Thao	W	290977	1471069	26-Mar-13	7.0	3.5	0.27	6.79	28.5	0.56	4.6	236	280
XQA01	Xuan Quang 1	Ba Dau, Phu Tam	Tre Ngo stream	S	278073	1480402	2-Jul-12			0.10	7.46	28	0.046	8.1	140	23
XQA02	Xuan Quang 1	Suoi Truong, Phu Tam	Nguyen Tho	W	279280	1479695	2-Jul-12	9.0	2.0	0.29	5.77	28	0.096	2.7	196	48
XQA03	Xuan Quang 1	Suoi Truong, Phu Tam		W	279835	1479476	2-Jul-12			0.33	6.67	30	0.065	4.2	166	33
XQA04	Xuan Quang 1	Suoi Truong, Phu Tam	Public well	W	279850	1479244	2-Jul-12	9.0	2.8	4.55	7.14	29	0.74	3.6	175	370
XQA04R	Xuan Quang 2	Ky Lo	Public well	W	279849	1479242	18-Mar-13	9.0	2.0	4.59	7.14	27	0.753	0.7	120	377
XQA05	Xuan Quang 1	Dong Hoi	Vo Cuc	W	280826	1479397	2-Jul-12			0.21	5.81	30	0.101	3.5	224	51
XQA06	Xuan Quang 1		Tu Van Xiem	W	280514	1479564	2-Jul-12			0.16	5.67	30	0.08	3.6	238	40

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Sample ID	Commune	Village	Name of owner	Type	Easting (UTM) (m)	Northing (UTM) (m)	Sampling Date	Well Depth (m)	Water Level (m)	F` (FISE) (mg/L)	pH	Temp (°C)	EC (mS/cm)	DO (mg/L)	Eh (mV)	TDS (mg/L)
XQA07	Xuan Quang 1	Ky Lo	Than Van Loi	W	280599	1478746	2-Jul-12	5.0	4.0	0.18	5.76	30	0.274	4.1	180	137
XQA08	Xuan Quang 1	Ky Lo	river water sample	W	280481	1479242	2-Jul-12			0.29	8.38	32	0.05	8.4	176	25
XQA09	Xuan Quang 1	Ky Lo	Nguyen Van Muoi	W	280820	1478294	2-Jul-12	5.5	3.4	0.39	6.03	29	0.143	2.7	240	72
XQA10	Xuan Quang 1	Ky Lo	Tran Minh Trong	W	280989	1477892	2-Jul-12	14.0	9.5	0.92	5.80	29	0.089	3.8	225	45
XQA11	Xuan Quang 1	Ky Lo	Nguyen Duy Sinh	W	281491	1477443	2-Jul-12	10.0	5.0	0.11	6.39	29	0.297	5.7	230	149
XQA12	Xuan Quang 1	Suoi Coi 1	Le Thanh Dong	W	282214	1477164	2-Jul-12	7.0	3.0	0.10	5.63	29	0.278	1.9	175	139
XQA13	Xuan Quang 1	Suoi Coi 2	La Lan Dong	W	284357	1474302	2-Jul-12	6.7	3.8	4.25	7.03	28	1.348	3.5	203	674
XQA14	Xuan Quang 1	Suoi Coi 3	Ma Viet	W	284461	1474064	2-Jul-12	5.2	4.2	3.92	7.15	29	1.416	3.3	165	708
XQA15	Xuan Quang 1	Suoi coi 2	La Lan Thien	W	284683	1473613	17-Mar-13	6.5	3.0	1.55	7.02	20.7	1.283		218	642
XQA16	Xuan Quang 1	Suoi coi	So Mai	W	284620	1473787	17-Mar-13	7.5	3.0	3.15	7.06	20.4	0.563	1.6	205	282
XQA17	Xuan Quang 1	Suoi coi 2	Public well	W	284763	1473355	17-Mar-13	3.5	1.0	0.84	6.48	21.8	0.602	1.1	235	301
XQA18	Xuan Quang 1	Suoi Coi	Public well	W	284408	1474192	17-Mar-13	7.5	5.0	1.02	6.91	27.1	1.194	4	210	597
XQA19	Xuan Quang 1	Suoi Coi	Public well	W	284330	1474506	17-Mar-13	8.0	0.5	3.76	7.45	22.6	1.059	6.4	221	530
XQA20	Xuan Quang 1	Suoi Coi 2	Ma Suu	W	284155	1474698	17-Mar-13	5.0	2.5	0.24	6.54	21.2	0.1277	5.5	258	64
XQA21	Xuan Quang 1	Suoi Coi 1	Vo Xuan Ly	W	283274	1476420	17-Mar-13	8.0	2.0	0.12	6.97	22.9	0.529	5.9	225	265
XQA22	Xuan Quang 1	Suoi Coi 2	Nguyen Van Hong	W	283188	1476761	17-Mar-13	8.0	3.5	0.22	6.00	23.3	0.53	4.7	276	265
XQA23	Xuan Quang 1	Suoi Coi 1	Bui Van Minh	W	282971	1476892	17-Mar-13	4.5	0.5	0.07	5.15	23.7	0.1648	2.4	331	82
XQA24	Xuan Quang 1	Suoi Coi 1	Nguyen Huynh Ly	W	282662	1476963	18-Mar-13	5.0	1.0	0.14	5.47	27.4	0.1625	1.6	289	81
XQA25	Xuan Quang 1	Suoi Coi 1	Nguyen Xuan Minh	W	282355	1477105	18-Mar-13	6.0	2.0	0.20	6.26	27.5	0.297	5.7	259	149
XQA26	Xuan Quang 1	Ky Lo	Khuong Trong Hieu	W	280952	1477664	18-Mar-13	7.0	1.0	0.11	6.38	26	0.0734	4.5	250	37
XQA27	Xuan Quang 1	Ky Lo	Tran Van Lan	W	281296	1478042	17-Mar-13	4.5	3.0	0.10	6.03	23	0.0785	5	273	39
XQA28	Xuan Quang 1	Dong Hoi	Nguyen Thien Ly	W	280262	1479727	17-Mar-13	7.0	2.0	0.12	5.90	25.2	0.07	5	295	35
XQA29	Xuan Quang 1	Suoi Coi 1	Khanh	W	285390	1476980	17-Mar-13	5.5	1.2	0.11	5.83	25.4	0.23	4.7	293	115
XQA30	Xuan Quang 1	Suoi Coi 1	Nguyen Van Cu	W	285550	1476866	17-Mar-13	5.0	1.2	1.06	7.48	25	0.41	5.8	233	205
XQA31	Xuan Quang 1		Ky Lo river	S	280469	1479216	18-Mar-13			0.21						
XQB01	Xuan Quang 2	Triem Duc	hot springs	HS	289709	1477064	6-Jul-12			22.04	8.45	63	0.683			342
XQB02	Xuan Quang 2	Triem Duc	hot springs	HS	289654	1476955	6-Jul-12			20.67	8.22	69	0.66		-108	330
XQB02R	Xuan Quang 2			HS	289657	1476956	16-Mar-13			20.87	8.62	78.3	0.652		-32	326
XQB03	Xuan Quang 2	Triem Duc	Mr Lam	W	289620	1477005	6-Jul-12			20.92	8.48	36	0.602	2.4	59	301
XQB04	Xuan Quang 2	Triem Duc	Manh Ngoc Anh	W	290524	1478073	6-Jul-12	5.0	3.5	0.16	5.84	30	0.112	2.3	130	56
XQB05	Xuan Quang 2	Triem Duc	Ho Quang So	W	290788	1477960	6-Jul-12	4.6	2.5	0.16	5.77	29	0.172	2.7	182	86
XQB06	Xuan Quang 2	Triem Duc	Nguyen Van Ngai	W	290516	1477653	6-Jul-12	8.5	4.0	3.54	7.49	28	3.46	1.8	160	1730
XQB07	Xuan Quang 2	Triem Duc	Nguyen Huu Hon	W	290374	1477104	6-Jul-12	6.0	3.0	3.86	6.70	29	0.421	6.7	105	211
XQB08	Xuan Quang 2	Triem Duc	Nguyen Thanh Ky	W	289961	1477210	6-Jul-12	7.8	7.2	12.48	7.72	30	0.644	4	140	322
XQB08R	Xuan Quang 2	Triem Duc	Nguyen Thanh Ky	W	289967	1477210	16-Mar-13	5.0	1.0	6.64	7.05	29.6	0.58	3.7	202	290
XQB09	Xuan Quang 2	Triem Duc	Nguyen Khac Toan	W	291171	1477960	6-Jul-12	9.5	7.5	0.18	6.22	29	0.536	4.8	165	268
XQB10	Xuan Quang 2	Triem Duc	Nguyen Van Duc	W	291079	1477628	6-Jul-12	3.2	2.2	0.06	4.75	29	0.715	3.5	235	358
XQB11	Xuan Quang 2	Triem Duc	Tran Van Bay	W	291512	1477878	6-Jul-12	5.5	3.5	0.08	6.31	29	1.03	4.8	205	515
XQB12	Xuan Quang 2	Phu Son	Public well	W	287746	1477258	11-Jul-12	6.0	2.5	0.24	6.73	30	0.055	4	185	28
XQB13	Xuan Quang 2	Phu Son	Nguyen Tan Si	W	287946	1477103	11-Jul-12	8.1	1.0	0.32	8.22	30	0.335	8.3	183	168

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Sample ID	Commune	Village	Name of owner	Type	Easting (UTM) (m)	Northing (UTM) (m)	Sampling Date	Well Depth (m)	Water Level (m)	F⁻ (FISE) (mg/L)	pH	Temp (°C)	EC (mS/cm)	DO (mg/L)	Eh (mV)	TDS (mg/L)
XQB14	Xuan Quang 2	Phu Son	Nguyen Van Tien	W	288152	1476802	11-Jul-12	6.0	1.0	0.51	7.08	29	0.615	4.7	160	308
XQB15	Xuan Quang 2	Phu Son	Tu Thi Thanh Nhan	W	288326	1476780	11-Jul-12	6.5	1.3	1.34	7.69	29	0.34	2	140	170
XQB16	Xuan Quang 2	Phu Son	Le Van Thanh	W	288639	1476898	11-Jul-12	9.5	6.5	11.35	6.97	29	0.498	4.5	175	249
XQB17	Xuan Quang 2	Phu Son		W	288716	1476924	11-Jul-12	9.3	3.5	4.85	7.12	29	1.052	2	180	526
XQB18	Xuan Quang 2	Phuoc Hue	Vo Kim Thien	W	292226	1478966	11-Jul-12	8.5	5.5	3.87	7.65	30	1.56	4.9	100	780
XQB19	Xuan Quang 2	Phuoc Hue	Public well	W	291870	1478441	11-Jul-12	4.5	3.0	0.09	5.84	29	0.313	3.5	150	157
XQB20	Xuan Quang 2	Phuoc Hue	Duong Tan Bat	W	292261	1478654	11-Jul-12	3.0	2.2	0.11	5.79	30	0.228	3.3	190	114
XQB21	Xuan Quang 2	Triem Duc	Nguyen Thi Thiet	W	290498	1477429	11-Jul-12	6.2	3.2	6.51	7.51	28	1.497	3.9	136	749
XQB22	Xuan Quang 2	Triem Duc	Nguyen Thi Hanh	W	290109	1477096	16-Mar-13	8.0	2.0	0.47	7.57	27	0.82	6.8	187	410
XQB23	Xuan Quang 2	Triem Duc	Le Van Minh	W	289778	1477367	16-Mar-13	4.0	1.2	1.50	6.20	28.6	0.1585	3.6	212	79
XQB24	Xuan Quang 2	Triem Duc	Chau Van Tam	W	289663	1477211	16-Mar-13	3.5	1.0	6.29	6.87	28.5	0.549	4.3	237	275
XQB25	Xuan Quang 2	Phu Xuan	Nguyen Quang Lam	W	288741	1476950	16-Mar-13	8.0	4.0	0.45	6.68	28.5	0.658	3.7	229	329
XQB26	Xuan Quang 2	Phu Xuan	Huynh Van Hung	W	288465	1476867	16-Mar-13	9.0	7.0	2.93	6.98	27.1	1.622	4	226	811
XQB27	Xuan Quang 2	Triem Duc	Le Hoa	W	290140	1476878	16-Mar-13	4.0	1.5	0.80	7.57	27	0.562	6.8	187	281
XQB28	Xuan Quang 2	Triem Duc	Pham Ngoc Quan	W	290401	1476826	16-Mar-13	4.0	1.5	0.48	6.34	26.5	0.362	2.3	253	181
XQB29	Xuan Quang 2	Triem Duc	Nguyen Binh Sinh	W	290291	1476631	16-Mar-13	8.0	2.0	0.17	6.31	28.1	0.18	3.9	270	90
XQB30	Xuan Quang 2	Triem Duc	Nguyen Nghiem	W	290466	1477202	16-Mar-13	8.0	6.0	18.28	8.24	27.7	0.848	3.4	192	424
XQB31	Xuan Quang 2	Triem Duc	Le Van Danh	W	290826	1477953	16-Mar-13	4.0	3.0	0.07	6.15	26.5	0.146	2.6	65	73
XQB32	Xuan Quang 2	Phuoc Hue	Nguyen Cuong	W	292171	1478811	16-Mar-13	4.0	1.5	0.08	6.17	27.3	0.08	3.7	250	40
XQB33	Xuan Quang 2	Phuoc Hue	Ngo Quang Quynh	W	292297	1478974	16-Mar-13	9.0	2.5	0.06	5.00	27.5	0.527	2.8	309	264
XQC01	Xuan Quang 3	Thanh Duc	Phan Thi Lien	W	289846	1473237	8-Jul-12	7.0	2.5	1.34	7.33	29	0.277	3.1	85	139
XQC02	Xuan Quang 3	group 1, Thanh Duc	Phan Van Thao	W	290169	1473389	8-Jul-12	8.0	2.8	1.77	7.36	29	1.139	3.8	160	570
XQC03	Xuan Quang 3	group 2, Thanh Duc	Doan Thi Tam	W	290300	1473784	8-Jul-12	5.7	3.0	1.42	6.82	29	0.762	2.3	175	381
XQC04	Xuan Quang 3	group 4, Thanh Duc	Do Van Hoa	W	290368	1474489	8-Jul-12	5.8	4.5	2.65	7.40	29	0.92	4.7	200	460
XQC05	Xuan Quang 3	group 5, Thanh Duc	Huynh Van Xuan	W	290518	1475052	8-Jul-12	7.8	4.5	0.93	6.78	30	1.629	3.8	145	815
XQC06	Xuan Quang 3	group 6, Thanh Duc	Truong Thi Minh Tam	W	290705	1475395	8-Jul-12	6.6	3.0	1.02	6.88	28	0.505	4	100	253
XQC07	Xuan Quang 3	group 6, Thanh Duc	Le Xuan Long	W	290718	1475665	8-Jul-12	7.5	5.5	0.40	6.36	28	0.216	5.4	170	108
XQC08	Xuan Quang 3	group 7, Thanh Duc	Phan Duc Phuc	W	291187	1475582	8-Jul-12	8.0	2.5	0.75	6.77	29	2.09	2.9	200	1045
XQC09	Xuan Quang 3	group 8, Thanh Duc	Nguyen May	W	291680	1475721	8-Jul-12	9.0	4.5	6.27	7.79	29	1.179	4.7	160	590
XQC10	Xuan Quang 3	group 8, Thanh Duc	Le Dong Tien	W	292002	1475954	8-Jul-12	4.0	2.3	0.03	5.70	28	0.133	5.9	205	67
XQC11	Xuan Quang 3	group 9, Thanh Duc	Nguyen Van Ha	W	291755	1476146	8-Jul-12	8.5	5.5	0.40	7.09	28	1.079	5.4	190	540
XQC12	Xuan Quang 3	group 9, Thanh Duc	Pham Thi Yen	W	291886	1476104	8-Jul-12	6.7	1.5	0.05	6.59	28	1.74	3.7	200	870
XQC13	Xuan Quang 3	group 7, Phuoc Loc	Vo Xuan Canh	W	293240	1475641	9-Jul-12	9.3	1.7	0.02	6.10	28	0.207	4	190	104
XQC14	Xuan Quang 3	group 7, Phuoc Loc	Le Thi Tuyet Phuong	W	293414	1475890	9-Jul-12	5.0	4.3	0.11	6.58	28	0.167	5.3	220	84
XQC15	Xuan Quang 3	group 6, Phuoc Loc	Pham An Vuong	W	293353	1476271	9-Jul-12	5.5	4.5	0.32	6.47	28	0.295	4.8	215	148
XQC16	Xuan Quang 3	group 4, Phuoc Loc	Doan Thi Trinh	W	293168	1476884	9-Jul-12	7.4	6.5	0.64	6.65	28	0.566	2.9	202	283
XQC17	Xuan Quang 3	group 2, Phuoc Loc	Phan Thanh Hung	W	293045	1477349	9-Jul-12	5.5	3.5	0.08	6.15	28	0.118	2.5	212	59
XQC18	Xuan Quang 3	group 5, Phuoc Loc	Ho Thi Nghia	W	293612	1476498	9-Jul-12	8.0	7.7	0.64	6.73	28	0.304	5	200	152
XQC19	Xuan Quang 3	group 4, Phuoc Loc	Pham Thi Tuyet Mai	W	293109	1476720	9-Jul-12	7.2	2.8	1.09	7.15	29	1.62	4.7	188	810

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Sample ID	Commune	Village	Name of owner	Type	Easting (UTM) (m)	Northing (UTM) (m)	Sampling Date	Well Depth (m)	Water Level (m)	F⁻ (FISE) (mg/L)	pH	Temp (°C)	EC (mS/cm)	DO (mg/L)	Eh (mV)	TDS (mg/L)
XQC20	Xuan Quang 3	group 5, Phuoc Loc	Tran Ngoc Binh	W	293373	1476776	9-Jul-12	9.2	4.5	0.17	6.92	28	0.554	6.6	190	277
XQC21	Xuan Quang 3	group 1, Phuoc Nhuan	Trịnh Kỳ Phuong	W	292902	1475509	9-Jul-12	8.0	4.8	0.32	7.52	28	0.826	4.4	180	413
XQC22	Xuan Quang 3	group 2, Phuoc Nhuan	Bui Tam	W	292602	1475239	9-Jul-12	4.0	1.5	0.18	6.16	28	0.46	3.4	270	230
XQC23	Xuan Quang 3	group 3, Phuoc Nhuan	Lê Van Muoi	W	292275	1475105	9-Jul-12	7.5	7.0	0.87	7.13	28	1.008	3.9	215	504
XQC24	Xuan Quang 3	group 4, Phuoc Nhuan	Tran Dam	W	292008	1474725	9-Jul-12			0.18	6.52	28	0.246	2.7	225	123
XQC25	Xuan Quang 3	group 7, Phuoc Nhuan	Nguyen Thi An	W	292102	1474334	9-Jul-12	8.5	4.2	0.09	6.43	28	0.656	4.1	240	328
XQC26	Xuan Quang 3	group 8, Phuoc Nhuan	Nguyen Ngoc Trinh	W	292109	1474032	9-Jul-12	8.0	4.5	0.02	5.11	28	0.333	5.5	267	167
XQC27	Xuan Quang 3			W	291893	1475804	26-Mar-13			0.09	6.34	28.6	1.543	2.6	278	772
XQC28	Xuan Quang 3			W	291431	1475687	26-Mar-13			2.18	7.28	28.1	2.036	3	235	1018
XSB01	Xuan Son Bac	Tan Tho	Thanh Tam	W	302122	1476171	15-Jul-12	6.1	5.3	0.25	6.61	28	0.811	3.1	185	406
XSB02	Xuan Son Bac	Tan Tho	Nguyen Van Giong	W	302722	1476506	15-Jul-12	6.5	3.1	1.63	6.61	29	0.512	2.4	204	256
XSB02R	Xuan Son Bac	Tan Tho	Nguyen Van Giong	W	302719	1476509	20-Mar-13			1.43	6.75	28	0.534	2.4	251	267
XSB03	Xuan Son Bac	Tan Tho	Dao Van Co	W	302334	1476788	15-Jul-12	4.7	3.2	0.89	6.64	28	1.816	5.7	210	908
XSB04	Xuan Son Bac	Tan Tho	Huynh Van Giang	W	301802	1476589	15-Jul-12	4.0	2.0	0.11	6.14	29	0.16	4.8	190	80
XSB05	Xuan Son Bac	Tan Phuoc	Tran Anh Dung (public well)	W	301858	1477168	15-Jul-12	4.5	2.5	0.23	5.59	30	0.103	3.6	180	52
XSB06	Xuan Son Bac	Tan Phuoc	Le Ba Tung	W	301857	1477541	15-Jul-12	5.3	5.0	0.42	5.90	29	0.183	5.2	190	92
XSB07	Xuan Son Bac	Tan Phuoc	Ho Thanh No	W	301503	1477661	15-Jul-12	5.0	3.1	0.45	6.20	29	0.54	3.8	195	270
XSB08	Xuan Son Bac	Tan Phuoc	Nguyen Van Thu	W	301224	1477853	15-Jul-12	5.5	3.0	1.18	6.37	29	0.224	5.1	182	112
XSB09	Xuan Son Bac	Tan Phuoc	Nguyen Van Luon	W	300821	1478066	15-Jul-12	4.0	2.5	0.25	6.21	29	0.38	3.7	192	190
XSB10	Xuan Son Bac	Tan Binh	public well	W	300266	1477792	15-Jul-12	8.3	4.3	0.73	6.63	29	0.526	3.7	186	263
XSB11	Xuan Son Bac	Tan Binh	Nguyen Van Hau	W	299303	1478329	15-Jul-12	7.5	6.0	0.43	6.75	30	1.327	2.1	142	664
XSB12	Xuan Son Bac	Tan Binh	Le Van Minh	W	298790	1478288	15-Jul-12	7.5	3.0	0.21	6.24	29	0.369	3.2	160	185
XSB13	Xuan Son Bac	Tan Binh	Nguyen Thi Huong	W	298041	1478458	15-Jul-12	7.0	3.5	0.17	6.05	28	0.654	3.3	190	327
XSB14	Xuan Son Bac	Tan Binh	Do Van Nien	W	298733	1479781	15-Jul-12	4.2	4.0	0.14	5.69	29	0.285	4.9	210	143
XSB15	Xuan Son Bac	Tan Binh	Do Van Tung	W	298719	1479449	15-Jul-12	3.0	1.1	0.11	6.03	36	0.361	5	220	181
XSB16	Xuan Son Bac	Tan Binh	Nguyen Van Su	W	298786	1479112	15-Jul-12	6.5	2.0	0.12	6.41	30	1.095	8.4	200	548
XSB17	Xuan Son Bac	Tan Binh	public well	W	298830	1478749	15-Jul-12	4.0	1.4	0.11	6.30	29	0.39	5.7	190	195
XSB18	Xuan Son Bac	Tan Binh	Huynh Van Thanh	W	297934	1478438	20-Mar-13	9.0	1.5	0.19	5.65	28	0.457	2.5	310	229
XSB19	Xuan Son Bac	Tan Binh	Vo Dong	W	298570	1478257	20-Mar-13	7.0	2.0	0.31	6.53	28.5	0.818	3.4	270	409
XSB20	Xuan Son Bac	Tan Binh	Public well	W	298734	1478471	20-Mar-13	4.0	3.0	0.55	6.72	27.9	0.771	4.5	268	386
XSB21	Xuan Son Bac	Tan Binh	Le Thanh Tam	W	299155	1478121	20-Mar-13	7.0	2.0	0.24	6.41	27.7	0.417	2.4	277	209
XSB22	Xuan Son Bac	Tan Tho	Public well	W	300083	1478210	20-Mar-13	5.0	2.0	0.35	6.20	27.2	0.142	2.7	277	71
XSB23	Xuan Son Bac	Tan Phuoc	Duong Van Phuong	W	300606	1478027	20-Mar-13	3.0	2.0	2.13	6.43	27	0.694	2.7	255	347
XSB24	Xuan Son Bac	Tan Phuoc	Pham Ai	W	301071	1478107	20-Mar-13	5.5	2.0	1.41	6.60	26	0.393	3.8	225	197
XSB25	Xuan Son Bac	Tan Phuoc	Truong Tan Bac	W	301067	1477729	20-Mar-13	3.0	1.5	0.20	6.24	27.7	1.096	2.4	236	548
XSB26	Xuan Son Bac	Tan Tho	Le Ba Khai	W	302009	1476369	20-Mar-13	4.0	1.5	0.21	6.11	27.5	0.929	2.4	284	465
XSN01	Xuan Son Nam	Tan An	Ngo Thanh Tung	W	298646	1477784	17-Jul-12	5.0	4.1	0.18	6.03	28	0.438	3.8	180	219
XSN02	Xuan Son Nam	Tan An	Truong Tan Hung	W	298878	1477476	17-Jul-12	4.8	4.1	0.12	6.25	29	0.359	5.5	205	180
XSN03	Xuan Son Nam	Tan Phu	Do Thanh Nguyen	W	299129	1477201	17-Jul-12	8.7	2.8	0.11	6.28	28	0.433	3.9	216	217
XSN04	Xuan Son Nam	Tan Phu	Nguyen Thi Nhung	W	299254	1476801	17-Jul-12	6.5	2.0	0.67	6.96	28	1.052	4.8	200	526

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Sample ID	Commune	Village	Name of owner	Type	Easting (UTM) (m)	Northing (UTM) (m)	Sampling Date	Well Depth (m)	Water Level (m)	F⁻ (FISE) (mg/L)	pH	Temp (°C)	EC (mS/cm)	DO (mg/L)	Eh (mV)	TDS (mg/L)
XSN05	Xuan Son Nam	Tan Vinh	Nguyen Thi Phuoc	W	299508	1476272	17-Jul-12	5.5	3.5	1.30	7.70	28	3.84	4.5	145	1920
XSN06	Xuan Son Nam	Tan An	well for clean water system	B	299215	1477745	17-Jul-12			0.06	5.87	29	0.092	4.4	135	46
XSN07	Xuan Son Nam	Tan Vinh	Pham Dinh Thuan	W	299768	1475861	17-Jul-12	2.8	1.5	0.32	6.15	29	0.216	2.1	183	108
XSN08	Xuan Son Nam	Tan Vinh	Le Van Sinh	W	299350	1475754	17-Jul-12	6.0	4.0	0.06	4.51	29	0.139	5.2	240	70
XSN08R	Xuan Son Nam	Tan Vinh	Le Van Sinh	W	299351	1475751	20-Mar-13			0.06	4.05	28.5	0.126	3.8	328	63
XSN09	Xuan Son Nam	Tan Vinh	Nguyen Nhuan	W	299314	1475851	17-Jul-12	8.7	3.2	9.10	7.05	29	0.967	4.4	200	484
XSN09R	Xuan Son Nam	Tan Vinh	Nguyen Nhuan	W	299318	1475854	19-Mar-13			13.70	7.47	27	1.119	2.5	225	560
XSN10	Xuan Son Nam	Tan Vinh 2	Nguyen Dinh	W	300259	1475347	17-Jul-12	3.4	2.0	0.14	6.22	29	0.747	3.8	220	374
XSN11	Xuan Son Nam	Tan Long	Nguyen Van Ly	W	300379	1476302	17-Jul-12	3.0	1.3	0.24	6.50	30	0.547	3.1	155	274
XSN12	Xuan Son Nam	Tan Lam	Pham Van Thuan	W	300969	1475909	17-Jul-12	8.0	7.0	0.33	6.07	29	0.377	2.4	180	189
XSN13	Xuan Son Nam	Tan Lam	Phan Van Than	W	300998	1475650	17-Jul-12	4.0	2.7	0.16	6.14	29	0.488	3.9	200	244
XSN14	Xuan Son Nam	Tan Hoa	Doan Dan	W	301548	1475260	17-Jul-12	4.5	2.0	0.29	6.28	30	0.271	2.6	160	136
XSN15	Xuan Son Nam	Tan Hoa	Truong Dong Sy	W	301642	1474835	17-Jul-12	5.5	5.2	0.23	6.35	29	0.719	2.5	193	360
XSN16	Xuan Son Nam	Tan Hoa	Pham Thanh Tam	W	301028	1474468	17-Jul-12	5.5	3.5	0.05	5.72	30	0.159	3.4	195	80
XSN17	Xuan Son Nam	Tan Vinh	Nguyen Trung Guong	W	299266	1475825	19-Mar-13	20.0	10.0	4.87	6.94	28	0.59	4.5	252	295
XSN18	Xuan Son Nam	Tan Vinh	Nguyen Thi Lun	W	299393	1475880	19-Mar-13	7.0	3.0	6.03	6.77	28	0.747	3.2	259	374
XSN19	Xuan Son Nam	Tan Vinh	Le Minh Duc	W	299453	1475930	19-Mar-13	10.0	5.5	1.89	6.91	29	0.314	4.5	241	157
XSN20	Xuan Son Nam	Tan Vinh	Do Hong Nhu	W	299272	1475708	19-Mar-13	7.0	1.5	0.05	5.20	27.7	0.154	3.3	318	77
XSN21	Xuan Son Nam	Tan Vinh	Nguyen Thi Nghe	W	299408	1475808	19-Mar-13	9.0	2.0	1.48	6.45	28.2	0.337	3.7	248	169
XSN22	Xuan Son Nam	Tan Vinh	Lam Dinh Long	W	299414	1475570	19-Mar-13	7.0	2.0	0.44	5.40	27.9	0.1897	3.3	318	95
XSN23	Xuan Son Nam	Tan Vinh	Tran Van Ba	W	299534	1475925	19-Mar-13	6.0	1.5	0.31	5.60	28.3	0.079	6.7	296	40
XSN24	Xuan Son Nam	Tan Huynh	Ngo Van Kinh	W	299914	1476151	19-Mar-13	4.0	3.0	0.34	6.60	27	1.44	1.6	266	720
XSN25	Xuan Son Nam	Tan Huynh	Luu Dinh Quy	W	300854	1476367	19-Mar-13	10.0	2.0	0.13	6.40	26	0.434	3.5		217
XSN26	Xuan Son Nam	Tan Vinh	Kim Cuc	W	299728	1475351	19-Mar-13	6.0	2.5	0.35	6.40	28.5	0.628	3.3	268	314
XSN27	Xuan Son Nam	Tan Hoa	Tran Van Trung	W	301686	1474072	19-Mar-13	5.5	4.5	0.15	6.16	27.1	0.155	1.6	280	78
XSN28	Xuan Son Nam	Tan Hoa	Pham Hieu	W	301255	1475007	19-Mar-13	3.0	1.8	0.07	6.10	27	1.09	2.4	270	545
XSN29	Xuan Son Nam	Tan Vinh	Le Minh Tien	W	299685	1475704	19-Mar-13	3.0	1.5	0.15	5.80	28.1	0.243	2.2	298	122
XSN30	Xuan Son Nam	Tan Vinh	Nguyen Quang Hung	W	299319	1475800	19-Mar-13	12.0	1.0	11.05	7.65	28.5	0.979	4.5	224	490

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APPENDIX B

All concentrations are in mg/L unless stated otherwise.

Sample ID	Major Anions								Major Cations				Trace Elements						Total Hardness (mg $CaCO_3$/L)	Total Alkalinity (mg $CaCO_3$/L)
	F^- (FISE)	F^- (HPIC)	Cl^- (HPIC)	Br^- (HPIC)	NO_3^- (HPIC)	PO_4^{3-} (HPIC)	SO_4^{2-} (HPIC)	HCO_3^- (titration)	Na^+ (HPIC)	K^+ (HPIC)	Mg^{2+} (HPIC)	Ca^{2+} (HPIC)	Al (ICP-OES)	Si (ICP-OES)	P (ICP-OES)	S (ICP-OES)	Mn (ICP-OES)	Fe (ICP-OES)		
DLC03	0.88	0.91	48.71	0.14	0.39	< 0.05	19.58	170.73	41.01	0.39	11.85	17.06	< 0.01	33.39	0.02	4.63	0.05	0.01	91.3	140
DLC07	0.45	0.43	56.29	0.16	11.10	< 0.05	20.66	109.78	40.81	2.62	12.06	23.91							109.3	90
DLC10	0.18	0.12	133.02	0.39	30.01	0.16	57.75	219.53	31.46	0.94	22.44	101.60	< 0.01	21.41	0.13	15.78	0.01	< 0.01	345.8	180
DLC14	0.29	0.26	32.77	0.06	10.39	0.26	13.75	182.94	27.43	2.10	11.36	38.89							143.8	150
DLC16	0.11	0.07	404.42	0.37	37.71	0.08	19.04	231.63	54.71	2.94	47.10	168.04							613.0	190
DLC17	0.33	0.18	64.93	0.11	42.90	< 0.05	17.86	243.85	46.39	1.68	16.99	37.62							163.8	200
LHA02	0.12	0.10	19.98	< 0.05	20.56	0.09	2.71	48.80	16.94	0.42	4.27	14.85							54.6	40
LHA05R	0.63	0.54	71.82	0.10	0.14	0.10	31.40	92.64	62.14	8.40	9.33	11.64							67.4	76
LHA08	0.24	0.14	39.71	0.12	25.21	6.83	21.25	201.21	32.91	29.71	9.84	37.04							132.9	165
LHA11	0.14	0.12	63.18	0.11	122.76	13.94	25.42	73.20	47.54	52.08	10.08	34.98	< 0.01	19.51	3.73	6.98	< 0.01	< 0.01	128.7	60
LHA13	0.68	0.51	22.78	0.06	3.25	0.06	5.90	201.20	35.86	2.98	4.51	45.06							131.0	165
LHA15	0.26	0.20	111.50	0.19	66.59	12.70	29.98	122.00	50.46	58.16	11.84	53.35							181.8	100
LHA17	2.87	2.78	155.98	0.35	29.43	< 0.05	48.79	329.06	85.38	0.88	17.46	133.00							403.7	270
LHA20	0.44	0.39	39.56	0.05	13.02	0.18	11.44	146.33	34.60	3.02	13.65	24.48							117.2	120
LHA22	0.46	0.31	89.92	0.10	34.22	< 0.05	29.69	231.64	53.04	0.77	26.71	64.80	< 0.01	18.15	0.02	11.63	0.01	< 0.01	271.5	190
LHA24	0.72	0.58	6.18	< 0.05	0.36	0.23	2.24	54.89	9.76	0.49	1.83	12.03							37.5	45
LHA28	0.62	0.63	10.00	< 0.05	13.10	0.31	4.24	18.30	9.93	2.34	0.76	4.39	0.05	16.44	0.01	1.05	0.02	0.01	14.1	15
LHA30	0.10	0.08	58.19	0.09	84.86	1.09	16.54	24.40	42.17	24.90	8.69	29.82							110.1	20
LHA31	0.27	0.24	32.35	0.06	25.30	0.41	10.33	63.44	24.79	5.55	2.96	23.71							71.3	52
LHA32	0.44	0.41	111.62	0.21	36.71	0.82	16.47	195.11	77.48	27.89	8.53	29.28							108.1	160
LHA33	0.17	0.13	7.15	0.06	0.33	0.09	3.17	163.36	21.43	0.90	3.66	37.49							108.6	134
LHA35	0.78	0.69	31.14	0.09	4.41	0.09	8.72	336.37	33.05	4.02	19.09	78.92							275.4	276
LHA36	0.21	0.17	29.09	0.08	0.10	13.53	3.05	284.68	25.90	18.93	4.55	70.18							193.8	234
LHA37	0.44	0.41	33.64	0.06	32.52	0.20	7.33	85.39	23.86	1.56	10.22	22.27	< 0.01	14.57	< 0.01	1.93	4.71	< 0.01	97.6	70
LHA38	< 0.1	0.05	9.17	< 0.05	10.20	1.24	8.40	34.16	8.92	5.67	2.78	8.07	< 0.01	8.09	0.15	2.03	6.28	< 0.01	31.6	28
LHA39	0.66	0.64	333.91	0.69	7.21	0.86	65.77	273.08	188.28	25.52	28.67	101.00							369.9	224
LHA40	0.10	0.08	110.53	0.15	171.97	20.11	46.95	221.88	76.03	74.80	15.51	56.91							205.8	182
LHA41	0.39	0.33	113.98	0.23	51.96	1.43	66.40	231.68	79.72	8.06	28.85	80.04							318.4	190
LHA42	0.24	0.22	19.20	0.08	11.91	0.38	9.65	87.82	20.69	2.36	5.64	18.86							70.3	72
LHA43	0.64	0.27	13.44	0.05	0.53	0.05	4.21	63.42	15.26	1.57	3.60	9.66							38.9	52
PHM01	0.38	0.29	4.76	< 0.05	0.45	0.13	9.60	134.07	19.28	0.85	2.18	26.13							74.2	110
PHM02	< 0.1	< 0.05	7.21	< 0.05	12.17	0.12	0.51	12.20	5.81	4.83	0.74	4.16							13.4	10
PHM04R	0.30	0.22	42.70	0.19	3.32	0.11	38.12	164.61	57.22	23.27	3.41	28.50							85.1	136
PHM06	0.26	0.22	14.47	< 0.05	11.98	0.10	8.29	128.06	19.86	2.91	2.91	31.04	< 0.01	16.85	0.01	2.24	< 0.01	< 0.01	89.4	105
PHM11	0.25	0.16	18.84	< 0.05	2.62	< 0.05	6.76	164.61	18.92	5.84	2.29	47.87	< 0.01	6.71	0.02	3.72	0.01	< 0.01	128.9	135
PHM13	< 0.1	< 0.05	2.44	< 0.05	0.62	< 0.05	1.14	24.40	3.68	0.45	0.36	3.74	< 0.01	4.42	< 0.01	0.54	16.23	< 0.01	10.8	20

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Sample ID	Major Anions								Major Cations				Trace Elements						Total Hardness (mg $CaCO_3/L$)	Total Alkalinity (mg $CaCO_3/L$)
	F^- (FISE)	F^- (HPIC)	Cl^- (HPIC)	Br^- (HPIC)	NO_3^- (HPIC)	PO_4^{3-} (HPIC)	SO_4^{2-} (HPIC)	HCO_3^-	Na^+ (HPIC)	K^+ (HPIC)	Mg^{2+} (HPIC)	Ca^{2+} (HPIC)	Al (ICP-OES)	Si (ICP-OES)	P (ICP-OES)	S (ICP-OES)	Mn (ICP-OES)	Fe (ICP-OES)		
PHM14	2.83	2.74	106.57	0.14	4.30	0.42	49.65	453.96	142.54	9.06	32.31	68.95							304.9	374
PHM15	0.49	0.43	18.46	0.06	4.88	0.05	12.65	148.76	17.52	7.14	4.11	43.70							125.9	122
PHM16	0.23	0.13	5.20	< 0.05	2.31	< 0.05	5.77	65.85	7.18	3.59	1.58	13.61							40.5	54
PHM17	0.16	0.14	3.95	< 0.05	0.14	0.05	0.70	21.96	5.08	1.49	0.74	2.60							9.5	18
XLG01	19.28	17.69	41.97	0.08	< 0.05	0.05	21.20	131.81	82.65	1.85	< 0.05	3.74							9.5	115
XLG01R	19.19	18.83	45.85	0.10	< 0.05	0.19	26.00	158.71	90.78	2.27	< 0.05	4.17	0.45	11.27	< 0.01	0.26	2.55	0.25	10.5	144
XLG02	1.08	1.07	17.71	0.06	2.60	< 0.05	5.51	42.69	22.50	4.52	1.18	5.76							19.2	35
XLG03	3.34	3.41	18.24	0.07	1.72	0.60	6.65	121.96	16.47	4.61	2.58	14.12							45.8	100
XLG03R	1.13	0.93	37.30	0.11	2.00	0.31	11.68	195.15	40.43	25.56	6.84	29.16							100.9	160
XLG04	0.16	0.17	32.25	0.06	14.30	0.08	6.43	67.09	22.85	5.45	6.67	15.26							65.5	55
XLG05	< 0.1	0.05	20.03	0.05	11.45	0.07	8.31	30.50	12.06	1.39	3.50	4.42							25.4	25
XLG08	0.12	0.11	11.17	< 0.05	4.87	0.10	8.27	36.60	13.38	1.64	2.90	8.10	< 0.01	14.25	0.03	2.38	< 0.01	< 0.01	32.1	30
XLG10	0.15	0.12	7.60	< 0.05	6.29	0.06	4.02	42.69	6.55	0.53	1.70	7.73							26.3	35
XLG14	< 0.1	0.07	56.55	0.07	32.28	0.53	24.28	36.54	29.67	2.42	1.47	31.68							85.1	30
XLG15	< 0.1	< 0.05	24.11	< 0.05	43.82	0.07	9.20	53.67	16.91	21.90	2.98	8.42	< 0.01	8.18	< 0.01	1.97	4.20	< 0.01	33.3	44
XLG16	0.14	0.13	13.61	0.05	3.03	< 0.05	2.08	26.83	13.19	0.61	2.26	9.69							33.5	22
XLG18	5.29	5.37	19.44	0.07	< 0.05	< 0.05	3.55	131.70	29.46	13.70	3.89	15.58							54.9	108
XLG20	0.92	0.80	12.15	< 0.05	0.05	< 0.05	3.53	48.37	12.36	1.01	2.63	9.31							34.0	40
XLN02	0.34	0.30	6.73	< 0.05	1.03	0.13	4.48	48.66	11.09	3.10	2.26	7.69							28.5	40
XLN05	1.00	0.86	132.47	0.12	135.62	0.73	76.65	182.45	141.80	14.88	17.06	54.03	< 0.01	16.68	0.25	20.21	< 0.01	< 0.01	205.0	150
XLN08	0.21	0.12	2.81	< 0.05	2.53	0.08	3.28	67.09	7.37	3.28	0.91	11.27							31.9	55
XLN09	3.89	3.64	70.72	0.16	7.53	0.12	31.50	359.37	39.64	0.41	28.98	28.15							189.4	295
XLN09R	3.96	3.75	82.85	0.13	25.56	0.05	48.46	404.41	73.60	0.56	48.46	80.45							400.1	332
XLN11	1.61	1.43	16.43	0.06	2.34	0.16	4.44	219.44	35.20	8.42	6.46	16.27							67.2	180
XLN12	1.77	1.54	136.72	0.25	11.98	< 0.05	31.28	249.80	99.56	18.25	15.05	42.28							167.4	205
XLN13	1.52	1.39	15.07	0.05	2.54	0.12	9.24	128.06	25.74	1.26	6.73	25.01							90.1	105
XLN15	1.58	0.89	137.83	0.15	64.38	< 0.05	51.14	377.23	87.57	13.36	45.62	17.90							232.3	310
XLN20	3.18	2.99	22.99	0.08	0.43	< 0.05	5.14	347.35	41.60	0.55	8.37	32.90							116.5	285
XLN25	3.86	3.58	41.72	0.06	53.70	1.51	17.75	151.69	80.74	4.18	6.53	31.49							105.4	125
XLN25R	7.38	7.26	67.05	0.14	7.36	0.05	23.35	333.70	126.99	1.13	14.93	23.58							120.2	274
XLN27	0.10	0.09	10.42	< 0.05	14.55	< 0.05	5.45		11.98	6.14	3.27	10.41							39.4	
XLN29	0.16	0.12	5.36	< 0.05	5.12	< 0.05	3.02		11.43	0.71	0.92	6.36							19.7	
XLN30	0.80	0.58	59.94	0.13	0.89	0.26	10.32	268.40	70.82	54.58	5.42	23.18							80.1	220
XLN32	0.19	0.09	85.13	0.11	118.30	0.13	13.07	60.99	20.59	0.86	6.96	43.65							137.5	50
XLN34	0.43	0.34	74.43	0.12	23.28	< 0.05	24.01	48.79	36.41	0.53	5.77	27.26							91.7	40
XLN35	0.53	0.46	88.22	0.07	49.42	0.60	30.12	182.94	38.61	5.71	16.96	50.10							194.8	150
XLN40	1.77	1.61	265.02	0.30	34.51	0.21	77.61	350.97	154.32	3.89	41.60	94.54	< 0.01	13.42	< 0.01	5.54	270.33	< 0.01	407.0	288
XLN41	3.58	3.21	67.71	0.13	6.47	< 0.05	42.83	470.27	136.84	0.55	28.51	48.50							238.3	386
XLN43	1.29	1.15	59.49	0.11	21.28	0.20	26.44	134.16	47.81	0.90	10.38	41.07							145.2	110
XLN44	1.36	1.22	38.71	0.06	40.51	0.07	19.91	165.84	38.96	1.93	10.97	50.27							170.5	136

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Sample ID	Major Anions								Major Cations				Trace Elements						Total Hardness (mg $CaCO_3$/L)	Total Alkalinity (mg $CaCO_3$/L)
	F^- (FISE)	F^- (HPIC)	Cl^- (HPIC)	Br^- (HPIC)	NO_3^- (HPIC)	PO_4^{3-} (HPIC)	SO_4^{2-} (HPIC)	HCO_3^-	Na^+ (HPIC)	K^+ (HPIC)	Mg^{2+} (HPIC)	Ca^{2+} (HPIC)	Al (ICP-OES)	Si (ICP-OES)	P (ICP-OES)	S (ICP-OES)	Mn (ICP-OES)	Fe (ICP-OES)		
XLN45	0.15	0.15	28.94	0.05	26.33	< 0.05	18.69	53.67	20.18	2.80	4.95	22.13	< 0.01	11.91	< 0.01	5.44	2.88	< 0.01	75.6	44
XLN46	0.46	0.41	11.02	< 0.05	1.20	0.10	8.12	102.42	19.99	1.75	1.85	14.17							43.0	84
XLN47	0.95	0.83	150.64	0.23	14.05	0.16	28.51	153.66	93.01	2.20	14.65	53.37							193.4	126
XLN50	0.98	0.94	14.84	0.05	0.06	< 0.05	3.79	58.28	10.71	1.13	2.64	10.07							36.0	48
XPU01	1.67	1.30	122.95	0.12	75.07	8.98	69.11	340.75	151.04	28.45	17.09	59.77	< 0.01	21.62	2.63	23.65	< 0.01	< 0.01	219.4	280
XPU02	6.55	6.07	153.50	0.15	0.70	< 0.05	56.74	407.89	100.86	1.02	11.57	48.67	< 0.01	17.18	< 0.01	15.34	0.36	0.02	169.0	335
XPU04	4.67	4.30	130.57	0.14	1.39	0.65	31.24	304.61	134.38	4.12	15.48	43.94							173.3	250
XPU06	0.12	0.09	11.30	< 0.05	5.36	< 0.05	3.07	67.08	8.02	3.12	1.55	8.83							28.4	55
XPU08	1.82	1.75	151.05	0.21	24.65	0.31	20.05	280.31	81.37	22.32	15.89	43.40							173.6	230
XPU10	0.11	0.06	26.71	< 0.05	6.37	< 0.05	9.61	79.29	21.46	6.10	2.39	15.07							47.4	65
XPU11	0.58	0.50	157.33	0.17	18.70	< 0.05	45.05	304.69	59.11	27.45	17.27	31.45	< 0.01	11.88	< 0.01	4.58	13.02	< 0.01	149.5	250
XPU14	0.84	0.81	55.49	0.11	13.79	< 0.05	9.11	152.37	36.22	0.33	13.93	26.02	< 0.01	11.52	< 0.01	10.90	< 0.01	< 0.01	122.2	125
XPU18	1.04	0.78	24.82	0.05	4.05	0.30	8.23	407.35	49.60	0.95	14.78	20.71							112.5	335
XPU19	< 0.1	< 0.05	4.43	< 0.05	4.05	0.17	1.06	54.83	5.02	0.64	0.29	14.82	3.00	14.89	0.01	0.55	< 0.01	0.89	38.2	45
XPU20	0.10	0.10	7.86	< 0.05	0.05	< 0.05	1.29	48.62	4.29	0.29	2.98	6.42							28.3	40
XPU22	0.28	0.22	9.42	< 0.05	1.04	< 0.05	2.45	60.98	6.56	0.48	3.01	8.11							32.6	50
XPU23	< 0.1	< 0.05	13.26	< 0.05	1.50	0.19	7.48	36.59	23.75	3.94	1.51	11.86							35.8	30
XPU28	0.58	0.32	35.31	< 0.05	25.52	< 0.05	15.69	182.73	35.64	16.37	5.66	33.28							106.3	150
XPU30	8.15	7.86	27.95	0.07	0.70	< 0.05	16.93	463.60	94.64	1.44	5.11	31.70							100.1	380
XPU31	1.36	1.17	14.69	0.06	< 0.05	0.13	6.51	109.75	17.74	1.29	3.65	20.17							65.3	90
XPU35	0.37	0.33	131.62	0.24	13.70	0.67	33.13	243.75	48.98	48.72	22.34	44.85	< 0.01	21.07	0.43	12.22	0.48	< 0.01	203.8	200
XPU38	0.67	0.60	169.97	0.24	13.60	0.09	32.81	194.93	46.19	7.99	12.11	52.55							180.9	160
XPU39	2.95	2.60	176.40	0.49	3.20	0.23	26.40	493.60	129.46	0.30	32.85	36.79	< 0.01	20.58	0.05	10.76	0.14	< 0.01	226.9	405
XPU40	6.43	6.17	47.60	0.10	2.16	0.19	12.87	469.70	105.44	5.38	24.61	64.52							262.2	385
XPU41	0.51	0.40	26.10	0.07	0.75	0.84	2.59	121.96	26.56	7.24	5.54	11.01							50.3	100
XPU42	7.97	7.45	63.08	0.22	0.16	0.33	21.83		216.20	0.33	15.33	19.43							111.5	
XPU42R	7.70	7.53	66.35	0.20	0.09	0.18	23.33	591.94	232.51	0.42	16.71	34.73							155.4	486
XPU43	6.62	6.53	114.57	0.18	2.34	< 0.05	26.93	401.84	123.68	1.10	16.70	40.88							170.7	330
XPU44	3.83	2.69	181.71	0.25	8.36	0.14	24.65		107.13	3.16	35.56	29.02							218.7	
XPU45	4.50	4.14	215.37	0.25	19.97	2.16	107.42	607.69	184.14	27.81	36.35	42.98	< 0.01	18.04	0.61	27.77	0.01	< 0.01	256.8	500
XPU48	0.46	0.40	70.18	0.06	15.45	0.11	28.85	121.94	61.94	2.28	5.91	11.26							52.4	100
XPU50	0.34	0.33	12.56	< 0.05	3.28	0.51	6.99	92.67	17.82	10.47	1.48	16.21							46.5	76
XPU51	0.25	0.19	55.82	0.09	17.95	0.23	22.96	141.48	38.48	42.09	8.94	22.78							93.6	116
XPU52	0.80	0.68	121.25	0.15	14.77	0.55	26.75	357.65	73.84	1.28	43.13	42.62							283.8	294
XPU53	0.26	0.23	200.61	0.40	3.01	0.75	46.83	421.93	99.46	33.30	41.07	110.00	< 0.01	12.83	< 0.01	12.89	< 0.01	< 0.01	443.4	346
XPU54	7.92	7.50	49.00	0.12	6.52	0.18	20.32	301.79	89.28	2.18	11.15	30.97							123.1	248
XPU55	1.64	1.47	20.75	0.07	5.06	0.11	2.18	200.96	31.69	13.68	7.00	30.33	< 0.01	6.51	< 0.01	0.64	127.93	< 0.01	104.5	166
XPU60	2.29	2.07	201.62	0.26	2.33	< 0.05	61.52	360.56	139.25	9.59	32.73	89.95							359.1	296
XPU61	4.29	4.11	203.45	0.28	34.00	< 0.05	46.84	314.53	177.61	0.35	24.71	63.96							261.2	258
XPU62	0.39	0.34	375.88	0.40	84.52	0.13	77.91	231.72	150.10	6.09	42.30	123.47							482.1	190

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Sample ID	Major Anions								Major Cations				Trace Elements						Total Hardness (mg $CaCO_3/L$)	Total Alkalinity (mg $CaCO_3/L$)
	F^- (FISE)	F^- (HPIC)	Cl^- (HPIC)	Br^- (HPIC)	NO_3^- (HPIC)	PO_4^{3-} (HPIC)	SO_4^{2-} (HPIC)	HCO_3^-	Na^+ (HPIC)	K^+ (HPIC)	Mg^{2+} (HPIC)	Ca^{2+} (HPIC)	Al (ICP-OES)	Si (ICP-OES)	P (ICP-OES)	S (ICP-OES)	Mn (ICP-OES)	Fe (ICP-OES)		
XPU63	0.42	0.36	71.85	0.19	0.13	0.15	63.34	413.52	138.48	9.40	15.96	65.56							229.2	340
XPU66	1.20	0.71	189.97	0.27	18.10	0.07	12.09	153.64	74.96	4.29	21.48	32.21							168.7	126
XPU67	0.26	0.20	9.03	< 0.05	0.09	0.60	1.95	73.13	14.53	14.91	1.35	8.54							26.9	60
XPU68	5.69	4.77	158.54	0.27	21.76	0.26	70.95	530.73	212.29	0.80	48.61	16.36							240.8	436
XQA02	0.29	0.25	9.30	< 0.05	1.22	0.22	2.80	24.40	6.77	2.23	0.21	8.10							21.1	20
XQA03	0.33	0.27	4.30	< 0.05	0.45	0.05	0.94	30.48	7.84	1.29	0.81	4.22							13.9	25
XQA04R	4.59	4.45	26.63	0.08	0.11	< 0.05	5.66	438.52	94.30	3.94	8.85	80.48							237.2	360
XQA06	0.16	0.09	5.33	< 0.05	8.67	< 0.05	1.95	24.40	6.95	0.98	1.46	5.23	< 0.01	8.79	< 0.01	0.19	0.01	0.15	19.1	20
XQA10	0.92	0.87	6.55	< 0.05	5.46	< 0.05	1.90	24.40	13.51	0.90	0.78	3.36							11.6	20
XQA16	3.15	2.97	28.41	0.10	1.06	< 0.05	6.32	299.73	75.77	12.06	4.98	43.01							127.8	246
XQA17	0.84	0.71	45.59	0.37	0.51	< 0.05	10.26	268.31	49.68	2.32	10.92	38.06							139.9	220
XQA18	1.02	1.11	93.30	0.19	32.16	< 0.05	55.47	363.23	82.44	15.49	19.53	72.35							260.9	298
XQA20	0.24	0.18	11.40	0.08	0.41	< 0.05	3.12	53.66	16.53	0.98	1.63	8.16							27.1	44
XQA21	0.12	0.08	42.73	0.07	36.45	< 0.05	10.23	109.69	23.41	28.78	1.81	27.26							75.5	90
XQA22	0.22	0.19	69.71	0.13	73.77	< 0.05	1.91	48.79	35.39	31.61	3.47	29.40							87.6	40
XQA23	< 0.1	< 0.05	27.01	0.06	25.37	< 0.05	2.28	9.76	14.60	8.32	1.58	6.98	< 0.01	6.85	< 0.01	0.48	96.55	0.20	23.9	8
XQA24	0.14	0.14	15.93	0.07	10.96	0.31	6.93	43.92	11.13	14.20	1.55	9.85	< 0.01	7.71	< 0.01	1.81	43.57	< 0.01	31.0	36
XQA25	0.20	0.15	33.96	0.13	45.79	0.07	11.84	46.35	30.45	15.59	2.83	15.55							50.4	38
XQA26	0.11	0.10	5.16	< 0.05	0.30	< 0.05	0.94	31.71	5.13	1.53	0.57	6.59							18.8	26
XQA27	0.10	0.10	7.85	< 0.05	0.87	0.05	1.47	26.84	6.93	6.46	0.75	3.76							12.5	22
XQA29	0.11	0.09	22.22	0.05	37.25	< 0.05	4.11	24.40	19.39	6.81	2.84	6.58							28.1	20
XQB01	22.04	21.31	43.07	0.09	< 0.05	0.13	21.63	224.71	75.70	1.29	0.18	5.78							15.2	190
XQB02	20.67	20.08	39.12	0.09	< 0.05	< 0.05	19.93	209.60	62.68	1.10	< 0.05	3.70							9.4	175
XQB02R	20.87	20.62	39.60	0.09	< 0.05	< 0.05	20.68	237.78	135.13	2.54	< 0.05	4.45	< 0.01	23.30	< 0.01	4.87	3.93	< 0.01	11.2	204
XQB05	0.16	0.14	23.90	0.06	11.41	< 0.05	8.05	30.50	8.70	4.63	1.49	5.19							19.1	25
XQB06	3.54	2.99	727.79	1.56	0.31	< 0.05	306.90	528.87	395.20	44.38	94.97	134.66							726.6	435
XQB08	12.48	12.25	45.41	0.10	0.26	< 0.05	27.90	254.70	89.92	1.30	2.77	11.42	< 0.01	11.36	0.01	7.68	0.01	< 0.01	39.9	210
XQB08R	6.64	6.57	66.62	0.10	15.25	0.89	23.98	168.15	97.14	11.50	3.02	14.23	0.22	7.84	0.18	6.30	8.80	< 0.01	47.9	138
XQB10	< 0.1	< 0.05	85.08	0.20	14.21	0.16	25.29	12.20	53.25	24.26	6.19	13.75							59.8	10
XQB12	0.24	0.23	4.38	< 0.05	0.81	0.08	0.98		5.62	2.01	0.89	3.18							11.6	
XQB13	0.32	0.26	28.30	< 0.05	30.41	0.08	13.09	77.85	23.32	5.32	5.26	19.39							70.0	65
XQB15	1.34	1.22	15.02	< 0.05	0.14	0.17	6.29	175.93	36.33	2.87	2.88	17.00	< 0.01	12.87	0.04	1.80	0.15	< 0.01	54.3	145
XQB17	4.85	4.32	76.75	0.22	19.49	0.36	23.71	353.28	82.56	22.53	20.05	30.81							159.3	290
XQB18	3.87	3.75	99.03	0.29	3.01	0.24	81.72	776.91	317.63	5.43	16.19	44.12	< 0.01	33.00	0.17	20.90	0.03	< 0.01	176.7	640
XQB19	< 0.1	< 0.05	51.73	0.14	18.18	2.16	10.25	30.50	26.84	28.17	4.13	8.11							37.2	25
XQB22	0.47	0.42	116.11	0.18	43.81	0.78	64.52	138.50	74.99	4.36	13.28	71.33							232.6	114
XQB23	1.50	1.40	11.69	< 0.05	4.07	< 0.05	12.22	53.67	24.00	1.50	1.19	8.36							25.8	44
XQB24	6.29	6.33	55.41	0.09	30.48	1.73	18.64	146.28	59.62	50.90	3.07	19.87							62.2	120
XQB25	0.45	0.40	60.34	0.19	20.86	0.27	30.38	236.55	47.09	26.02	13.69	60.96							208.4	194
XQB26	2.93	2.82	278.27	0.53	12.50	0.08	48.63	455.79	151.10	15.69	50.15	135.99							545.6	374

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Sample ID	Major Anions								Major Cations				Trace Elements						Total Hardness (mg $CaCO_3$/L)	Total Alkalinity (mg $CaCO_3$/L)
	F^- (FISE)	F^- (HPIC)	Cl^- (HPIC)	Br^- (HPIC)	NO_3^- (HPIC)	PO_4^{3-} (HPIC)	SO_4^{2-} (HPIC)	HCO_3^-	Na^+ (HPIC)	K^+ (HPIC)	Mg^{2+} (HPIC)	Ca^{2+} (HPIC)	Al (ICP-OES)	Si (ICP-OES)	P (ICP-OES)	S (ICP-OES)	Mn (ICP-OES)	Fe (ICP-OES)		
XQB27	0.80	0.71	18.36	0.06	1.05	0.79	21.45	183.70	33.64	15.12	3.86	41.55							119.5	151.2
XQB28	0.48	0.44	25.56	0.12	0.66	0.11	21.85	151.24	45.25	16.61	6.80	15.07							65.6	124
XQB29	0.17	0.15	9.33	0.06	0.56	< 0.05	7.34	93.51	20.95	0.82	3.63	13.78							49.3	76.666667
XQB30	18.28	18.13	60.61	0.13	0.17	< 0.05	56.34	282.42	176.25	3.49	2.22	13.71	< 0.01	8.57	< 0.01	15.15	0.80	< 0.01	43.3	236
XQB31	< 0.1	0.07	12.44	< 0.05	< 0.05	< 0.05	6.02	51.23	12.20	4.15	1.28	11.56							34.1	42
XQB32	< 0.1	0.05	5.62	< 0.05	1.98	0.31	3.58	34.15	10.82	0.58	0.95	4.56							15.3	28
XQB33	< 0.1	0.05	110.53	0.19	41.23	0.07	21.68	12.20	55.26	20.79	10.03	9.48							64.9	10
XQB34	0.22	0.21	5.28	< 0.05	0.26	0.14	0.97	21.96	6.53	1.39	1.55	4.19							16.8	18
XQC04	2.65	2.16	23.34	0.06	0.94	0.07	4.79	608.29	54.86	0.31	65.21	17.89							312.9	500
XQC06	1.02	0.87	38.64	0.10	12.32	0.31	10.74	219.41	26.78	4.41	7.10	29.73							103.4	180
XQC08	0.75	0.51	144.33	0.39	30.82	6.36	54.40	463.29	85.81	75.99	32.15	119.32							430.0	380
XQC10	< 0.1	< 0.05	21.98	0.05	2.67	1.78	4.61	12.20	12.63	4.11	1.14	6.04							19.8	10
XQC12	< 0.1	0.06	325.84	0.48	70.85	3.40	33.66	256.20	168.91	98.59	22.72	56.76	< 0.01	16.23	1.21	9.43	0.06	< 0.01	235.1	210
XQC13	< 0.1	0.07	17.04	0.05	10.75	0.09	21.08	48.79	16.64	4.71	0.93	12.61							35.3	40
XQC15	0.32	0.31	11.55	< 0.05	8.68	0.12	5.05	134.16	16.68	1.09	9.38	18.27							84.2	110
XQC19	1.09	0.75	242.30	0.29	17.63	1.19	111.99	414.14	211.46	6.23	31.31	24.31							189.4	340
XQC20	0.17	0.12	37.23	< 0.05	40.15	0.23	31.15	243.77	45.85	6.63	5.94	49.14	< 0.01	12.25	0.03	5.85	0.04	< 0.01	147.0	200
XQC24	0.18	0.13	14.92	< 0.05	1.13	1.52	9.12	67.08	15.55	14.16	2.20	8.86	0.05	14.40	0.51	4.26	0.02	0.04	31.2	55
XQC27	< 0.1	0.09	244.31	0.38	83.00	11.02	34.14	246.38	125.78	146.60	30.65	52.78							257.8	202
XQC28	2.18	1.51	332.63	0.61	19.88	0.39	57.69	613.57	178.74	4.39	102.35	20.53	< 0.01	14.67	< 0.01	16.92	14.96	< 0.01	472.2	504
XSB01	0.25	0.17	90.53	0.35	3.87	0.24	38.97	292.67	75.85	7.49	16.36	54.79							204.0	240
XSB02	1.63	1.10	34.30	0.09	0.05	< 0.05	7.68	256.08	59.74	0.53	15.36	36.16							153.4	210
XSB02R	1.43	1.32	39.92	0.10	0.32	0.31	8.98	260.92	62.27	0.69	15.78	39.29							162.9	214
XSB06	0.42	0.38	18.73	0.05	4.63	0.10	2.68	54.90	22.35	0.34	4.44	9.02	< 0.01	20.01	0.01	0.70	< 0.01	< 0.01	40.8	45
XSB11	0.43	0.26	164.86	0.53	< 0.05	1.69	19.34	487.69	151.56	25.90	29.50	44.67							232.8	400
XSB16	0.12	0.06	66.38	0.07	31.01	0.05	23.41	73.18	42.01	28.26	3.84	12.15	< 0.01	10.37	0.03	17.97	< 0.01	< 0.01	46.1	60
XSB18	0.19	0.14	48.34	0.07	39.57	0.15	11.97	78.08	32.98	13.99	3.05	30.21	< 0.01	18.10	< 0.01	3.91	3.93	< 0.01	87.9	64
XSB19	0.31	0.23	76.82	0.16	31.20	0.48	35.40	224.39	60.80	43.22	14.88	41.34							164.4	184
XSB20	0.55	0.45	65.28	0.17	40.15	0.39	31.27	268.24	68.83	13.37	15.91	60.23							215.7	220
XSB21	0.24	0.19	29.87	0.05	18.38	13.37	11.15	97.57	22.28	35.14	3.85	13.22							48.8	80
XSB22	0.35	0.31	16.39	0.08	0.88	0.19	3.01	43.91	18.01	2.90	2.54	6.44							26.5	36
XSB23	2.13	1.96	84.23	0.17	4.82	0.39	31.84	219.53	54.54	8.37	19.45	62.56							236.1	180
XSB24	1.41	1.26	30.32	0.07	5.06	< 0.05	9.65	173.16	50.31	2.06	9.38	22.52							94.8	142
XSB25	0.20	0.19	239.15	0.35	20.85	0.10	29.64	175.65	87.65	8.05	28.71	84.47							328.9	144
XSB26	0.21	0.17	170.14	0.20	42.65	8.02	34.17	134.18	83.21	65.79	16.24	40.16							167.0	110
XSN01	0.18	0.16	50.50	0.10	33.48	0.22	13.05	109.79	38.27	10.28	8.72	17.04	< 0.01	14.01	< 0.01	1.04	< 0.01	< 0.01	78.4	90
XSN08R	< 0.1	< 0.05	14.25	< 0.05	30.76	0.08	2.76	4.88	12.31	6.80	1.65	1.83	< 0.01	16.43	< 0.01	0.28	17.78	< 0.01	11.4	4
XSN09	9.10	8.77	69.95	0.14	23.31	< 0.05	53.15	377.73	202.17	6.72	4.66	12.08	< 0.01	10.76	< 0.01	13.93	< 0.01	< 0.01	49.3	310
XSN09R	13.70	13.29	62.92	0.13	4.51	< 0.05	46.93	491.26	231.84	3.41	3.17	10.37							38.9	404
XSN11	0.24	0.16	52.80	0.10	17.36	0.37	26.09	146.35	49.83	23.58	10.42	21.83	< 0.01	17.77	0.02	4.74	0.03	0.07	97.3	120

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Sample ID	Major Anions								Major Cations				Trace Elements						Total Hardness (mg $CaCO_3$/L)	Total Alkalinity (mg $CaCO_3$/L)
	F^- (FISE)	F^- (HPIC)	Cl^- (HPIC)	Br^- (HPIC)	NO_3^- (HPIC)	PO_4^{3-} (HPIC)	SO_4^{2-} (HPIC)	HCO_3^-	Na^+ (HPIC)	K^+ (HPIC)	Mg^{2+} (HPIC)	Ca^{2+} (HPIC)	Al (ICP-OES)	Si (ICP-OES)	P (ICP-OES)	S (ICP-OES)	Mn (ICP-OES)	Fe (ICP-OES)		
XSN14	0.29	0.20	34.63	0.09	0.47	1.80	8.82	85.40	26.43	18.44	4.54	11.08							46.3	70
XSN16	< 0.1	< 0.05	12.99	< 0.05	8.36	0.31	3.91	36.60	12.32	7.15	1.55	5.05							19.0	30
XSN17	4.87	4.67	41.72	0.07	18.67	< 0.05	22.89	202.32	101.66	3.56	2.49	8.71							32.0	166
XSN18	6.03	5.85	39.15	0.07	24.74	< 0.05	26.00	265.78	109.43	9.11	3.91	9.80							40.5	218
XSN20	< 0.1	< 0.05	20.07	< 0.05	7.57	0.08	5.06	9.76	11.23	13.71	0.94	1.00	< 0.01	14.21	< 0.01	1.72	88.06	< 0.01	6.4	8
XSN22	0.44	0.45	27.88	0.07	10.26	0.08	16.13	24.40	26.90	8.43	1.76	2.04	< 0.01	9.69	< 0.01	3.87	9.64	< 0.01	12.3	20
XSN23	0.31	0.34	7.30	< 0.05	3.66	< 0.05	5.27	19.52	11.84	2.05	1.13	1.74							9.0	16
XSN24	0.34	0.28	272.59	0.38	7.98	3.38	58.43	268.28	151.19	55.01	12.58	48.36							172.4	220
XSN25	0.13	0.10	53.27	0.08	9.04	3.14	17.83	124.41	39.28	15.79	6.36	24.00							86.0	102
XSN26	0.35	0.32	92.64	0.18	0.13	0.46	16.14	185.39	52.45	13.92	7.64	32.96							113.7	152
XSN27	0.15	0.10	16.59	0.06	0.41	0.18	7.28	53.67	21.98	1.27	1.54	8.03							26.4	44
XSN28	< 0.1	0.05	228.20	0.22	61.70	2.76	40.03	90.27	90.43	23.77	16.62	41.17							171.1	74
XSN30	11.05	9.92	65.64	0.12	3.55	0.08	38.31	407.88	221.90	9.79	3.20	9.22							36.16	336

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