Arsenic in Groundwater in the Surrey-Langley Area

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26 May, 2008

Executive Summary

This study was initiated by Fraser Health Authority and BC Ministry of Environment to provide a greater understanding of the extent, concentrations and possible sources of arsenic in drinking water from private wells in the White Rock-Surrey-Langley area. Elevated arsenic levels have been reported in a number of locations in B.C. in the past few years, and because arsenic is a carcinogen that can cause cancers and other chronic health effects over a lifetime of ingestion, it has become a source of increased concern. Health Canada recently reduced the maximum acceptable concentration (MAC) for arsenic from 0.025 to 0.010 mg/L, based on municipal and residential scale treatment achievability and a consideration of the health effects (2006 Guideline for Canadian Drinking Water Quality – GCDWQ). Chronic health effects may be observed after long-term ingestion of lower levels of arsenic in drinking water (Wang and Mulligan, 2006). Health Canada considers arsenic concentrations below 0.0003 mg/L to have essentially negligible[1] risk of health effects over a lifetime of exposure. However, arsenic concentrations above 0.0003 mg/L in surface and groundwater wells are recorded in BC, Canada and globally, in natural and untreated spring water.

The aim of the project was to determine the spatial extent of arsenic concentrations in groundwater in relation to geology and land use in the White Rock-Surrey-Langley area. Private well owners were invited to participate on a voluntary basis in a survey and 98 well sites were tested in August 2007 to ensure that the spatial distribution of the samples covered the extent of the White Rock-Langley-Surrey area and the major groundwater aquifers in the area.

The results showed that 43% of privately owned ground-water wells had total arsenic levels above the MAC of 0.010 mg/L. A further 40% fell between 0.0003 mg/L and 0.010 mg/L, levels which may still be associated with chronic adverse health effects. There is a significant relationship between arsenic and well depth with deeper wells having generally higher arsenic levels. The majority of well owners that obtain their groundwater from deposits associated with marine and glaciomarine materials have a high probability of elevated arsenic contamination. Given that the majority of the high arsenic levels occurred in deep wells and in marine types of deposits it is postulated that the arsenic originates from natural sources in marine deposits that accumulated in the area after glacial retreat.

Significant positive correlations were found between arsenic and boron, and to a much lesser extent between arsenic and chlorine, further suggesting that the occurrence of arsenic is from natural geological sources.

82 of the wells analysed in August were re-tested in October 2007 to assure that the elevated arsenic concentrations could be corroborated. A high level of agreement was found between the two test results. It was also possible to test the effectiveness of filter systems that were used in 13 of the 98 wells. The results indicate that only about half of the different types of filter systems were effective in reducing arsenic levels in the drinking water by more than 10%. Because all available filter systems were of different

[1] *Health Canada has defined the term "essentially negligible" as a range from one new cancer above background per 100 000 people to one new cancer above background per 1 million people over a lifetime.*

make and vintage no detailed testing was pursued and well owners are urged to contact different suppliers for information on effective treatment systems.

Historic data on arsenic from wells that serve multiple users and are under the jurisdiction of the Fraser Health Authority were also included in the analysis and the results confirmed that arsenic is primarily associated with marine and glacial-marine deposits. Only data since 2000 were included because the analytical detection limits were insufficient prior to that date.

All well owners were informed of their individual results. The Fraser Health Authority issues a public media release outlining the preliminary results of the study and provided the public with information on the best available options to reduce the health risks of arsenic in their drinking water and well owners are encouraged to conduct regular testing using a certified water analysis lab.

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1. Introduction/Background

1.1. Arsenic in groundwater

Arsenic is a metal that occurs naturally in the environment in a wide variety of forms. It is a component of several minerals in the Earth's crust, and often ends up in groundwater through the erosion and weathering of minerals and soils (BC MoE, 2007a). The process of arsenic entering groundwater depends upon local geology, hydrogeology, geochemical characteristics of the aquifer, plus climate changes and human activity (Wang & Mulligan, 2006). The most common sources of arsenic in the natural environment are from volcanic rocks (specifically weathering products of basalt and volcanic ash), marine sedimentary rocks, hydrothermal ore deposits (and associated geothermal waters) and fossil fuels. Arsenic is present in trace amounts in all living matter and there are also anthropogenic sources of arsenic, such as from the manufacture of wood preservatives and some pesticides (Wang & Mulligan, 2006). In the Langley – Surrey region marine and glaciomarine deposits are widespread, and no arsenic bearing bedrock formations are present.

The average arsenic concentration in the Earth's crust is 2 parts per million (ppm), i.e. equivalent to 2 mg/L, but it can be much more concentrated in arsenic-bearing ores such as arsenopyrite (FeAsS), realgar (AsS) and orpiment (As_2S_3) (Wang & Mulligan, 2006). In groundwater it is usually found in two oxidation states: As (III) or As (V). Arsenic binds with water to form H_3AsO_3 (arsenite) or $H_2AsO_4^-$ (arsenate) (Wang & Wai, 2004). Arsenite ions are found in anoxic conditions, whereas arsenate ions are most common in oxic environments (Wang & Mulligan, 2006). These authors have postulated that the geochemical oxidation of exposed sulphide minerals will release arsenic into surface and groundwater, and this process is catalyzed by certain bacteria. It is also hypothesized that the reductive dissolution of Fe (III) oxides and hydroxides leads to high arsenic concentrations in anoxic groundwater (i.e. deep wells). In this reducing environment, the electron donor can be organic matter in sediments, such as peat (Wang & Mulligan, 2006). The aqueous chemistry of arsenic is discussed in the excellent review by Cullen and Reimer (1989).

1.2. Health effects of arsenic in drinking water

Arsenic is classified as a human carcinogen and is becoming a major concern as elevated levels continue to be reported worldwide (Nickson et al., 1998; Stone et al., 2007; Wang & Wai, 2004; Welch et al., 2000). Arsenic is found in both organic and inorganic forms, most of which are odourless and tasteless and thus often remain undetected (Wang & Mulligan, 2006). It enters the body when it is swallowed in drinking water – arsenic in water is not appreciably absorbed through inhalation or through the skin when showering or bathing (Federal-Provincial-Territorial Committee on Drinking Water, 2006).

Arsenic in drinking water can have both short and long-term health effects (Wang & Mulligan, 2006). Short term effects usually begin about 30 minutes after ingestion and include abdominal pain, vomiting, diarrhea, muscle weakness and flushing of the skin.

These effects are typically seen at arsenic concentrations above 1.2 mg/L, although symptoms may be seen in children at levels as low as 0.2 mg/L. Consumption of water with arsenic levels exceeding 60 mg/L can be fatal (Wang & Mulligan, 2006). Long term exposure to lower concentrations of arsenic can result in chronic, adverse health effects (Nichols et al., 1998). These include peripheral vascular disease, hypertension, thickened skin, wart-like lesions and skin cancers. Of most concern is the ability of arsenic to cause internal cancers; long-term or lifetime exposure to arsenic in drinking water is associated with the development of lung, liver and bladder cancers.

It is arsenic's status as a carcinogen that has prompted the development of guidelines for arsenic in drinking water. The Guidelines for Canadian Drinking Water Quality (GCDWQ) have set a Maximum Acceptable Concentration (MAC) of 0.01 mg/L of arsenic in drinking water, reduced in 2006 from 0.025 mg/L (Federal-Provincial-Territorial Committee on Drinking Water, 2006). This mirrors the standard set by the World Health Organization and follows a similar reduction by the United States in 2002, based on the National Research Council's conclusion that the previous guideline did not sufficiently protect public health (Stone et al., 2007). The MAC as set out by the GCDWQ is based on both the health effects of arsenic and the ability of municipal and residential treatment facilities and devices to reduce arsenic concentrations to 0.010 mg/L or less (Federal-Provincial-Territorial Committee on Drinking Water, 2006). However, long-term consumption of water with arsenic levels at or even below 0.010 mg/L has been associated with a small increase in cancer risk. The risk decreases with decreasing arsenic level and at 0.0003 mg/L falls to a risk of 1 excess cancer per 100,000 people exposed, or "essentially negligible" health risk (Federal-Provincial-Territorial Committee on Drinking Water, 2006). For this reason it is desirable to reduce arsenic levels in drinking water to the maximum extent practical.

1.3. Worldwide occurrence of arsenic in drinking water

High concentrations of arsenic have been found in many parts of the world, particularly in Bangladesh, Taiwan, and Chile (Appendix A).

Arsenic is found in both surface and groundwater, and levels are generally higher in groundwater (Wang & Mulligan, 2006). In Canada, total arsenic levels in drinking water generally fall well below the MAC, although elevated concentrations have been found in areas with natural sources of arsenic. High levels of arsenic have been found in Saskatchewan, Manitoba, Ontario, and Nova Scotia, and in British Columbia (Table 1). Many of the Canadian arsenic occurrences have been associated with naturally occurring mineralized deposits, usually of volcanic origin. Finding high levels of arsenic in surficial materials is somewhat unusual unless they can be traced to the mineralized source area.

Previous studies on Bowen Island and the Sunshine Coast in British Columbia have shown highly spatially variable levels of arsenic in the groundwater (Carmichael, 1995; Mattu & Schreier, 1999). It is postulated that most of the arsenic in these areas is associated with exposed fissures of volcanic origin in granitic bedrock (Mattu and Schreier, 1999). If a well intercepts these fissures, there is an increased probability of elevated arsenic in the well water.

Table 1. Documented studies of arsenic concentrations in Canadian waters (modified from Wang and Mulligan, 2006).

Location	***As concentration average (range) (mg/L)***	***References***
Surface water		
British Columbia	0.0175 (<0.0002–0.556)	Azcue et al. (1994)
British Columbia	0.00028 (<0.0002–0.00042)	Azcue et al. (1994, 1995)
Saanich Inlet, BC	0.0012–0.0025	Peterson and Carpenter (1983)
Meager Creek, BC	0.0056 (cold) 0.28 (0.237–0.303) (hot)	Koch et al. (1999)
Northwest Territories	0.27 (0.064–0.53)	Bright et al. (1996)
Lakes near Yellowknife	0.7–5.5	Wagemann et al. (1978)
Kam Lake, Yellowknife	1570	Coumans (2003)
Ontario	0.0007	Azcue and Nriagu (1995)
Ontario	0.035–0.1	Azcue and Nriagu (1995)
Moira Lake, ON	0.022 (winter) – 0.062 (summer) 0.04–0.05	Azcue and Nriagu (1995) Zheng et al. (2003)
Moira River, ON	0.002–0.14 37.5	Zheng et al. (2003) Owen and Galloway (1969)
Mitchell Brook, NS	0.037–0.19	Brooks et al. (1982)
Gegogan Brook, NS	0.03–0.23	Wong et al. (1999)
Groundwater		
Bowen Island, BC	0.0005–0.58	Boyle et al. (1998)
Ellis Pool, Alberta	0.23	White et al. (1963)
Virden, MB	0.065–0.07	OSMONICS (2002)
Sediment porewater		
Mining contaminated, BC	0.05–0.36	Azcue et al. (1994)
Baseline, clays, Saskatchewan	0.0032–0.098	Yan et al. (2000)
Moira Lake, ON	495–1565 (mg/kg)	Azcue and Nriagu (1995)
Tailing impoundment, ON	0.3–100	McCreadie et al. (2000)
Suspended particulates, Gegogan Lake, NS	1500–5000 (mg/kg)	Wong et al. (1999)
Gegogan Brook, NS	170–2000 (mg/kg)	Wong et al. (1999)

It is suggested that the arsenic in marine and glacial marine deposits is a result of secondary enrichment during the glacial and post glacial period when glacial-fluvial processes transported and deposited arsenic rich material into the marine estuary environment. Because of the isostatic rebound after glaciation some of these deposits are now above the current sea level. The original source of the arsenic is likely from highly mineralizes or volcanic material from the Interior of B.C.

Links to more information on arsenic and arsenic research are provided in Appendix B.

2. Aims and Objectives

The main aims of this study are to identify and characterize the distribution and concentration of arsenic in existing private wells (unregulated) and public wells (regulated) in the Surrey-Langley area, and to determine the possible sources of contamination.

The specific objectives are to:

1. Determine the spatial and depth distribution of arsenic in the wells of the study area

2. Identify possible sources of arsenic (surficial materials or land use)

3. Examine relationships between arsenic and physical and chemical variables

4. Compare the results with historic data for the same area

5. Evaluate the effectiveness of treatment systems in reducing arsenic in drinking water to acceptable concentrations

3. Study area

The Surrey-Langley area of the Lower Fraser Valley is an area in BC where elevated concentrations of arsenic have been reported by the Fraser Heath Authority in a number of groundwater wells on a number of occasions. Preliminary groundwater tests have shown high levels of arsenic in deeper wells (> 20m, >60 ft); 46% of 121 samples had arsenic level > 0.010 mg/L with a maximum value of 0.067 mg/L (Fraser Health, 2007). The origin of the arsenic in groundwater is different from those on the Sunshine Coast because the Fraser Valley wells are not in bedrock, but in unconsolidated surficial materials.

Ryder (1978) provides a comprehensive account of the glacial history and the resultant surficial deposits in the region. These surficial materials were formed during and since the Fraser glaciation (20,000 to about 8000 years ago). Drift material including till, fluvioglacial and glaciomarine sediments were deposited during ice retreat. Glaciomarine materials were deposited during the time of high sea level at the end of the Fraser glaciation as an accumulation of particles released from floating, melting ice. These materials consist of stony, silty clays and in places contain shells of ancient marine molluscs. In more recent geologic times, fluvial and organic sediments have been deposited on valley floors and depressions in the area. The organic materials consist of peat, which accumulated in depressions and in areas with a high water table. Glaciomarine materials cover gently sloping and depressional areas in the western part of the Fraser Lowland (Ryder, 1978).

The study area includes the City of Surrey, White Rock and the Township of Langley. The boundaries extend east-west from 276th Street to Mud Bay (122°27'34.7"W to 122°53'27.2"W), and north-south from the Fraser River to the U.S. Border (0 Ave.) (49°12'26.9"N to 49°00'08.1"N) (Fig. 1).

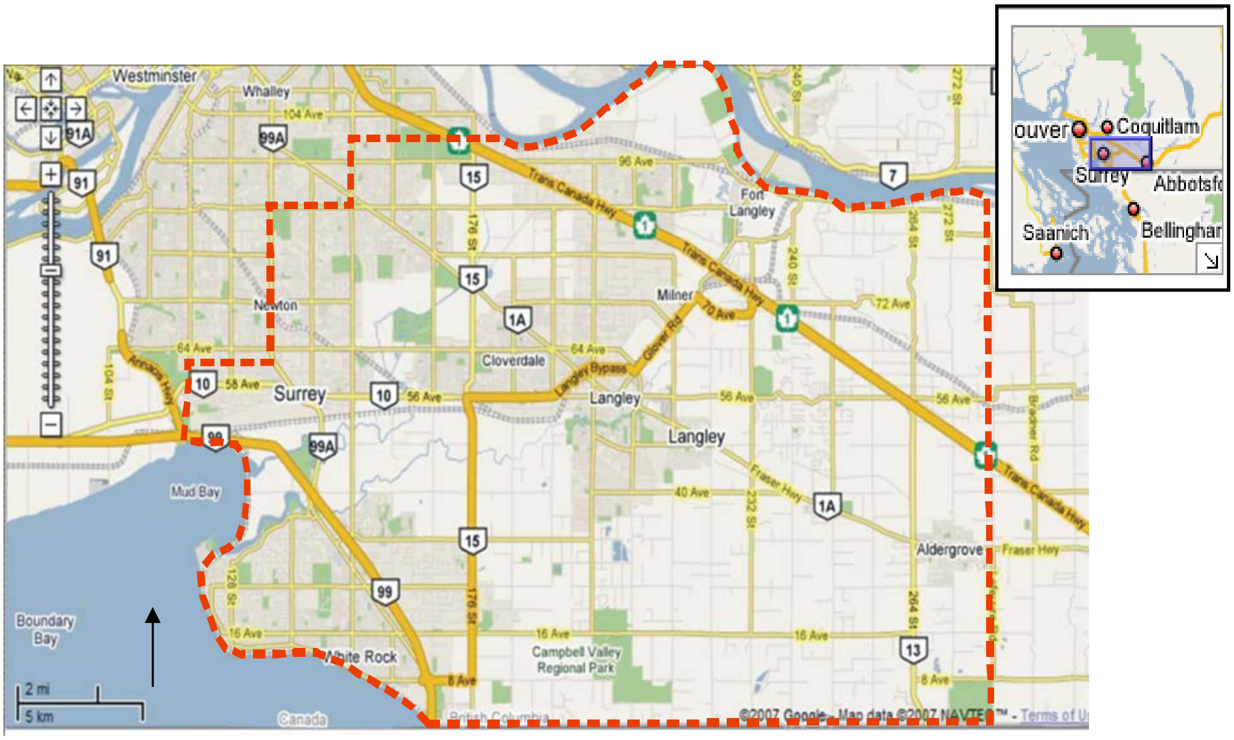


Figure 1. Map of Surrey-Langley region. Study area enclosed by red line. © 2007 Google

4. Methods

A range of techniques and methods were used to conduct a comprehensive evaluation of the presence of arsenic in the study area, including stratified well selection, groundwater water sampling, ICP-MS analysis for total and dissolved metals, re-verification of elevated levels, and statistical and spatial (GIS) analysis.

4.1. Well selection and sampling design

This study relied on voluntary participation from private well owners to supply water samples. The BC Water Resources Atlas Mapping Service (online) was used to identify potential private well locations (BC MoE, 2007b). Each well on this map is identified by a unique Well Tag Number, which applies to all registered wells in the province. The Water Well Application database provides a detailed well record for each registered well (BC MoE, 2007c). The well records include: owner's name, address, well depth (at time of drilling), construction date, drilling company, and general lithology information from a borehole record.

Private wells were selected across the study area, including those that fall on the major aquifers of the region. Locations within the study area that are serviced by Greater

Vancouver Regional District (GVRD) water or mixed GVRD / groundwater systems were not included as there is no evidence of arsenic in GVRD water. A quadrat system was also used to ensure that well selection was distributed spatially throughout the area.

Letters requesting volunteers (Appendix C) were mailed to the addresses obtained from the online well records, and previously sampled private wells with elevated arsenic levels obtained from the FHA and MoE database. Previously sampled community and observation well data is provided in Appendix D. A total of 486 letters were sent out, 175 to Surrey and 311 to Langley. There were 36 responses from Surrey, and 62 from Langley for a total of 98 participants. This equates to an approximately 20% response rate.

The volunteers were contacted via telephone, fax and e-mail, and the following information was obtained from each volunteer:

- Well depth
- Well age
- Any treatment or filtration of drinking water
- Concerns with water quality

Most of the owner's accounts coincided with the MoE Well Records, although it appeared that some MoE records were out of date. Using Geographic Information Systems (GIS), a map of the well locations was generated (Figure 2). Characteristics of the sampled wells (depth class and aquifer vulnerability classification) are provided in Tables 2 and 3. This study focuses on deep wells (>30m, >100 ft.) since it was predominantly deep wells that showed elevated levels of arsenic in previous results.

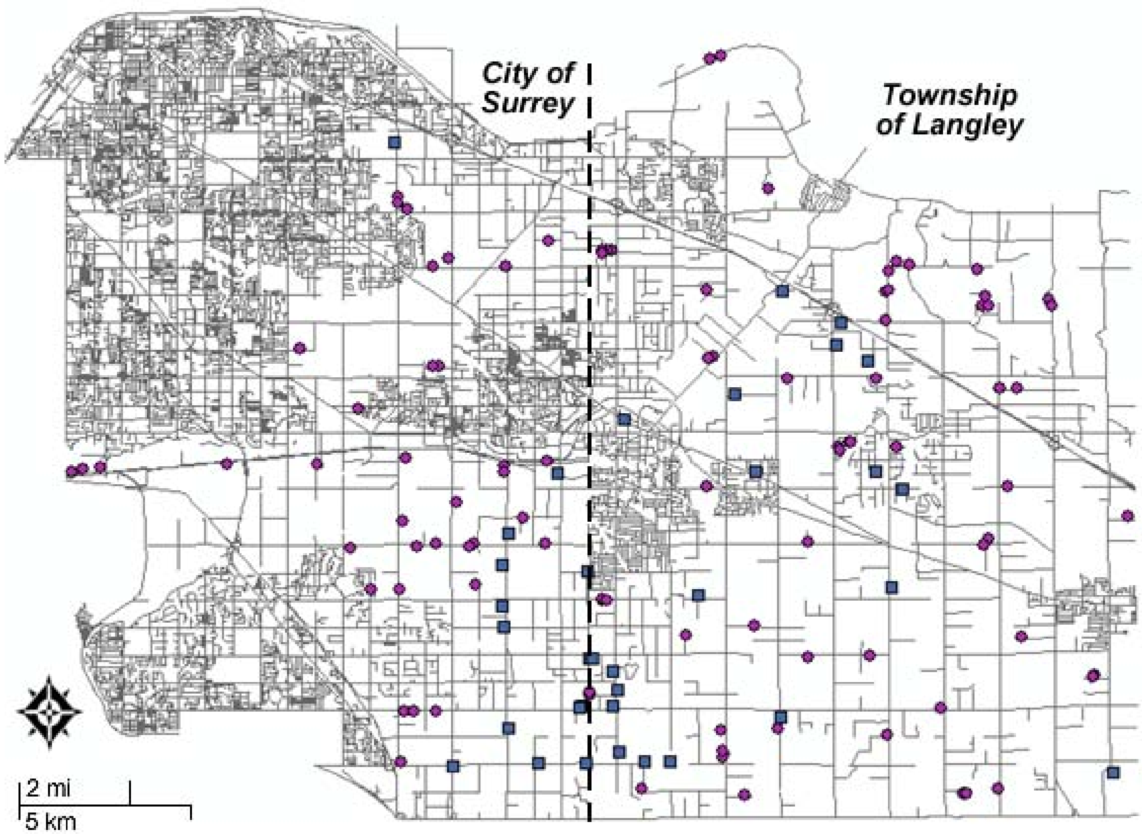


Figure 2. Road map of study area. Purple circles indicate private wells sampled in August, 2007. Blue squares indicate community/observation wells previously sampled (2004-2007).

Table 2. Number of wells sampled in different depth categories and vulnerability classifications of underlying aquifers (N=98).

Aquifer Vulnerability	Number of Wells				Total
	0-99 ft depth	100-199 ft depth	200+ ft depth	Unknown depth	
Low	18	33	17	5	73
Medium	3	1	1	0	5
High	8	9	2	1	20
TOTAL	29	43	20	6	98

4.2. Water collection and lab analyses

Each well owner was responsible for providing a sample of their raw well water. They were provided with 125mL plastic sample bottles and detailed sampling instructions (Appendix E) in mid-August, 2007. Grab samples were collected from a tap near the wellhead, refrigerated at 5°C, and delivered to three different labs for analysis within four hours of collection. One sample of reverse-osmosis (RO) treated water was also collected. The analyses were done on August 20 and 21, 2007.

Total and dissolved arsenic and a range of other elements were analysed by Bodycote Testing Group (104-19575 55A Ave., Surrey) (Table 4). The U.S. EPA approved Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) analytical method was used (HC, 2006).

Campylobacter, E. coli and Total Coliform were analysed at the B.C. Centre for Disease Control Laboratory (655 W. 12th Ave., Vancouver) using standard methods.

Analyses of nitrate, orthophosphate and chloride concentrations were completed at a water quality laboratory at UBC (2357 Main Mall, Vancouver) using the LaChat 8000 QuikChem Flow Injection Analyzer (6645 Westmill Rd., Milwaukee, WI USA). The QuikChem methods used to determine concentrations of nitrate, orthophosphate and chloride were *12-107-04-1-B, 12-115-01-1-A* and *10-117-07-1-A,* respectively.

Fluoride, which is often associated with hydro-thermal deposits, was not analysed in this study because: a) fluoride can not be detected by ICP-MS analysis and would have required other analytical methods that would have added significant costs to the project, and b) there was no particular evidence that fluoride is of concern in this study area.

Table 3. Elements analysed by the Bodycote Lab using the ICP-MS method.

Metals Total	*Metals Dissolved*
Aluminum	Aluminum
Antimony	Antimony
Arsenic	Arsenic
Barium	Barium
Beryllium	Beryllium
Bismuth	Bismuth
Boron	Boron
Cadmium	Cadmium
Calcium	Chromium
Chromium	Cobalt
Cobalt	Copper
Copper	Lead
Iron	Lithium
Lead	Molybdenum
Lithium	Nickel
Magnesium	Selenium
Manganese	Silicon
Molybdenum	Silver
Nickel	Strontium
Potassium	Sulfur
Selenium	Thallium
Silicon	Tin
Silver	Titanium
Sodium	Uranium
Strontium	Vanadium
Sulfur	Zinc
Thallium	
Tin	
Titanium	
Uranium	
Vanadium	
Zinc	
Zirconium	

4.3. Re-sampling

The first set of 98 samples was collected and analysed on August 20 and 21, 2007. To corroborate the total arsenic levels, a second set of 82 samples was collected from wells with results exceeding 0.0003 mg/L total arsenic. Also, additional samples of treated water were collected from 13 of the re-sampled wells to evaluate the effectiveness of arsenic removal treatment devices. Sampling took place on October 16 and 24, 2007. At this time, an additional volunteer provided a well water sample to test for total arsenic.

4.4. Statistical analysis

Standard statistical techniques were used to analyse the data. Correlation techniques were used to determine relationships between physical and chemical variables, and the non-parametric Mann-Whitney-U test was used to determine significant differences between sample sets.

4.5. GIS analysis and well record data

Both the Township of Langley and the City of Surrey provided data layers which permitted the geo-referencing of each well, and the ability to link the wells layer with the surficial materials of the area. The surficial geology map by Armstrong and Hicock (1976) was used to determine the surficial material for each well.

4.6. Ministry of Environment well record database

From the MoE Well Record Database the stratigraphy specific to each well was determined. Of the 98 sampled groundwater wells 44 (45%) were found in the provincial data base and the depth and thickness of key surficial material layers were determined from the borehole records.

5. Results

The results of the water sample analysis were placed into a database, and the digital version annexed to the report (Appendices F and G).

5.1. Summary of total and dissolved arsenic data

In the initial data set, both total and dissolved arsenic were analysed. The values for total and dissolved arsenic correlate very well, with a few discrepancies (Spearman's rho, $r=0.984$, $p<0.0001$) (Figure 3). Dissolved arsenic is generally of greater concern than total arsenic because it can be absorbed more readily in the body. The reason for measuring both total and dissolved arsenic was to determine the difference and as shown in Figure 3 almost all arsenic is in the dissolved form. In fact, the dissolved arsenic values were slightly higher than the total arsenic, but this is well within the accuracy of the ICP-MS laboratory method that was used. This suggests that the use of total arsenic is appropriate, which conforms to the health guidelines and regulations that require testing for total arsenic. Only two samples had discrepancies between total and dissolved arsenic around the 0.010 mg/L MAC. Re-sampling wells with total arsenic >0.0003 mg/L confirmed the initial values. The MAC, as set out by the GCDWQ, applies to total arsenic, and therefore, further analyses were done only for total arsenic.

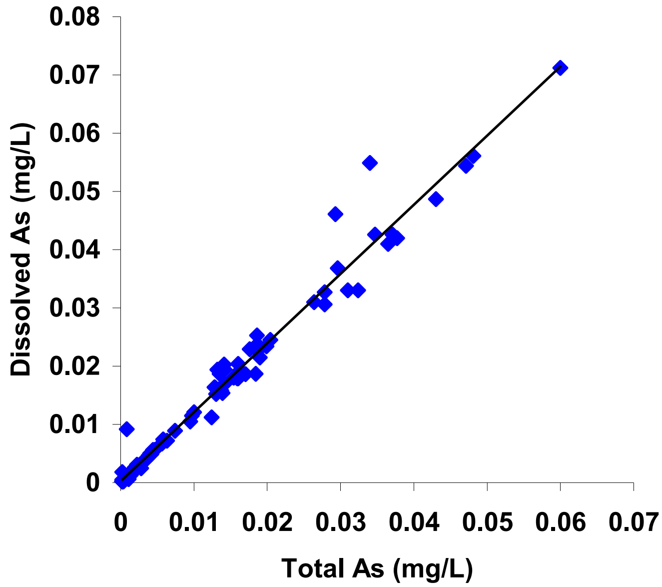


Figure 3. Relationship between total and dissolved arsenic. (N=98; r=0.98)

Table 5 summarizes the total arsenic results compared to the MAC and to the level where health effects are "essentially negligible". The maximum total arsenic concentration at the tested wells was 0.060 mg/L.

Table 4. Number and percent of samples with total arsenic (As) results above guidelines. (August 2007 results)

	ALL	*SURREY*	*LANGLEY*
% above 0.025 mg/L total As (previous guidelines)	15.3	33.3	4.8
% above 0.01 mg/L total As (current guidelines)	42.9	61.1	32.3
% between 0.0003 and 0.01 mg/L total As	39.8	36.1	41.9
% below 0.0003 mg/L total As	17.3	2.8	25.8
# above 0.025 mg/L total As (previous guidelines)	15	12	3
# above 0.01 mg/L total As (current guidelines)	42	22	20
# between 0.0003 and 0.01 mg/L total As	39	13	26
# below 0.0003 mg/L total As	17	1	16

The results of the re-sampling showed a significant positive correlation of total arsenic values with the original samples (Spearman's rho, $r=0.969$, $p<0.0001$) (Figure 4). Six samples showed a greater than 100% difference, and five of these samples fell below the MAC. One sample which came from the post-RO treatment had a large reduction in total arsenic, because a membrane in the treatment system had been replaced between the first and second sampling dates (see Figure 4).

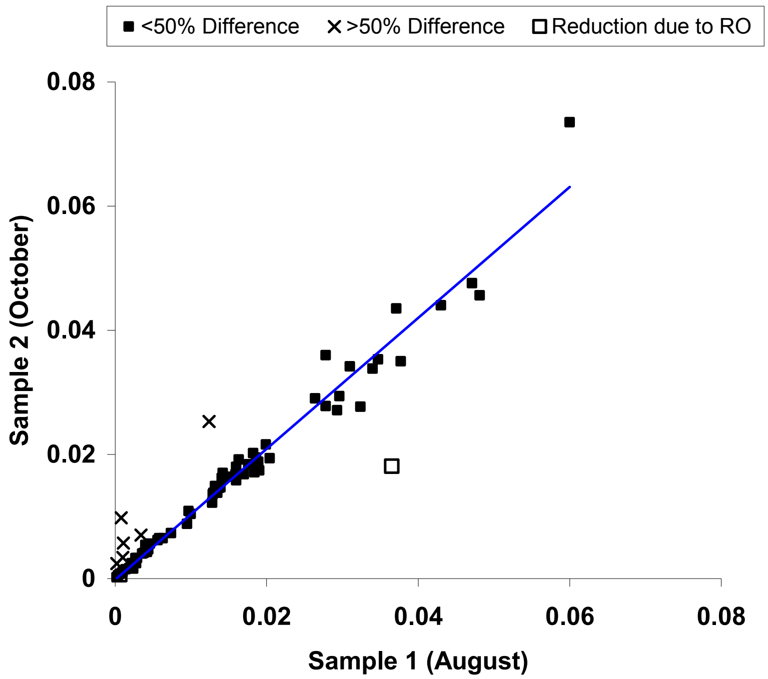


Figure 4. Correlation between initial and re-sampled total arsenic values. X symbols show a greater than 50% difference. The open square symbol shows a reduction after the replacement of a reverse-osmosis treatment filter. (N=82; r=0.97)

5.2. Relationship between total arsenic and other parameters

The 98 samples collected in this study were first analysed in relation to the well depth and then in relation to the type of surficial material and the thickness of any clay layers in the borehole record.

The relationship between well depth and total arsenic concentration was evaluated to assess if the source of arsenic is natural or potentially associated with land use activities. Deep wells are generally less sensitive to contamination from land use activities (Welch et al., 2000). If the high arsenic levels are predominantly in deep wells and confined aquifers it is hypothesized that the source of the high arsenic concentrations is from natural sources contained in the surficial materials in the region from which the groundwater is extracted. The results provided in Figure 5 show that there is a significant positive correlation between well depth and arsenic, with deeper wells having significantly higher arsenic concentrations (Spearman's rho, $r=0.512$, $p<0.0001$). Figure 6 is a graphical representation of a statistical comparison of total arsenic among three well depth categories. These results are summarized in Table 6. Each category is statistically different from the others. Well depth is unknown for six of the sampled wells. Under the previous guidelines (MAC = 0.025 mg/L), exceedences primarily affected deep wells (200+ feet).

Potential anthropogenic sources of arsenic are wood preservative treatment operations and/or long-term application of fertilizer and fungicides. Wood preservation is site specific, and not a potential source for the regional distribution of arsenic in groundwater seen in the Langley-Surrey region. Land application of fertilizers and fungicides containing arsenic are unlikely sufficient to cause the regional distribution of arsenic, and this would primarily affect shallow wells, and would preclude the relationships found with surficial materials.

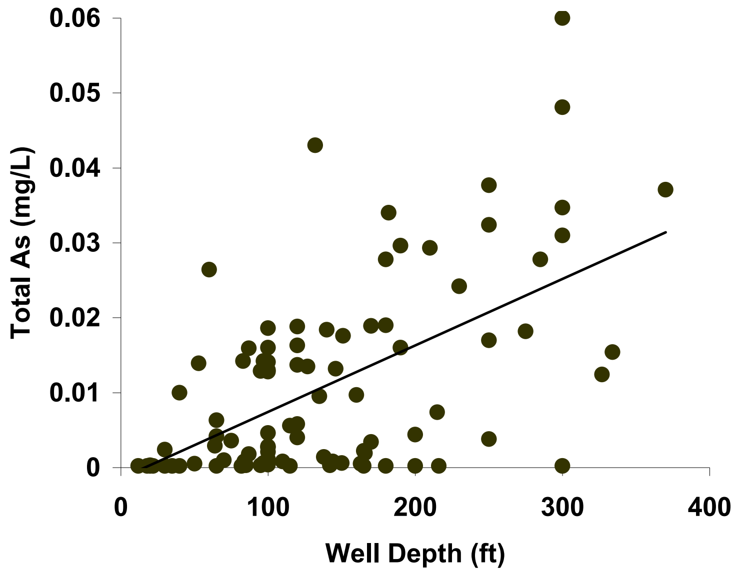
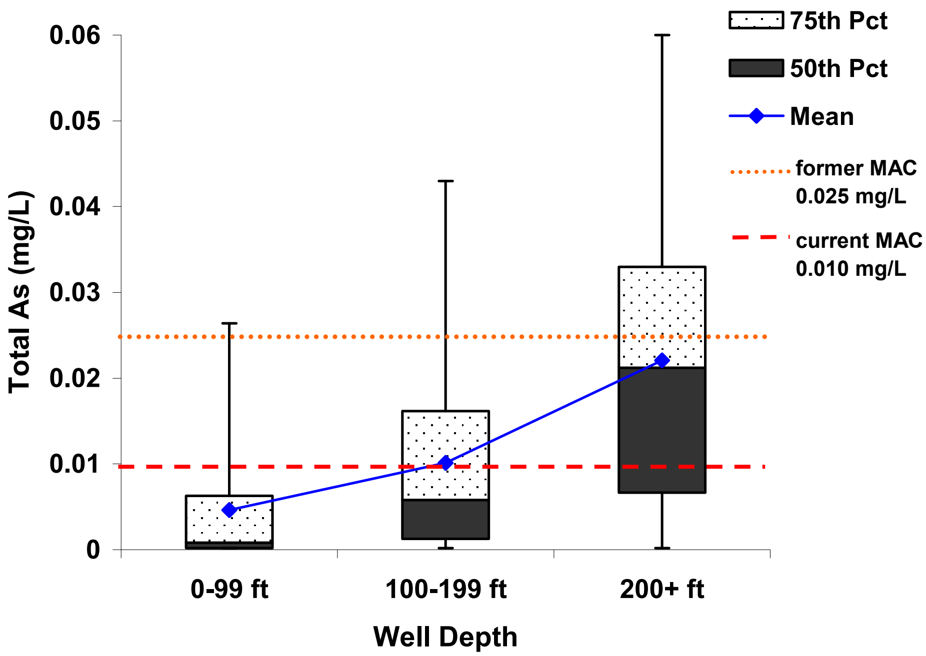


Figure 5. Relationship between total arsenic and well depth. (N=92, r=0.51)



The 75th percentile means that 75% of all the values fall below this number (the top bound of the dotted box). The 50th percentile (or median) is the number below which 50% of all the values fall, and is indicated by the line between the dotted and black boxes. 25% of the values fall between the bottom bound of the black box and the minimum value, indicated by the lower error bar.

Figure 6. Total arsenic vs. well depth, separated into three categories. Red dashed line is MAC and whiskers equal max/min values. ($n_{0\text{-}99}$=29, $n_{100\text{-}199}$=43, n_{200+}=20)

Table 5. Non-parametric (Mann-Whitney U) comparison of total arsenic concentrations between three well depth categories. (α=0.05)

	100-199 ft		***200+ ft***	
0-99 ft	M-W	366.5	M-W	108.5
	p	0.0031	p	0.0002
100-199 ft			M-W	263.0
			p	0.0136

The next step in the analysis involved the linkage of total arsenic concentrations with the type of the surficial materials. Based on GIS and Armstrong and Hicock's surficial geology map (1976) each well location was associated with a surficial material. Figure 7 shows that those wells associated with organic, marine and glaciomarine materials, which are dominated with clay-sized particles, have the greatest total arsenic concentrations. There were significant differences between aquifers near marine-dominated surficial materials and those originating from fluvial and glaciofluvial materials (Mann-Whitney U=372.0, p<0.0001).

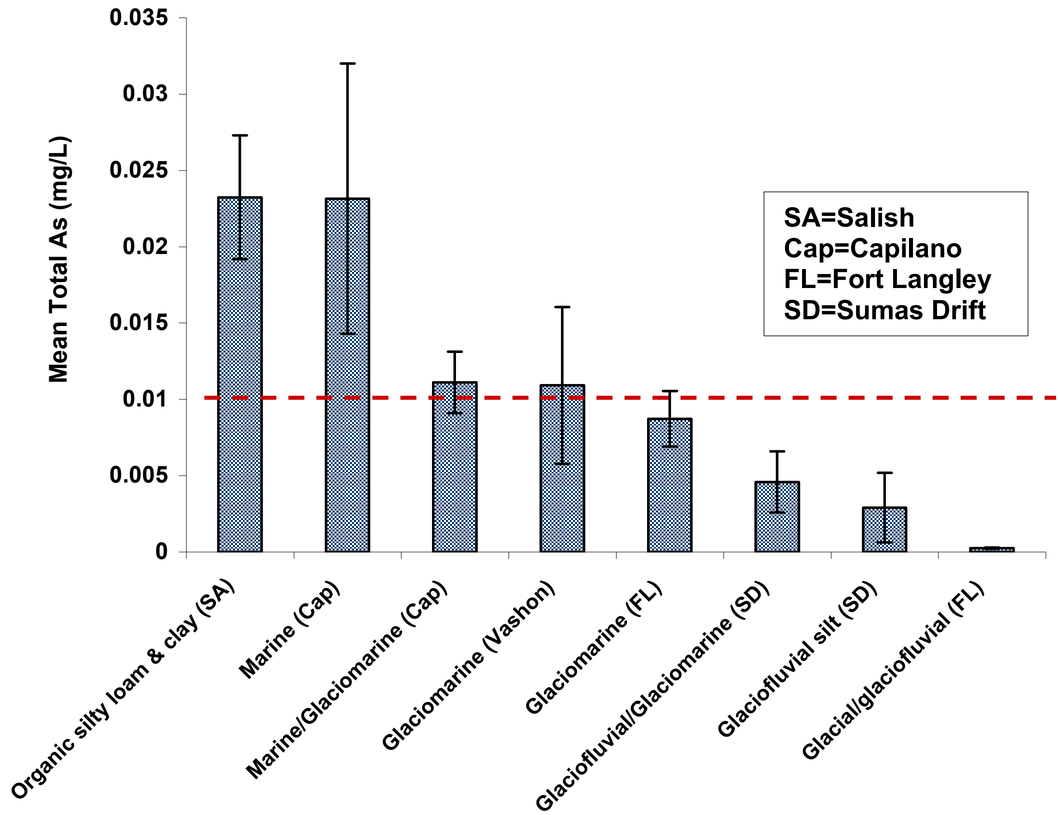


Figure 7. Mean total arsenic and underlying surficial materials (from Armstrong and Hicock, 1976). Red dashed line indicates the MAC. (Mean ± 1 S.E.) Note wells may or may not be screened in the surficial material shown on the map.

The analysis was further refined by separating marine dominated surficial materials from glacial and fluvial materials and comparing well depth with arsenic levels (Figures 8a & 8b). There is no significant correlation between well depth and total arsenic in glacial/glaciofluvial materials (Spearman's rho, r=0.094, p=0.684) (Figure 8a). There is a significant positive correlation between well depth and total arsenic associated with marine materials (Spearman's rho, r=0.587, p<0.0001) (Figure 8b). This suggests that the source of arsenic is primarily from deep wells associated with marine materials, the marine materials may occur either above or below the water extracting layer. This further corroborates that anthropogenic activities likely do not play a significant role in arsenic contamination.

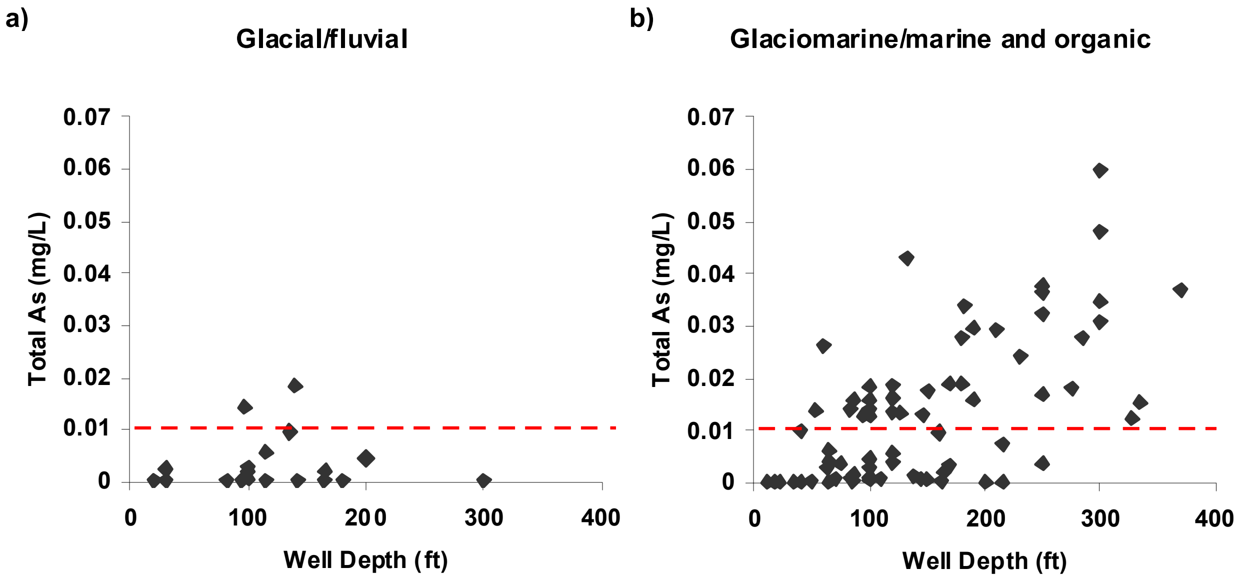


Figure 8. Relationship between total arsenic and well depth in private wells that intersect a) *Glacial/glaciofluvial gravel and sand* and b) *Marine, glaciomarine and organic materials*. Red dashed line indicates the MAC.

Data was available for an additional 121 wells in the study area with historic total arsenic values. Because of the significant improvement in arsenic detection levels in recent years, only historic data since 2004 were used in this analysis (60 samples). This increased the sample number for the analysis to 158 wells. These were combined with the current data set, and depth and surficial material relationships with arsenic were analysed in a similar fashion. Well depth is unknown for seven of the wells.

The results confirm the findings that significant positive relations were found between well depth and total arsenic concentrations (Spearman's rho, $r=0.587$, $p<0.0001$) (Figure 9). There was also a significant difference in total arsenic levels between the marine / glaciomarine materials and the surficial materials dominated by fluvial processes (Figure 10). The likely source of arsenic in these deposits is from terrestrial bedrock formations (volcanic, hydrothermal and/or highly mineralized rocks) which have been weathered and transported by glacial and fluvial processes into the marine environment, where they were deposited and enriched through mobilization under anoxic conditions (Stone et al., 2007; Smedley and Kinniburgh, 2002).

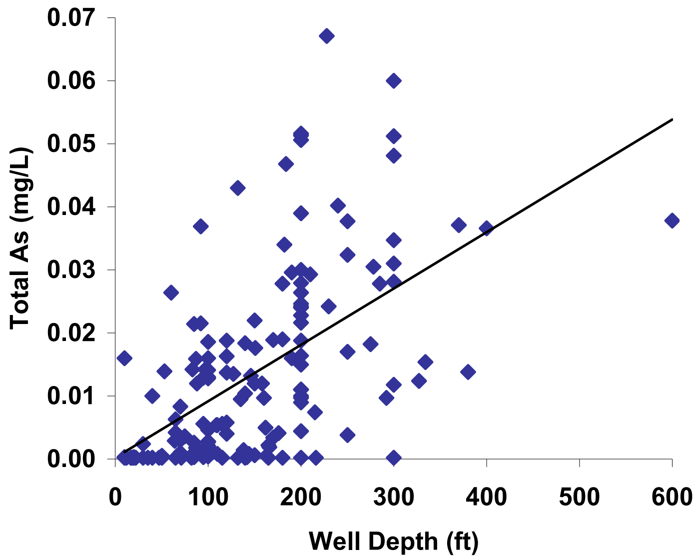


Figure 9. Relationship between total arsenic vs. well depth, including previously sampled wells. (N=151; r=0.59)

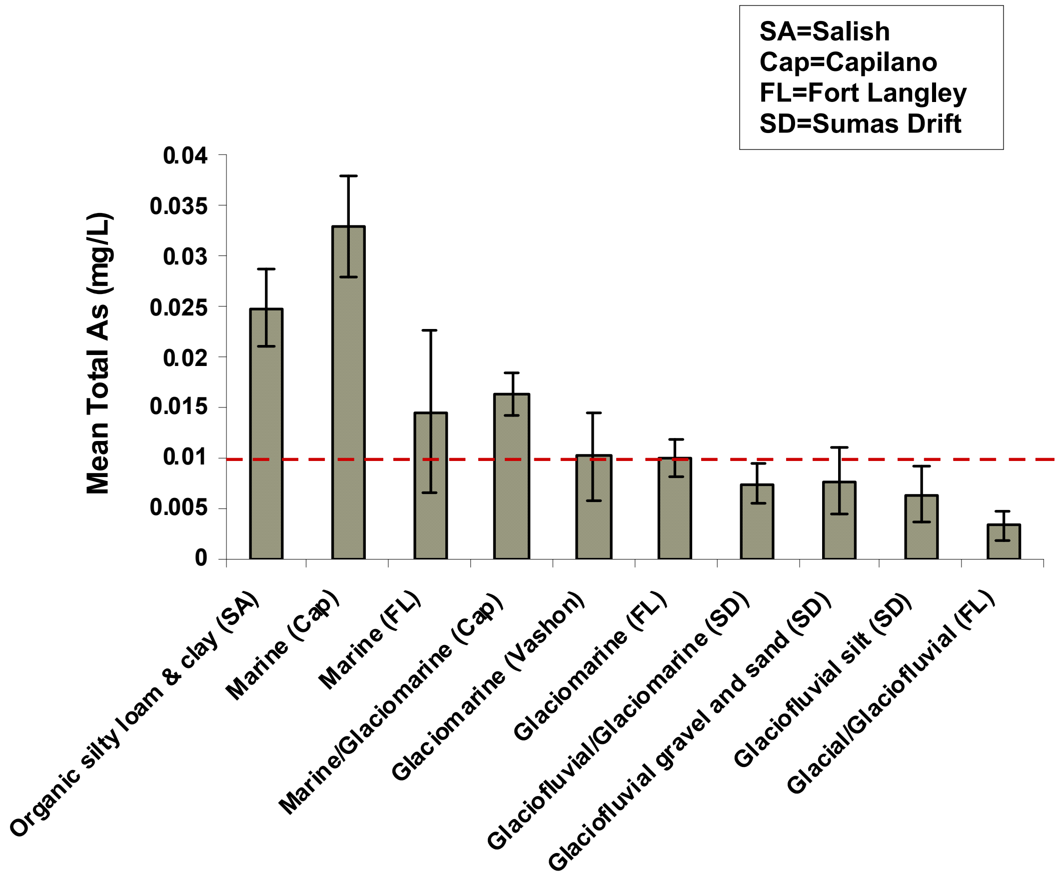


Figure 10. Mean total arsenic and underlying surficial materials (from Armstrong and Hicock, 1976), including previously sampled wells. Red dashed line indicates the MAC. (Mean ± 1 S.E., N=158)

5.3. Spatial distribution of arsenic

The spatial distribution of arsenic was displayed and analysed in two ways: 1) spatial extent by aquifer and surficial materials and 2) arsenic levels in relation to aquifer vulnerability.

The spatial distribution of arsenic in relation to surficial materials is shown in Figure 11. It illustrates the locations of the wells and the total arsenic concentrations using a tri-colour scheme (Red > 0.010 mg/L, Orange 0.0003-0.010 mg/L, Green < 0.0003 mg/L). Well depth is also represented by the size of the circle corresponding to each well. This suggests that there is a high probability of elevated total arsenic levels in the groundwater in specific low lying areas dominated by marine deposits.

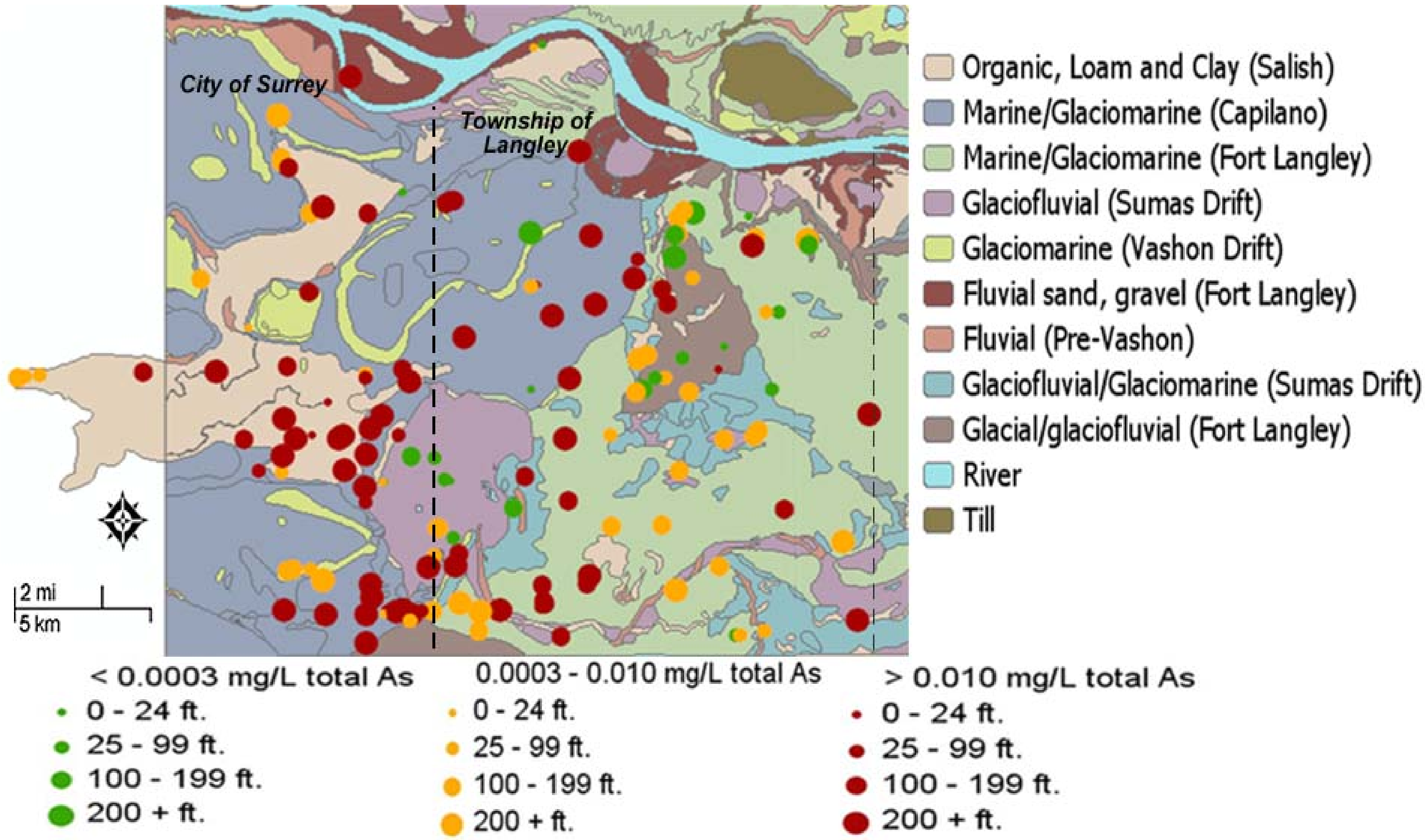


Figure 11. Well location, depth, and total arsenic levels are indicated by the circles. Underlying surficial geology in the Surrey-Langley area is colour-coded (refer to legend). Includes previously tested wells (N=158).

Analysis of arsenic in relation to geological materials at depth was limited due to a lack of detailed well profile information. Bore hole records were retrieved from the MoE Water Well Application database (BC MoE, 2007c) to provide some geological detail for specific wells in the sample set. However, data were only available for 44 samples. Given that the borehole records are submitted on a voluntary basis and there is no standardized classification, interpretations of this data are difficult to make.

Analysis was conducted to determine if the depth and thickness of any clay layers in each of the well profiles is positively correlated with the total arsenic concentrations. A positive trend was seen between the thickness of clay in the well profile and total arsenic in the well water, but this relationship was not statistically significant (Appendix H). A geological cross-section of the Township of Langley was generated by Golder Associates, Ltd. (2005), and is shown in Figure 12. This cross section gives a good overview of the complexity of the surficial materials in the region. From Figure 12 it is evident that individual bore holes (depicted by gray lines) can tap into layers that are discontinuous, and or layered, and unless sufficient bore hole records are available it is difficult to arrive at a good spatial distribution of each type of deposit.

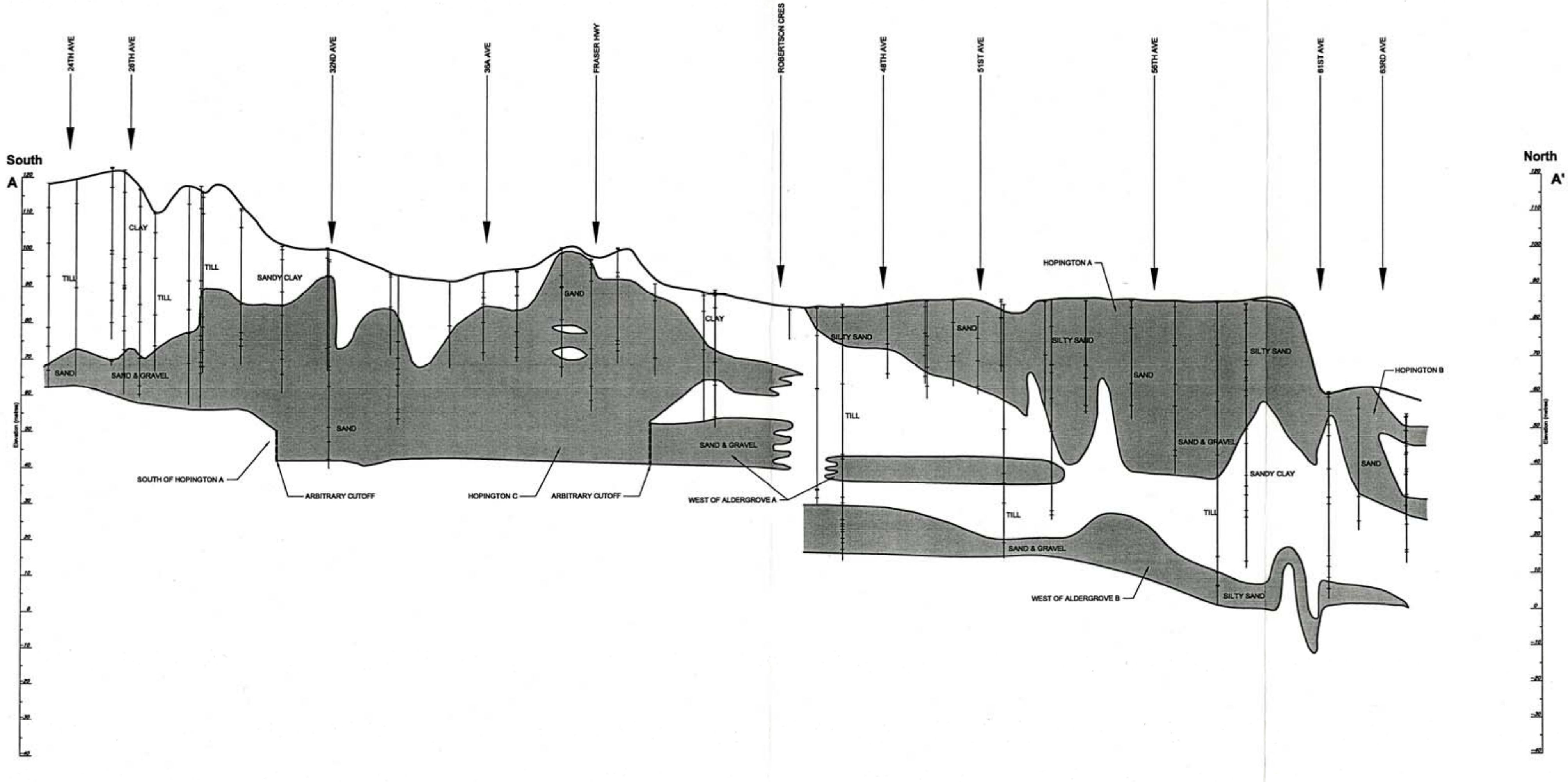


Figure 12. South-North geological cross section along 240 Street in the Township of Langley. (Source: Golder Associates Ltd., 2005)

5.3.1. Arsenic in relation to aquifer vulnerability

The vulnerability of each major aquifer in the Lower Fraser Valley was first classified by Kreye and Wei in 1994. A more detailed vulnerability classification was performed by Golder and Associates (2004) for the Township of Langley and the eastern portion of Surrey in 2004 only. Because of the differences in the two classifications it is not possible to present a combined map and only the Township of Langley map is presented here. The vulnerability classification is based on whether the aquifer is confined, how extensive it is used and what the risk of contamination from land use applications are. Confined aquifers usually have low vulnerability, semi-confined aquifers have moderate vulnerability and unconfined aquifers have high vulnerability, particularly if they consist of coarse gravel that reaches up to the land surface. The online B.C. Water Resource Atlas (BC MoE 2007b) was used to determine aquifer vulnerability classification for the remaining Surrey wells. Since no appropriate digital map was available for this report, the vulnerability classifications of each of the 36 wells in Surrey was identified in the atlas and were all found to be located on confined aquifers in the low vulnerability class.

The remaining well locations were superimposed with the vulnerability classes using GIS, and the results showed that there was a significant difference between the high and low vulnerability classes for several parameters. Only five of the 98 wells were associated with semi-confined aquifers and were therefore omitted from the statistical analysis.

As shown in Figure 13, mean concentrations of arsenic (Mann-Whitney U=276, p=1.22E-05), and B (M-W U=318, p=6.95E-05) were significantly higher in wells associated with confined aquifers (low vulnerability) than those over unconfined aquifers (high vulnerability). These parameters are associated with marine and glaciomarine mineral deposits. The vulnerability classification was determined on the basis of potential impacts from anthropogenic sources and did not consider contamination from natural sources from within the geological formation. The vulnerability classification is obviously directed towards impact from land use activities and this is the reason for the nitrate impacts on the high vulnerable aquifers (Figure 14). In contrast, arsenic contamination appears to be from natural sources from within the deposits and therefore does not conform to this type of vulnerability classification.

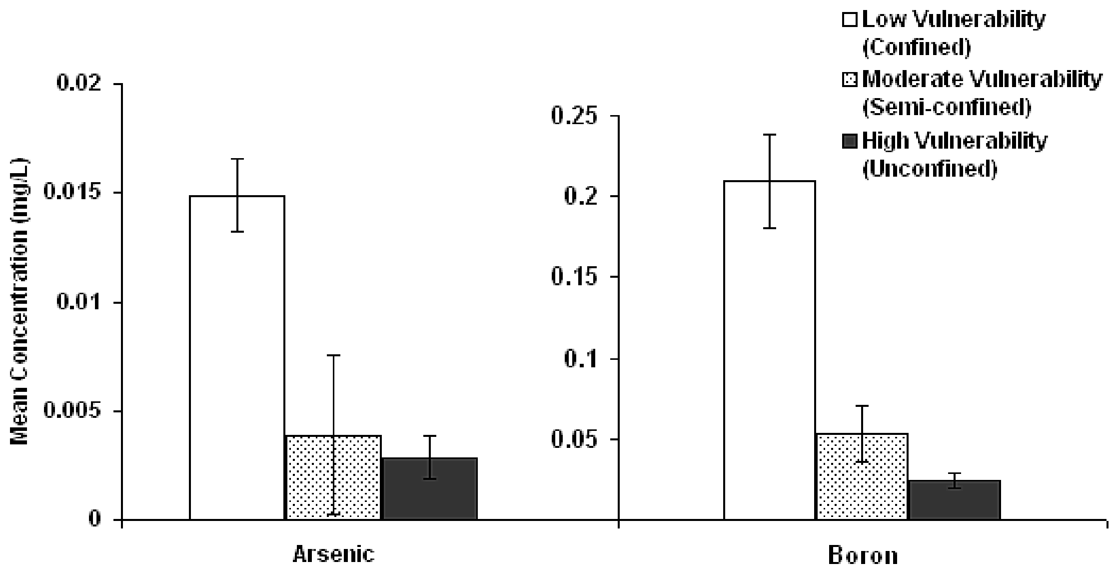


Figure 13. Mean concentrations of arsenic and boron in wells overlying low, moderate and high vulnerability aquifers. (Mean ± 1 S.E.)

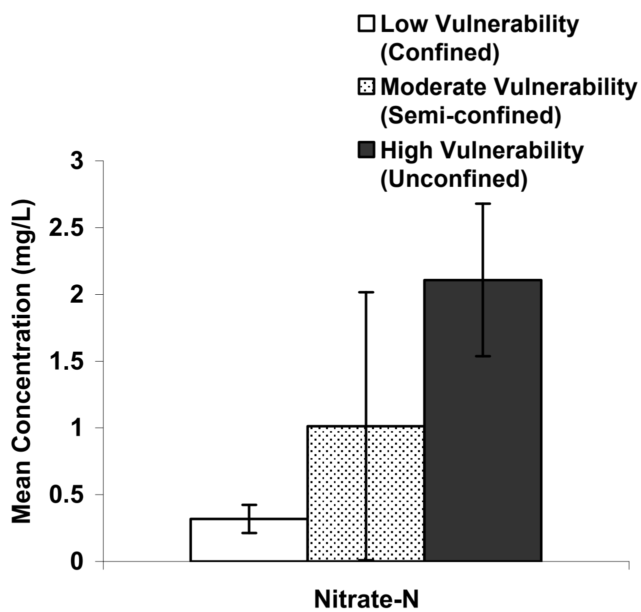


Figure 14. Mean concentration of nitrate-N in wells overlying low, moderate and high vulnerability aquifers. (Mean ± 1 S.E.)

These results corroborated the findings from the surficial material analysis. The highly vulnerable aquifers are those which are unconfined and dominated by fluvial-glacial deposits while the low vulnerability aquifers are mostly confined aquifers and are associated with marine and glaciomarine deposits.

5.3.2. Arsenic in relation to individual aquifers

Conducting the analysis of arsenic in relation to individual aquifers was more complicated as many aquifers overlay each other, some are interconnected and others are not. The spatial distribution did not provide a clear pattern for many water quality indicators except for nitrate, which shows that the high values were associated with the Brookswood and Hopington aquifers. These high concentrations are attributed to land use practices above these high vulnerability aquifers. In contrast, the arsenic distribution is primarily attributed to the surficial materials that are dominantly associated with marine deposits and there are no spatial patterns that would indicate land use practices as a potential source for arsenic in groundwater in the region (Figure 15).

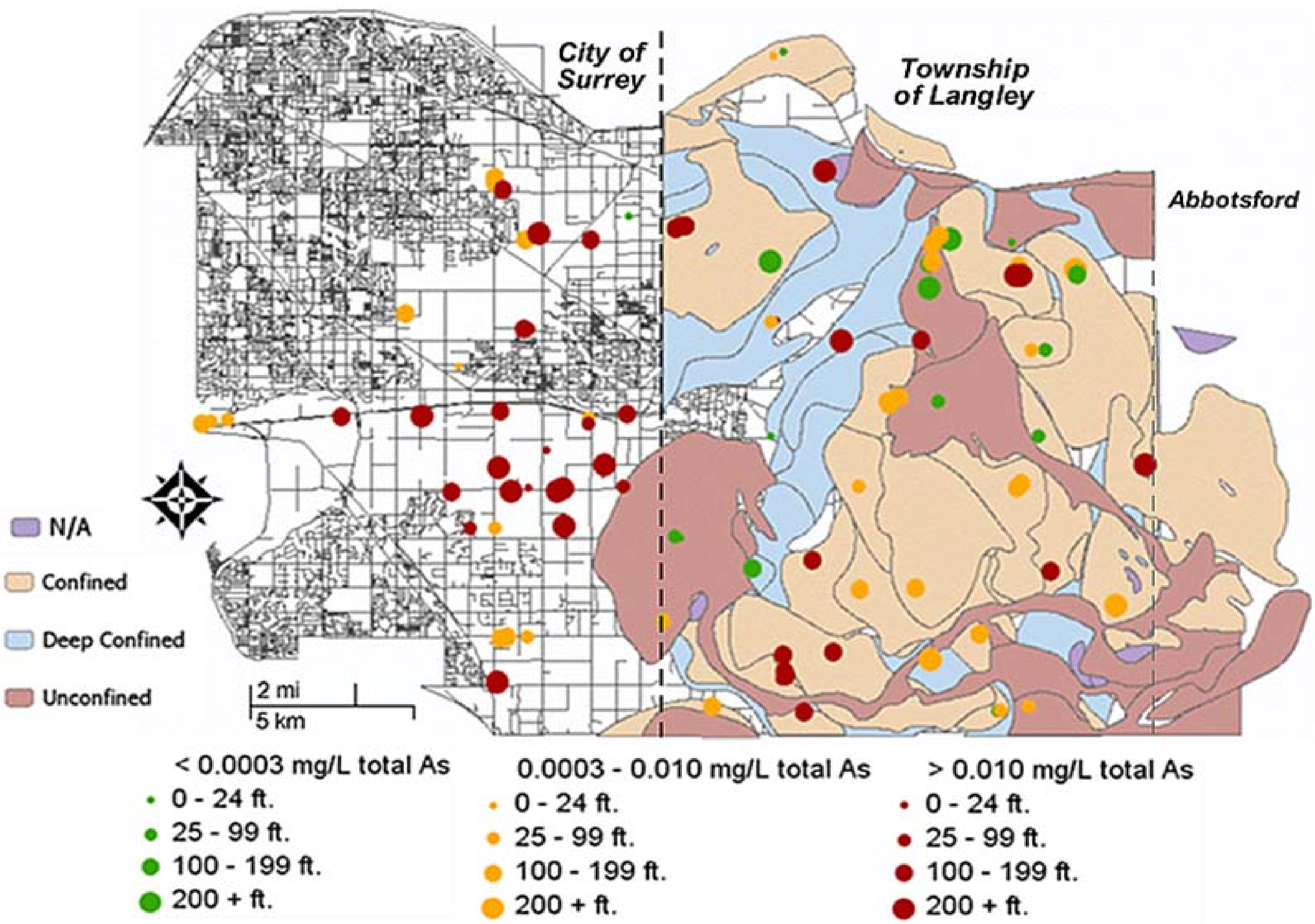


Figure 15. Well location, depth and arsenic concentrations in groundwater are indicated by the circles. Underlying aquifers and their classifications in the Township of Langley are colour coded (Golder Associates Ltd., 2005). (N=98)

5.4. Relationships between total arsenic and other water quality parameters

Arsenic and boron (B) are often correlated (Mattu and Schreier, 1999) as they are both soluble minerals found in hydrothermal / volcanic deposits. Figure 16 shows that a significant positive correlation exists between total arsenic and total B (Spearman's rho, r=0.786, p<0.0001). Chlorine (Cl), which is usually significantly higher in marine deposits than glaciofluvial deposits showed a relatively poor relationship with arsenic (Spearman's rho, r=0.243, p=0.017). Since land use applications (e.g. fertilizers, road salt) can influence Cl concentrations, and Cl is quite mobile in the environment and subject to leaching, it is likely that these factors could contribute to the poor relationship.

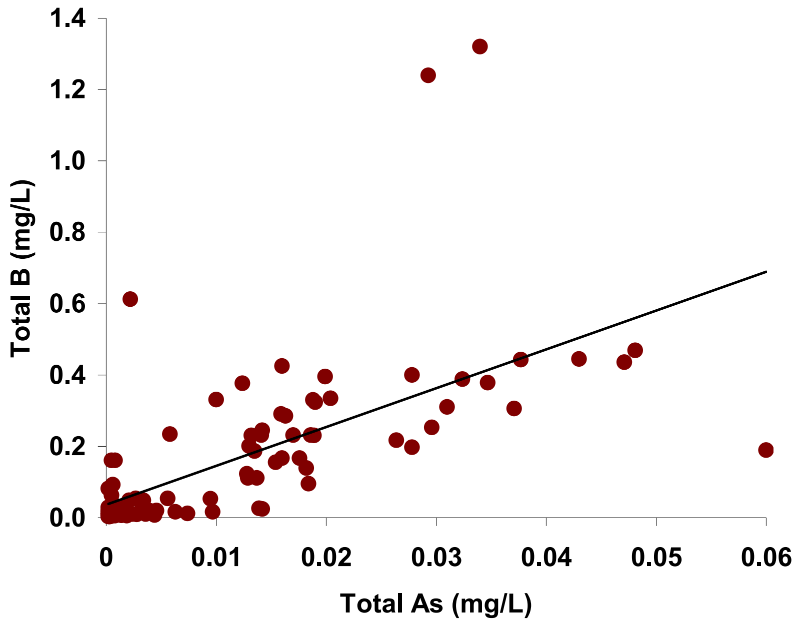


Figure 16. Relationship between total boron and total As. (N=98, r=0.79)

Arsenic was positively correlated to pH (Spearman's rho, r=0.683, p<0.0001) and specific conductivity (Spearman's rho, r= 0.730, p<0.0001). Arsenic was then compared to pH and specific conductivity in the groundwater of wells deeper than 30 feet (10 metres). The elimination of shallow wells was made because we were interested in these parameters in deep, anoxic groundwaters. Ocean water is alkaline (around pH 7.8-8.5) and has high specific conductivity, so we would expect sediments of marine origin to reflect these conditions. The analysis produced a correlation between arsenic and specific conductivity that resembled a step-wise relationship, while arsenic vs. pH showed a linear relationship (Figure 17).

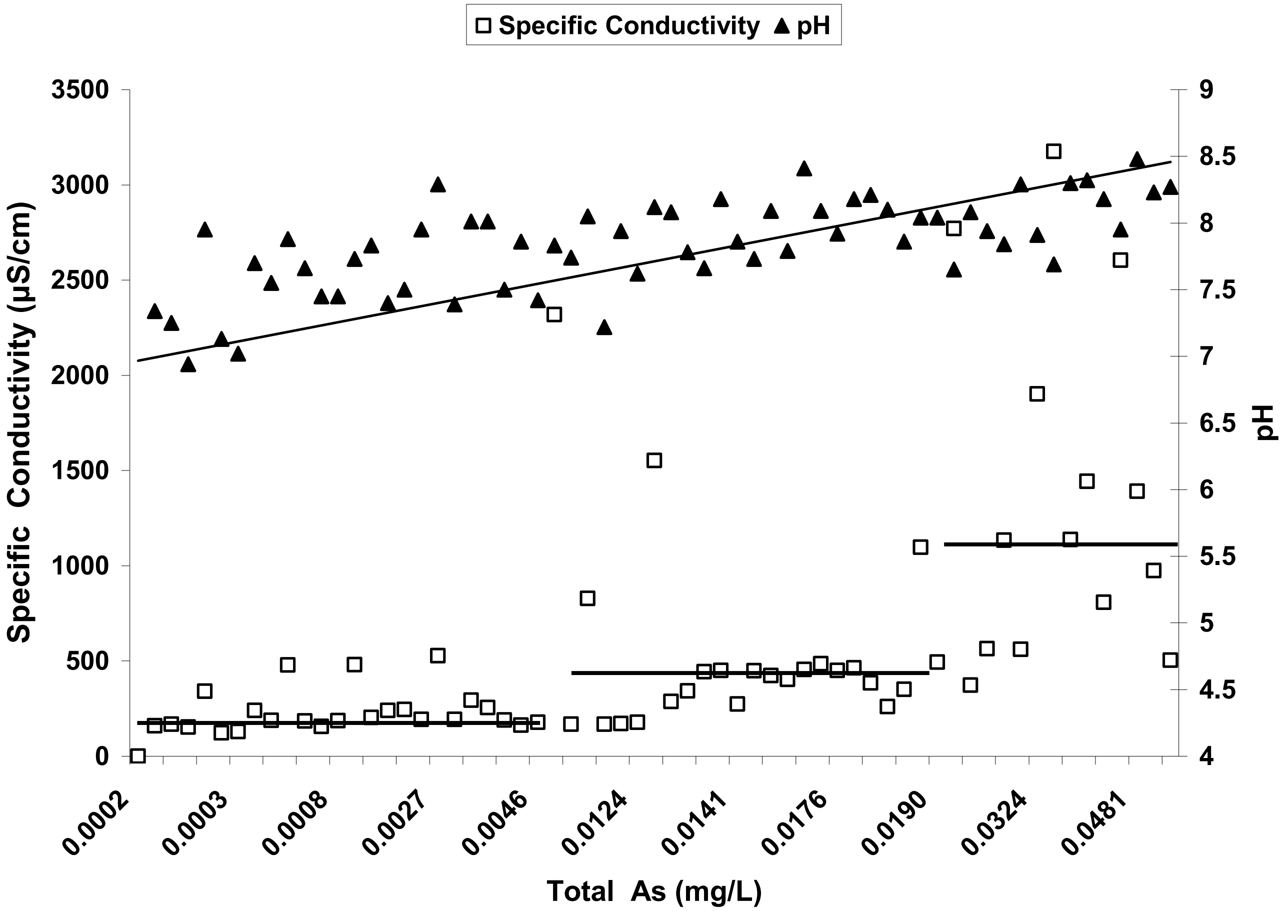


Figure 17. Total arsenic (arranged by increasing value) versus specific conductivity and pH in groundwater samples from wells deeper than 30 feet (10 metres). (N=62)

Further investigation was made on these relationships by incorporating the detailed classification of surficial materials according to the historic deposition phase of the material. The relationship between arsenic and pH varies in wells influenced by different surficial deposits, with the highest values of both parameters found in wells associated with marine/organic materials of the Salish deposit (Figure 18). Specific conductivity and arsenic showed a similar relationship.

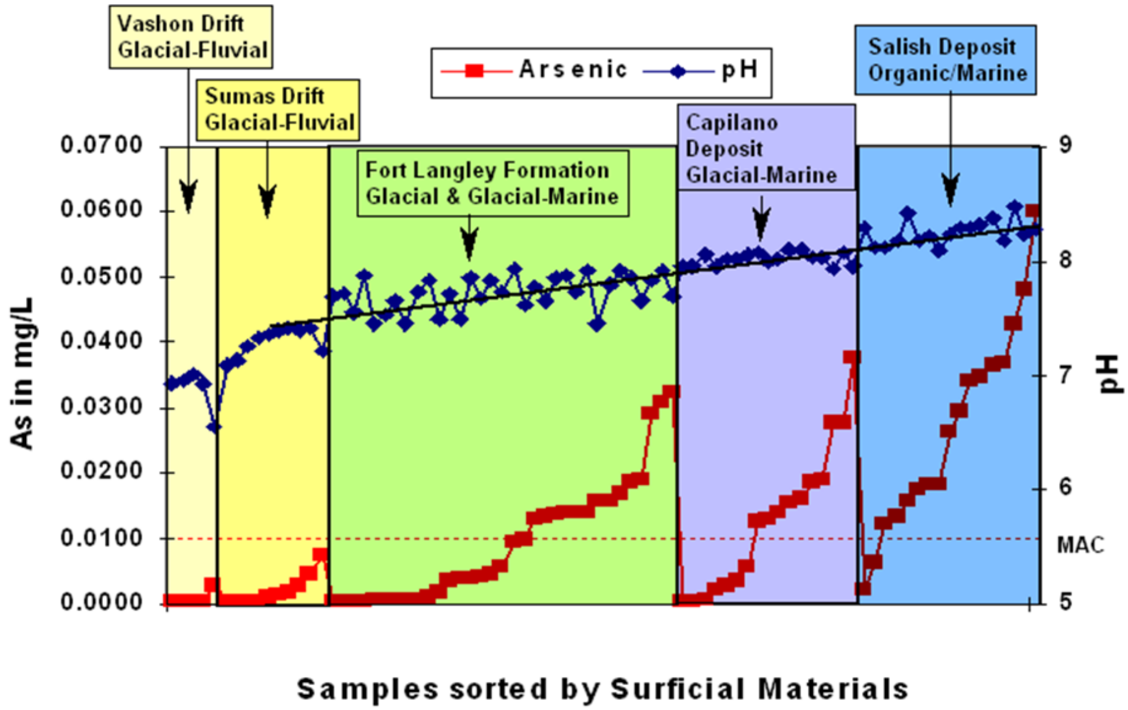


Figure 18. Total arsenic related to pH in five different categories of surficial materials. Includes groundwater samples from wells deeper than 30 feet (10 metres) (N=62). (See Armstrong & Hicock, 1976)

5.5. Origin of arsenic and possible release into groundwater

Arsenic originates in crystalline minerals in rocks containing sulfur and is often associated with pyrite (iron sulfide) and copper, gold, silver and other metal-rich ore rocks. Arsenopyrite is the most abundant among the dozen or so sulfides of arsenic. In geologic materials, e.g. arsenopyrite, the arsenic is in a reduced state (low valence or arsenite). When exposed to air (oxygen) and water, the arsenic is oxidized and released from the original minerals. This arsenic is slightly soluble in water and its solubility increases with an increase in acidity, which is the usual case as the associated sulfur also oxidizes in the presence of air and water to form sulfuric acid.

The form and behaviour (e.g., solubility and mobility) of arsenic in the environment is highly influenced by geochemical conditions. For example, arsenic may be sorbed onto charged surfaces in soils and sediments, such as clay and hydroxides and oxyhydroxides of iron, aluminum and manganese. If the pH increases, these charged surfaces lose some of their attractive charge and can re-release sorbed arsenic. Thus arsenic is found to be more soluble and mobile in water at high pH values (upwards of 8.5) in oxidizing conditions. However, high pH cannot explain the development of elevated arsenic concentrations in reducing conditions, since groundwaters in reducing environments typically have a pH that is near-neutral (Smedley and Kinniburgh, 2002).
In this case (near-neutral pH and reducing conditions), it is possible that the reductive dissolution and desorption of arsenic from clays and oxyhydroxides is the driver for elevated arsenic concentrations. There is evidence that the reduced form of arsenic (arsenite) is less strongly sorbed than the oxidized form of arsenic (arsenate), thus

leading to the desorption of arsenic in reducing conditions (Smedley and Kinniburgh, 2002).

According to Smedly and Kinniburgh (2002), there is considerable evidence that groundwaters under reducing conditions, such as deltaic environments, are associated with elevated arsenic concentrations. The presence of arsenic and its release in estuary environments was further confirmed by a recent study by Bolton (2004) in the Fraser Delta in Richmond. Hence, deep wells near deposits with high clay content and under reducing conditions are excellent environments for arsenic mobilization (Smedley and Kinniburgh, 2002).

5.6. Effectiveness of treatment

Thirteen well owners had point of use water treatment systems in their houses. This provided the opportunity to test the effectiveness of these systems by testing the well water before and after treatment. Since all treatments were of different origin and age and few owners knew his/her exact filter system, it was not possible to do an in depth evaluation; however, the results showed that only 5 of the 13 treatment devices were effective in reducing the total arsenic levels by more than 10%. In most cases (80%), the reduction of arsenic was insufficient to reduce the levels to below the MAC.

5.7. Options for addressing the arsenic problem

The technologies to remove arsenic from drinking water are well established. The selection of an appropriate treatment device depends primarily on the characteristics of the water and residential treatment devices are able to remove arsenic from drinking water to a level below 0.010 mg/L (Health Canada, 2006). However, many effective treatment systems for individual well owners are expensive and require regular maintenance.

The most common types of treatment devices in residential systems are reverse osmosis, steam distillation, activated alumina, electrodialysis reversal, lime softening, green sand filtration and/or iron/manganese removal processes (HC, 2006, US EPA 2007). No one particular type of treatment device is advocated over another; however, Health Canada does recommend that consumers use devices that are certified as meeting the appropriate National Science Foundation (NSF) standards (HC, 2006; BC MoE, 2007a). It is highly recommended that consumers consult a qualified water treatment professional and test their drinking water at least once per year. Raw and treated water should both be tested periodically at an accredited laboratory for arsenic by the well owner (BC MoE, 2007a). If a treatment device is not a viable option, it is recommended to find alternative sources of drinking water (BC MoE, 2007a).

6. Limitations of the Study

The study had a number of limitations:

Borehole records in B.C. are currently recorded on a voluntary basis and there is no standardized classification that describes the stratigraphic layers. Only 44 of the sampled wells had a recorded well log and the descriptions were insufficient to clearly determine the amount of clay above or below the water intake.

Since the health guidelines are based on total arsenic concentrations and since this was a regional study, no arsenic speciation was carried out. In oxic seawater As (V) dominates but As (III) becomes of increasing importance in anoxic bottom water. The relative proportion of As (V) and As (III) vary according to redox conditons, biological activities and change in inputs. Since As (III) is of greater health risk, it might be of interest to consider arsenic speciation analysis on selected samples. Because of the high cost of arsenic speciation analysis this was not pursued in this study.

There were great differences in the hydrogeological information available for the study area. For the Township of Langley a very detailed recent evaluation of the groundwater hydro-geology was available from Golder Associates Ltd. (2005). It included the identification of 18 individual aquifers and a detailed aquifer vulnerability classification. The same detail was not available for the Surrey and White Rock areas for this study and, as a result, a combination of the 1976 surficial materials map (Armstrong and Hicock) and the BC Water Resources Atlas (BC MoE, 2007b) were used to determine the vulnerability classifications.

7. Conclusions and Recommendations

Ninety eight well water samples from the Langley-Surrey-White Rock area of B.C. were analysed for total and dissolved arsenic on August 20 and 21, 2007. Eighty-two of those wells were re-sampled for total arsenic two months later to insure repeatability of the results, and they were evaluated along with historic (post 2004) data.

The following conclusions from this analysis can be made:

1. 43% of all privately owned groundwater wells had total arsenic levels above the MAC of 0.010 mg/L, and a further 40% were between 0.0003 mg/L and 0.010 mg/L which is considered of possible health concern if associated with long term exposure.
2. Good agreement was found between the arsenic values from the August and October 2007 sampling sets, and only a few samples with low arsenic concentrations showed high variability.
3. Significant positive correlations were found between arsenic levels and well depth, with deep wells having significantly higher levels. These relationships

were particularly significant when evaluating only those wells influenced by marine and glaciomarine deposits.

4. The arsenic was primarily found in groundwater wells influenced by marine and glaciomarine surficial materials, with the highest values in wells related to the Salish and Capilano marine deposits. Wells influenced by glacial-fluvial deposits showed the lowest levels of arsenic. Most of the high arsenic concentrations were found in wells with clay-dominated profiles.
5. Based on the depth and surficial materials analysis it is suggested that the origin of the arsenic is from natural sources deposited after deglaciation.
6. These relationships were confirmed when data from another 60 wells collected in the same area by other agencies over the past 3 years were incorporated into the study.
7. Arsenic was significantly correlated with boron, which confirms results from other studies reported in the literature.
8. Water treatment devices from ten households were tested; an evaluation of the effectiveness of these systems showed that five were capable of reducing the arsenic level by more than 10%.
9. A range of treatment systems exist but care should be taking in the selection because not all are effective and the cost can be significant.

Future work should focus on treatment devices for individual well owners, and include long term operation and maintenance of these devices. Fraser Health has informed all participants about approaches and options to manage the arsenic issue, and has issued a public statement for all private well owners in the Fraser Valley to test their well water, particularly for arsenic.

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9. Appendices

Appendix A. Summary of documented cases of naturally-occurring As problems in world groundwaters (Modified from Smedley & Kinniburgh, 2002), (1000 µg = 1 mg).

Country/ Region	***Area (km^2)***	***Population exposed****	***Concentration ranges ($\mu g\ L^{-1}$)***	***Aquifer type***	***Groundwater conditions***	***Reference***
Bangladesh	150,000	ca. $3x10^7$	<0.5 to 2500	Holocene alluvial/ deltaic sediments. Abundance of solid organic matter	Strongly reducing, neutral pH, high alkalinity, slow groundwater flow rates	DPHE/BGS/MML (1999); BGS and DPHE (2001)
West Bengal	23,000	$6x10^6$	<10 to 3200	As Bangladesh	As Bangladesh	CGWB (1999); PHED/UNICEF (1999)
China:		$5.6x10^6$				Sun *et al.* (2001)
Taiwan	4000	? 10^5 (formerly)	10 to 1820	Sediments, including black shale	Strongly reducing, artesian conditions, some groundwaters contain humic acid	Kuo (1968), Tseng *et al.*(1968)
Inner Mongolia (Huhhot Basin (HB), Bayingao, Hexi, Ba Meng, Tumet Plain)	4300 (HB) ? 30,000 total	? ca. 10^5 in HB	<1 to 2400	Holocene alluvial and lacustrine sediments	Strongly reducing conditions, neutral pH, high alkalinity. Deep groundwaters often artesian, some have high concentrations of humic acid	Luo *et al.* (1997), Zhai *et al.* (1998), Ma *et al.* (1999), Sun *et al.* (1999), Smedley *et al.* (2001a)
Xinjiang (Tianshan Plain)	38,000	? (500 diagnosed)	40 to 750	Holocene alluvial plain	Reducing, deep wells (up to 660 m) are artesian	Wang and Huang (1994)
Red River	1200	> 10^6	1 to 3050	Holocene	Reducing, high	Berg *et al.*

delta, Vietnam	identified			alluvial/deltaic sediments	Fe, Mn, NH_4, high alkalinity	(2001)
Hungary, Romania (Danube Basin)	110,000	29,000	<2 to 176	Quaternary alluvial plain	Reducing groundwater, some artesian. Some high in humic acid	Varsányi *et al.* (1991); Gurzau and Gurzau (2001)

**** Exposed refers to population drinking water with As >50 µg L^{-1} (drinking-water standard of most countries)***

Country/ Region	Area (km^2)	Population exposed	Concentration ranges (μg L^{-1})	Aquifer type	Groundwater conditions	Reference
Argentina (Chaco-Pampean Plain)	10^6	$2x10^6$	<1 to 5300 (7800 in some porewaters)	Holocene and earlier loess with rhyolitic volcanic ash	Oxidising, neutral to high pH, high alkalinity. Groundwaters often saline. As(V), accompanied by high B, V, Mo, U. Also high As concentrations in some river waters	Nicolli *et al.*, (1989), Sancha and Castro (2001), Smedley *et al*. (2002)
Northern Chile (Antofagasta)	125,000	500,000	100 to 1000	? Quaternary volcanogenic sediment	Generally oxidising. Arid conditions, high salinity, high B. Also high-As river waters	Cáceres *et al.* (1992), Karcher *et al.* (1999); Sancha and Castro (2001)
South-west USA:		$3.5x10^5$ (tot)				Smith *et al*. (1992)
Basin & Range, Arizona	200,000		up to 1300	Alluvial basins, some evaporites	Oxidising, high pH. As (mainly As(V)) correlates positively with Mo, Se, V, F	Robertson (1989)
Tulare Basin, San Joaquin Valley, California	5000		<1 to 2600	Holocene and older basinfill sediments	Internally-drained basin. Mixed redox conditions. Proportion of As(III) increases with well depth. High salinity in some shallow ground waters. High Se, U, B, Mo	Fujii and Swain (1995)
Southern Carson Desert, Nevada	1300		up to 2600	Holocene mixed Aeolian alluvial, lacustrine sediments, some thin volcanic ash bands	Largely reducing, some high pH. Some with high salinity due to evaporation. Associated high U, P, Mn, DOC (Fe to a lesser extent). Some saline ground waters, with high U	Welch and Lico (1998)
Mexico (Lagunera)	32,000	$4x10^5$	8 to 620	Volcanic sediments	Oxidizing, neutral to high pH, As mainly as As(V)	Del Razo *et al.* (1990)

Appendix B. Arsenic factsheets and links to arsenic information and research.

(Source: FH, 2006)

Health Information on Arsenic

Prepared by: Dr. A. Larder, Medical Health Officer, Fraser Health

Arsenic in drinking water can have serious short and long-term health effects.

Acute Health Effects

The symptoms of acute arsenic poisoning are stomach pain, vomiting, diarrhea, muscle pain and weakness, and flushing of the skin. These effects are typically seen at arsenic concentrations above 1200-micrograms/L. However in children with high fluid intake acute poisoning has been seen with concentrations in the range of 200-micrograms/L.

Chronic Health Effects

Long-term exposure to lower concentrations of arsenic can produce a number of chronic adverse health effects. The skin can become thickened, heavily pigmented, or develop multiple wart-like lesions. Blood vessels in the extremities can be damaged, affecting the blood supply to the feet and hands. Chronic exposure to arsenic can also be a cause of high blood pressure.

However of most concern is the fact that arsenic is a known cause of cancer. Chronic exposure to arsenic in the drinking water (over the course of a lifetime) can lead to several types of skin cancer, and cancers of the lung, liver and bladder.

It is the ability to cause cancer that is the critical health effect used in deciding the standards for arsenic in drinking water.

What are the current drinking water standards?

The Guidelines for Canadian Drinking Water Quality published by Health Canada set a Maximum Acceptable Concentration (MAC) of 0.010 mg/L (10 micrograms/L).

This MAC is based on the ability of municipal treatment facilities and residential water treatment devices to reduce arsenic concentrations to 0.010 mg/L or less. It is set at a level that is higher than would be associated with an "essentially negligible" risk of lung, bladder and liver cancers (1 new case per 100,000 people).

At 0.005 mg/L the estimated lifetime additional risk of these cancers is 2 – 20 cases per 100,000 people exposed. These are cancer cases over and above the cases due to other causes that would occur in the population anyway.

At 0.010 mg/L the additional risk of these internal organ cancers is 3 – 39 cases per 100,000 people exposed.

It is only at concentrations of arsenic of 0.0003 mg/L or less that the risk could be considered "essentially negligible".

The risks associated with consumption of water containing arsenic are the same for everyone. Groups such as children and pregnant women are not at any greater risk of developing health problems from exposure to arsenic than the general population.

Conclusions

1. Arsenic is a human carcinogen, which means that exposure to any level in drinking water may increase the risk of cancer.

2. At low concentrations of arsenic the increased risk of lung, bladder, liver and skin cancer is small when compared to the number of cases that occur in populations that are not exposed to arsenic.

3. Lowering the concentration of arsenic in your drinking water will lower your lifetime risk of developing lung, bladder, liver and skin cancer.

4. However at low arsenic concentrations the treatment costs may be large for a small reduction in risk.

The following links provide basic information about As:

British Columbia Ministry of Environment – *Water Stewardship Series: Arsenic in Groundwater*
Provides information on arsenic, its occurrence throughout the province and mitigation measures
http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/library/ground_fact_sheets/pdfs/as(020715)_fin3.pdf

US Geological Survey – *Arsenic in groundwater of the United States*
Provides information on basic geology, maps, and links to health information
http://water.usgs.gov/nawqa/trace/arsenic/

The National Drinking Water Clearinghouse – *All About Arsenic*
Discusses issues for small communities regarding the 0.010 mg/L drinking water standard
http://www.nesc.wvu.edu/ndwc/articles/OT/FA06/OTfl06_TB.pdf

Links to new areas of research on As in groundwater are provided below:

The University of Illinois – *Munching microbes could cleanse arsenic-contaminated groundwater*
Investigating the role of microbes in converting sulphate to sulphide, which binds to As and removes it from groundwater
http://www.news.uiuc.edu/NEWS/04/1026arsenic.html

The University of Nebraska Lincoln Water Center – *Water Scientists Working to Help Small Towns Reduce Arsenic in Drinking Water*
http://ianrnews.unl.edu/static/0403250.shtml

Appendix C. Sample letter sent out to private well owners in the Surrey-Langley region.

THE UNIVERSITY OF BRITISH COLUMBIA
INSTITUTE FOR RESOURCES, ENVIRONMENT & SUSTAINABILITY

To: Water Well Owners: Langley, Surrey and White Rock
Re: Ground water arsenic study – Public Participation

Study: The study objective is to evaluate the extent and concentrations of *naturally* occurring arsenic in ground water in the Langley-Surrey-White Rock area, and inform the public of the results. This study will be conducted by the Institute for Resources, Environment and Sustainability at the University of British Columbia, in collaboration with the Fraser Health Authority and the Ministry of Environment. The results of the study will be summarized in a report that will be publicly available online. The report will also provide well owners with information on the health effects of arsenic and how the arsenic in well water may be mitigated.

Background: Arsenic in drinking water can have serious short and long-term health effects, including several types of skin cancer and cancers of the lung, liver and bladder. The most recent Guideline for Canadian Drinking Water Quality, published by Health Canada, has set a Maximum Acceptable Concentration of 0.010 milligrams per litre (mg/L) for arsenic. According to the Fraser Health Authority, elevated arsenic concentrations up to 0.052 mg/L have been measured in some wells in the Langley-Surrey area. The distribution and extent of elevated arsenic within the study area has not yet been determined.

Well Owner Survey: We are looking for volunteers to participate in a well water quality survey, at no cost to the participant. This survey will involve collecting and testing samples of ground water from approximately 100 water wells. **All personal information (*i.e.* well owner contact information and well location) will be kept strictly confidential.** This study will give you an opportunity to have your water tested for arsenic and a range of other chemicals at no cost. You will be provided with an individualized report on the general status of the drinking water quality in your well.

Participation Instructions: If you are willing to participate, please provide us (see contact info below) with your name and contact details (telephone and/or e-mail), together with information on the **depth** and (approximate) **age** of your well. If you are selected for this study, you will be contacted in early August. We will then provide you with water sampling bottles and instructions on how, and when, to collect the water. It is anticipated that the sample collection will be done on a Monday or Tuesday during the second or third week in August. UBC staff and students and volunteers from the Langley Environmental Partners Society will help in the distribution and collection of the water samples, and you will be informed of the results one month after the analysis has been completed.

Your participation and cooperation in this study will be greatly appreciated. If you have any questions, please do not hesitate to contact us.

Dr. Hans Schreier and his Research Team

Appendix D. Depth and total As concentrations for community and observation well sampled from 2004-2007.

Sample ID	Well Type	Well depth (ft)	Total Arsenic (mg/L)	Date sampled (unconfirmed)
101	observation	50	0.0002(0.0002)*	Feb-05 - Feb-07
102	observation	47	0.0002(0.0002)*	Jan-04 - Feb-07
103	observation	138	0.0006(0.0006)*	Mar-04 - Feb-07
105	observation	85	0.0026(0.0029)*	Jan-04 - Feb-07
108	community	162	0.005	Dec-05
110	community	109	0.0054(0.006)*	Jan-93 - Feb-07
140	community	110	0.0054	Sep-06
109	community	95	0.0056	Nov-04
143	community	deep	0.009	Apr-05
112	community	292	0.0097	2004
114	community	deep	0.01	Jul-05
115	community	140	0.0104	Jan-06
116	community	deep	0.011	Jul-05
117	community	deep	0.011	Jul-05
118	community	158	0.012	Jun-06
119	community	88 (flowing well)	0.012	2006
148	community	150	0.012	Feb-06
120	community	380	0.0138	Feb-05
122	community	deep	0.015	Jul-05
124	community	deep	0.0188	2004
127	community	150	0.022	Dec-05
156	community	200	0.0242	Sep-06
157	community	deep	0.0246	Feb-06
128	community	deep	0.0264	Jan-06
129	community	deep	0.0279	Sep-07
159	community	278	0.0305	Sep-04
132	community	400	0.0366	Jan-07
160	community	92	0.0369	Oct-04
133	community	600	0.0378	Sep-06
168	community	240	0.0402	Mar-06
169	community	184	0.0468	Jun-06
174	community	deep	0.0506	Apr-06
175	community	300 (flowing well)	0.0512	Sep-05
177	community	deep	0.0516	May-06

*Indicates median (maximum) total arsenic concentration for several years of data.

Appendix E. Sample instructions for volunteers in the Surrey-Langley region.

THE UNIVERSITY OF BRITISH COLUMBIA
INSTITUTE FOR RESOURCES, ENVIRONMENT & SUSTAINABILITY

Dear Well Owner,

We have provided 8 labelled plastic bottles for water collection and 2 forms. If you have a filter system or a water softener please fill the bottles from a tap that bypasses this treatment (i.e. before entering the building).

Please follow the instructions below for the collection procedure:

1. Clearly fill in the labels on each water bottle. Under "Source" or "Location" please print your address, and under "Sent by" or "Project" please print your name. Fill in the highlighted sections of the included requisition forms. Pen or pencil is fine.
2. Tap without attachments - run cold water for 2 to 3 minutes before collecting sample.
3. Tap with attachments - remove attachments such as aerators, filters, hoses, screen or splash guard, run hot water for 2 minutes and then cold water for 2 to 3 minutes before sampling.
4. Remove cap of sample container without touching the mouth of the bottle or the inside of the cap.
5. Without rinsing, fill with water sample to 200 mL fill line marked on the container. If there is no fill line, fill bottle to the neck.
   N.B. Collect water sample only from the cold water tap
6. Replace cap of sample container securely (tight).
7. Return both forms to the zip lock plastic bags. Rewrap the form labeled "E. Coli" around the bottle marked "T/E #" with elastic band.
8. If nobody is home during the morning place the labeled bottles outside your front door **by 8:00 am** on Monday/Tuesday. Make sure the bottles are kept cool and out of direct sunlight.

After pick-up, the water bottles will be sent to 3 different laboratories which will test your water for:

- Arsenic and other metals
- Selected pathogens
- Nutrients (e.g. nitrate, phosphate)

Your individual water quality results will be mailed or e-mailed to you after analysis. If any contaminants exceed acceptable levels in your water, you may contact the Fraser Health Authority and they will assist you in interpreting the results.

The overall arsenic trends in the Surrey/Langley/White Rock area will be posted online this fall, and the web address will be provided to you with your water quality results. **Your information will be kept strictly confidential,** and no indication of the whereabouts of any particular well will be shown.

Dr. Hans Schreier & his Research Team

Appendix F. Data including water sample ID, well depth, nutrients and dissolved metals. (N=98)

		Nutrients (mg/L)			Dissolved Metals																		
Sample ID	Well Depth (ft)	Cl	OrthoP	NO3-N	Si	S	Al	As	Ba	B	Cr	Co	Cu	Pb	Li	Mo	Ni	Se	Ag	Sr	Ti	V	Zn
1	132	257.02	0.379	0.01	16.8	22.6	<0.005	0.0487	0.0270	0.455	0.0068	<0.0001	<0.001	<0.0001	0.004	0.029	<0.0005	<0.0002	<0.0001	0.2520	0.0016 0	<0.001	0.0020
2	250	583.09	0.676	0.01	11.2	49.0	< 0.05	0.0420	0.0500	0.460	< 0.005	<0.001	<0.01	<0.001	<0.01	0.030	0.012	<0.002	<0.001	0.3800	<0.005	<0.001	0.0100
3	250	588.39	0.755	0.01	11.1	49.0	< 0.05	0.0410	< 0.01	0.460	< 0.005	<0.001	<0.01	<0.001	<0.01	0.020	0.011	<0.002	<0.001	<0.01	<0.005	<0.001	0.0100
4	300	403.98	0.454	0.20	12.2	32.0	< 0.05	0.0330	0.0600	0.310	< 0.005	<0.001	0.03	<0.001	<0.01	0.020	0.012	<0.002	<0.001	0.3500	<0.005	<0.001	0.0300
5	370	106.67	0.455	0.01	18.6	7.7	<0.005	0.0426	0.0180	0.332	0.0041	<0.0001	<0.001	<0.0001	0.003	0.010	<0.0005	<0.002	<0.0001	0.1130	0.0007 0	0.0012	0.0010
6	84	3.27	0.115	0.01	10.7	3.8	< 0.05	0.0092	0.0060	0.027	0.0016	<0.0001	0.002	<0.0001	<0.001	0.002	<0.0005	<0.0002	<0.0001	0.0870	<0.0005	0.0001	0.0040
7	327	308.79	0.099	0.01	7.77	31.2	<0.005	0.0112	0.0240	0.404	0.0069	<0.0001	<0.001	<0.0001	0.002	0.037	0.002	<0.0002	<0.0001	0.3070	0.0020 0	0.0006	0.0020
8	300	122.21	0.740	0.01	14.4	11.6	0.005	0.0561	0.0140	0.507	0.0049	<0.0001	0.002	<0.0001	0.002	0.019	0.001	<0.0002	<0.0001	0.0980	0.0012 0	0.0033	0.0060
9	53	6.59	0.143	0.01	14.7	3.0	<0.005	0.0154	0.0110	0.027	0.0008	<0.0001	0.015	0.0022	0.001	0.002	<0.0005	<0.0002	<0.0001	0.1000	<0.0005	0.0003	0.0100
10		23.73	0.036	1.97	15.6	8.0	<0.005	0.0013	0.0070	0.012	0.0017	<0.0001	0.022	<0.0001	0.003	<0.001	<0.0005	<0.0002	<0.0001	0.1690	<0.0005	0.0038	0.0170
11	180	719.17	0.088	0.01	6.6	42.0	<0.005	0.0215	0.0480	0.276	0.0054	<0.0001	<0.001	<0.0001	0.002	0.042	<0.0005	<0.0002	<0.0001	0.5210	0.0029 0	0.0011	0.0060
12	300	294.34	0.370	0.01	16	23.7	<0.005	0.0426	0.0280	0.338	0.0098	<0.0001	0.002	<0.0001	0.004	0.021	<0.0005	<0.0002	<0.0001	0.2400	0.0017 0	0.0029	0.0160
13		116.07	0.610	0.10	15	11.2	<0.005	0.0544	0.0140	0.479	0.0036	<0.0001	0.018	0.0002	0.003	0.018	0.001	<0.0002	<0.0001	0.1100	0.0011 0	0.0018	0.0020
14		499.91	0.338	0.01	11.4	38.0	<0.005	0.0245	0.0430	0.289	0.0075	0.0002	<0.001	<0.0001	0.003	0.028	<0.0005	<0.0002	<0.0001	0.4260	0.0027 0	0.0016	0.0060
15	97	3.00	0.071	0.01	6	2.6	<0.005	0.0170	0.0070	0.023	0.0009	<0.0001	<0.001	<0.0001	0.001	0.001	<0.0005	<0.0002	<0.0001	0.0810	<0.0005	0.0002	0.0050
16	85	3.33	0.006	0.03	0.93	<0.3	0.054	0.0004	0.0030	0.003	<0.0005	<0.0001	0.166	0.0006	<0.001	<0.001	<0.0005	<0.0002	<0.0001	0.0040	<0.0005	0.0001	0.0110
17	87	17.89	1.643	0.01	10.2	5.7	0.006	0.0179	0.0030	0.287	0.0008	<0.0001	0.006	<0.0001	<0.001	0.006	0.0006	<0.0002	<0.0001	0.0210	0.0014 0	0.0017	0.0070
18	120	212.05	0.734	0.32	10.3	11.6	0.005	0.0228	0.0140	0.285	0.0077	<0.0001	0.023	0.0004	0.002	0.021	0.0009	<0.0002	<0.0001	0.0820	0.0012 0	0.0032	0.0120
19	230																						
20	190	29.11	0.789	0.01	14.5	5.6	0.015	0.0368	0.0140	0.231	0.003	<0.0001	<0.001	<0.0001	0.002	0.022	0.0006	<0.0002	<0.0001	0.0940	0.0006 0	0.0033	0.0070
21	60	2.74	0.523	0.02	13.2	1.7	<0.005	0.0310	0.0060	0.191	0.0012	<0.0001	<0.001	0.0001	<0.001	0.008	<0.0005	<0.0002	<0.0001	0.0590	<0.0005	0.0022	0.0040
23	120	4.91	1.604	0.01	9.14	1.0	0.005	0.0193	0.0040	0.287	0.0008	<0.0001	0.007	0.0003	<0.001	0.012	0.0006	<0.0002	<0.0001	0.0340	0.0005 0	0.0015	0.0040
24	12	8.53	0.005	1.29	6.8	1.1	<0.005	<0.0002	0.0170	0.004	0.0008	0.0005	0.012	<0.0001	<0.001	<0.001	0.0012	<0.0002	<0.0001	0.0940	<0.0005	0.0008	0.0110
25	120	1.39	0.646	0.01	7.7	<0.3	<0.005	0.0158	0.0050	0.116	<0.0005	<0.0001	0.003	<0.0001	<0.001	0.005	<0.0005	<0.0002	<0.0001	0.0630	<0.0005	0.0004	0.0020
26	20	8.60	0.009	0.21	12	1.0	0.01	<0.0002	0.0210	0.003	0.001	<0.0001	0.243	0.0004	<0.001	<0.001	0.001	<0.0002	<0.0001	0.1470	<0.0005	0.0003	0.0100
27	170	22.02	0.494	0.01	7.4	0.7	<0.005	0.0234	0.0050	0.199	0.002	<0.0001	<0.001	<0.0001	<0.001	0.040	<0.0005	<0.0002	<0.0001	0.0640	<0.0005	0.0032	0.0040
28	87	1.36	0.071	0.01	11.7	0.7	<0.005	0.0020	0.0060	0.010	0.0007	<0.0001	<0.001	<0.0001	<0.001	0.001	<0.0005	<0.0002	<0.0001	0.0640	<0.0005	0.0028	0.0110
29	285	16.91	1.372	0.01	7.82	6.4	0.015	0.0306	0.0020	0.400	0.0012	<0.0001	0.005	0.0006	<0.001	0.014	<0.0005	<0.0002	<0.0001	0.0150	0.0040 0	0.0010	0.0120
30	100	5.55	0.254	0.01	12.5	0.8	<0.005	0.0024	0.0220	0.045	0.0007	<0.0001	<0.001	<0.0001	<0.001	0.002	<0.0005	<0.0002	<0.0001	0.0630	<0.0005	0.001	0.0060
31	215	1.45	0.038	0.01	8.09	3.0	<0.005	0.0089	0.0090	0.011	0.0005	<0.0001	0.001	<0.0001	<0.001	<0.001	<0.0005	<0.0002	<0.0001	0.0630	<0.0005	0.0011	0.0050
32	100	4.84	0.285	0.01	12.9	0.7	<0.005	0.0032	0.0260	0.050	0.0006	<0.0001	<0.001	<0.0001	<0.001	0.002	<0.0005	<0.0002	<0.0001	0.0650	<0.0005	0.001	0.0030
33	82	7.14	0.016	6.16	11.1	3.5	<0.005	0.0002	0.0050	0.014	0.0014	<0.0001	0.004	<0.0001	<0.001	<0.001	0.00	<0.0002	<0.0001	0.1160	<0.0005	0.0013	0.0060
34	140	3.35	0.441	0.01	9.7	2.3	<0.005	0.0187	0.0080	0.092	0.0006	<0.0001	0.274	0.0008	<0.001	0.005	<0.0005	<0.0002	<0.0001	0.0700	<0.0005	0.0002	0.0150
35	115	2.91	0.277	0.01	13	0.8	<0.005	0.0067	0.0120	0.052	0.0005	<0.0001	<0.001	<0.0001	<0.001	0.003	<0.0005	<0.0002	<0.0001	0.0530	<0.0005	0.0009	0.0050
36		2.49	0.008	0.25	5.23	4.7	0.007	0.0003	0.0040	0.017	<0.0005	<0.0001	0.036	0.0005	<0.001	<0.001	<0.0005	<0.0002	<0.0001	0.0560	<0.0005	0.0003	0.0170
37	165	4.69	1.903	0.01	11.4	<0.3	<0.005	0.0031	0.0070	0.558	0.0016	<0.0001	0.008	0.0003	<0.001	0.017	<0.0005	<0.0002	<0.0001	0.0400	0.0026 0	0.0046	0.0060
38	250	13.33	0.165	0.01	15.9	1.6	<0.005	0.0046	0.0080	0.018	0.0007	<0.0001	<0.001	<0.0001	<0.001	0.002	<0.0005	<0.0002	<0.0001	0.0680	<0.0005	0.0006	0.0030
39	40	105.76	0.013	0.01	11	1.7	<0.005	0.0005	0.0170	0.072	0.0037	<0.0001	0.002	<0.0001	0.002	<0.001	<0.0005	<0.0002	<0.0001	0.2390	<0.0005	0.0014	0.0190
40	30	12.43	0.012	5.52	11.3	1.8	<0.005	0.0002	0.0060	0.022	0.0007	<0.0001	0.069	0.0019	<0.001	<0.001	0.00	<0.0002	<0.0001	0.0920	<0.0005	0.0009	0.0840
41	190	13.55	1.553	0.00	10.8	0.8	0.007	0.0204	0.0030	0.404	0.002	<0.0001	0.02	0.0005	0.015	0.011	0.00	<0.0002	<0.0001	0.0210	0.0044 0	0.0048	0.0070
42	170	1.67	0.120	0.01	13	6.2	<0.005	0.0039	0.0080	0.046	0.0007	<0.0001	0.002	<0.0001	<0.001	0.002	<0.0005	<0.0002	<0.0001	0.1050	<0.0005	0.0101	0.0070
43	100	5.82	0.013	0.08	8.06	5.2	<0.005	0.0006	0.0130	0.028	0.0006	<0.0001	0.003	<0.0001	<0.001	<0.001	<0.0005	<0.0002	<0.0001	0.0570	<0.0005	0.0007	0.0060
44	20	5.89	0.005	1.95	5.88	1.8	0.006	<0.0002	0.0020	0.010	<0.0005	<0.0001	0.024	0.0059	<0.001	<0.001	0.0006	<0.0002	<0.0001	0.0580	<0.0005	0.0003	0.0130
45	180	7.62	0.011	6.99	7.98	2.6	0.010	0.0002	0.0340	0.008	0.0005	<0.0001	0.107	0.0004	<0.001	<0.001	<0.0005	<0.0002	<0.0001	0.0880	<0.0005	0.0009	0.0100
46	110	4.26	0.063	2.23	11.9	4.1	<0.005	0.0010	0.0070	0.004	0.0008	<0.0001	0.003	<0.0001	<0.001	<0.001	<0.0005	0.0008	<0.0001	0.0710	<0.0005	0.0044	0.0130
47	210	56.89	2.683	0.01	7.55	0.6	0.019	0.0461	0.0080	1.160	0.0072	<0.0001	0.003	0.0003		0.020	0.0006	<0.0002	<0.0001	0.0320	0.0127 0	0.0177	0.0150
48	200	6.05	0.019	1.35	6.3	3.4	<0.005	0.0056	0.0070	0.007	0.0017	<0.0001	0.006	<0.0001	<0.001	<0.001	<0.0005	<0.0002	<0.0001	0.0660	<0.0005	0.0022	0.0060
49	70	3.59	0.016	0.49	9.69	4.1	<0.005	0.0011	0.0050	0.014	0.0006	<0.0001	0.004	<0.0001	<0.001	<0.001	<0.0005	<0.0002	<0.0001	0.0720	<0.0005	0.0019	0.2210
50	35	11.21	0.009	5.02	6.24	2.3	0.008	<0.0002	0.0090	0.020	0.0006	<0.0001	0.092	0.0061	<0.001	<0.001	0.0008	<0.0002	<0.0001	0.1160	<0.0005	0.0007	0.0180

Sample ID	Well Depth (ft)	Cl	OrthoP	NO3-N	Si	S	Al	As	Ba	B	Cr	Co	Cu	Pb	Li	Mo	Ni	Se	Ag	Sr	Ti	V	Zn
51	65	13.13	0.016	4.21	11.8	2.5	<0.005	<0.0002	0.0060	0.011	0.0015	<0.0001	0.025	0.0006	<0.001	<0.001	0.0018	<0.0002	<0.0001	0.1480	<0.0005	0.0007	0.0290
52	250	8.83	1.049	0.01	12.8	3.7	<0.005	0.0186	0.0100	0.233	0.0007	<0.0001	0.002	<0.0001	<0.001	0.011	<0.0005	<0.0002	<0.0001	0.0730	0.0008	0.0012	<0.001
53	150	1.70	0.020	0.01	10.2	1.8	<0.005	0.0007	0.0140	0.015	<0.0005	<0.0001	0.001	0.0001	<0.001	0.00	<0.0005	<0.0002	<0.0001	0.0620	<0.0005	0.0017	0.0050
54	165	8.67	0.008	4.26	7.3	2.5	<0.005	<0.0002	0.0050	0.010	0.0007	<0.0001	0.07	<0.0001	<0.001	<0.001	0.0005	<0.0002	<0.0001	0.0720	<0.0005	0.0001	0.0150
55	300	36.89	1.379	0.02	11.9	2.9	<0.005	0.0712	0.0050	0.187	0.0018	<0.0001	0.006	<0.0001	<0.001	0.013	0.0006	<0.0002	<0.0001	0.0370	0.00070	0.0024	0.0020
56	120	157.57	1.055	0.01	10.7	8.3	0.005	0.0074	0.0140	0.216	0.0043	<0.0001	0.002	0.0001	<0.001	0.015	<0.0005	<0.0002	<0.0001	0.1090	0.00110	0.0026	0.0140
57	160	2.63	0.217	0.01	14.2	2.6	<0.005	0.0115	0.0080	0.016	<0.0005	<0.0001	0.001	<0.0001	<0.001	0.002	<0.0005	<0.0002	<0.0001	0.0830	<0.0005	0.0006	0.0050
58	100	17.28	0.535	0.01	12.3	6.8	<0.005	0.0179	0.0150	0.174	0.0012	<0.0001	0.001	0.0001	<0.001	0.024	<0.0005	<0.0002	<0.0001	0.1090	0.00070	0.0017	0.0080
59	163	24.63	0.754	0.01	14.4	8.4	<0.005	0.0004	0.0120	0.162	0.0013	<0.0001	<0.001	<0.0001	<0.001	0.022	<0.0005	<0.0002	<0.0001	0.0970	0.00280	0.0028	0.0020
60	65	3.79	0.130	0.01	13.4	1.7	<0.005	0.0049	0.0180	0.014	<0.0005	<0.0001	<0.001	<0.0001	<0.001	0.001	<0.0005	<0.0002	<0.0001	0.0690	<0.0005	0.0027	0.0020
61	180	2.72	0.515	0.01	13.2	1.4	<0.005	0.0327	0.0080	0.199	<0.0005	<0.0001	<0.001	0.0001	0.002	0.007	<0.0005	<0.0002	<0.0001	0.0680	<0.0005	0.0015	0.0020
62	144	23.25	0.815	0.01	14.4	8.1	<0.005	0.0008	0.0130	0.162	0.0015	<0.0001	<0.001	<0.0001	<0.001	0.022	<0.0005	<0.0002	<0.0001	0.1040	0.00310	0.0033	0.0040
63	75	4.20	0.127	0.01	13.2	1.8	<0.005	0.0042	0.0140	0.010	<0.0005	<0.0001	0.013	<0.0001	<0.001	0.001	<0.0005	<0.0002	<0.0001	0.0770	<0.0005	0.0023	0.0040
64	250	812.42	0.206	0.16	12.9	47.0	<0.005	0.0330	0.0400	0.340	<0.0005	<0.0001	0.001	<0.0001	<0.01	0.030	0.011	<0.0002	<0.0001	0.7000	<0.0005	<0.001	0.0200
65	100	4.86	0.295	0.01	15.8	<0.3	<0.005	0.0006	0.0020	0.037	<0.0005	<0.0001	0.001	<0.0001	0.002	0.002	<0.0005	<0.0002	<0.0001	0.0780	<0.0005	0.0005	<0.001
66	216	3.20	0.013	3.36	8.28	0.5	<0.005	<0.0002	0.003	0.006	0.0023	<0.0001	0.010	0.0002	<0.001	<0.001	<0.0005	<0.0002	<0.0001	0.0550	<0.0005	0.0008	0.0030
67	100	6.28	0.024	0.34	7.4	9.4	<0.005	0.0002	0.004	0.004	0.0007	<0.0001	0.002	<0.0001	<0.001	<0.001	<0.0005	<0.0002	<0.0001	0.0950	0.00060	0.0016	0.0010
68	18	10.70	0.005	6.76	8.96	7.6	0.017	<0.0002	0.145	0.028	0.0008	<0.0001	0.198	0.0008	<0.001	<0.001	0.0303	<0.0002	<0.0001	0.2010	<0.0005	0.0001	0.1310
69	142	15.46	0.017	6.19	12	5.4	<0.005	0.0003	0.007	0.023	0.0028	<0.0001	0.011	0.0005	<0.001	<0.001	0.0010	<0.0002	<0.0001	0.1640	<0.0005	0.0008	0.0100
70	166	4.89	0.018	5.40	8.33	3.2	<0.005	0.0026	0.008	0.006	0.0027	<0.0001	0.002	0.0001	0.003	<0.001	<0.0005	<0.0002	<0.0001	0.1060	<0.0005	0.0021	0.0110
71	300	15.47	0.005	0.78	7.61	1.2	<0.005	<0.0002	0.006	0.011	0.0006	<0.0001	0.169	0.0019	<0.001	<0.001	0.001	<0.0002	<0.0001	0.0610	<0.0005	0.0004	0.0450
72	334	6.52	0.755	0.18	18.1	<0.3	<0.005	0.0180	0.010	0.167	<0.0005	<0.0001	0.003	0.0002	0.001	0.020	<0.0005	<0.0002	<0.0001	0.1310	<0.0005	0.0006	0.0140
73	115	15.29	0.011	1.46	12	1.1	<0.005	0.0003	0.008	0.008	0.0008	<0.0001	0.015	0.0001	0.001	<0.001	0.0007	<0.0002	<0.0001	0.0780	<0.0005	0.0007	0.0230
74	22	4.23	0.021	5.41	8.18	0.6	<0.005	<0.0002	0.003	0.004	0.0011	<0.0001	0.03	0.001	<0.001	<0.001	<0.0005	<0.0002	<0.0001	0.0950	<0.0005	0.0005	0.0110
75		374.53	0.199	0.42	7.65	28.5	<0.005	0.0234	0.027	0.372	0.0017	<0.0001	<0.001	<0.0001	0.002	0.027	<0.0005	<0.0002	<0.0001	0.2140	0.00180	0.0003	0.0650
76	40	209.50	0.435	0.24	12.5	14.5	<0.005	0.0121	0.018	0.292	0.0017	<0.0001	0.003	0.0002	0.001	0.017	0.0009	<0.0002	<0.0001	0.1190	0.00110	0.0006	0.0320
77	100	2.53	0.685	0.01	7.01	<0.3	<0.005	0.0152	0.004	0.191	0.0009	<0.0001	<0.001	<0.0001	<0.001	0.011	<0.0005	<0.0002	<0.0001	0.0480	<0.0005	0.0016	<0.001
78	200	20.58	0.013	0.01	18	14.0	<0.005	<0.0002	0.019	0.006	0.0012	<0.0001	0.057	0.0003	<0.001	<0.001	<0.0005	<0.0002	<0.0001	0.1140	0.00080	0.0004	0.0440
79	100	1.67	0.955	0.01	6.79	0.5	<0.005	0.0253	0.004	0.222	0.0014	<0.0001	0.001	<0.0001	<0.001	0.010	<0.0005	<0.0002	<0.0001	0.0370	<0.0005	0.0035	0.0020
80		5.56	0.112	0.13	12.8	1.5	<0.005	0.0018	0.0140	0.016	<0.0005	<0.0001	0.073	<0.0001	<0.001	0.001	<0.0005	<0.0002	<0.0001	0.0590	<0.0005	0.0005	0.019
81	50	110.17	0.012	0.01	12.9	2.2	<0.005	0.0006	0.0130	0.058	0.0021	<0.0001	0.002	<0.0001	0.002	<0.001	<0.0005	<0.0002	<0.0001	0.2430	<0.0005	0.0007	0.002
82	97	37.95	0.407	0.01	15	<0.3	<0.005	0.0006	0.0150	0.088	0.0021	<0.0001	<0.001	<0.0001	0.001	0.002	<0.0005	<0.0002	<0.0001	0.0850	0.00080	0.0009	0.003
83	65	2.93	0.026	0.01	8.3	4.6	<0.005	0.0072	0.0170	0.016	<0.0005	<0.0001	<0.001	<0.0001	0.002	0.001	<0.0005	<0.0002	<0.0001	0.0790	<0.0005	0.0009	0.003
84	138	9.55	0.014	2.34	8.48	8.6	<0.005	0.0013	0.0040	0.005	0.0013	<0.0001	0.015	0.0002	<0.001	<0.001	0.00	0.0003	<0.0001	0.0990	0.00050	0.0014	0.017
85	100	2.09	0.436	0.01	7.74	0.7	<0.005	0.0164	0.0060	0.116	0.0013	0.0001	0.004	0.0001	<0.001	0.007	<0.0005	<0.0002	<0.0001	0.0680	<0.0005	0.0026	0.004
86	146	2.72	1.433	0.01	####	3.3	0.006	0.0194	0.0020	0.238	0.0018	<0.0001	0.001	0.0001	<0.001	0.007	<0.0005	<0.0002	<0.0001	0.0360	0.00240	0.0057	0.010
87	95	1.46	0.604	0.01	7.85	0.3	<0.005	0.0163	0.0070	0.116	0.0006	<0.0001	<0.001	<0.0001	<0.001	0.005	<0.0005	<0.0002	<0.0001	0.0630	<0.0005	0.0017	0.002
88	127	7.00	1.250	0.01	####	1.4	<0.005	0.0187	0.0160	0.187	0.0015	<0.0001	0.009	0.0003	0.001	0.009	<0.0005	<0.0002	<0.0001	0.0990	0.00050	0.0043	0.006
89	135	3.07	0.357	0.01	####	0.8	<0.005	0.0105	0.016	0.055	0.0012	0.0001	0.001	0.0001	<0.001	0.003	<0.0005	<0.0002	<0.0001	0.0500	<0.0005	0.0003	0.003
90	30	5.10	0.019	0.01	####	4.5	<0.005	0.0027	0.0140	0.009	0.0007	<0.0001	<0.001	<0.0001	0.003	<0.001	<0.0005	<0.0002	<0.0001	0.1160	<0.0005	0.0014	<0.001
91	182	3.63	5.189	0.01	####	<0.3	<0.005	0.0549	0.011	1.360	0.0013	0.0001	0.007	<0.0001	0.002	0.041	0.001		<0.0001	0.044	0.003	0.012	0.006
92	151	27.30	0.471	0.01	####	6.8	<0.005	0.0229	0.0080	0.150	0.002	<0.0001	<0.001	<0.0001	0.001	0.010	<0.0005	<0.0002	<0.0001	0.0780	0.00050	0.0028	0.002
93	100	9.79	1.206	0.01	####	1.1	<0.005	0.0203	0.0060	0.227	0.0019	<0.0001	0.002	0.0001	<0.0001	0.011	0.0006	<0.0002	<0.0001	0.0370	0.00050	0.0045	0.002
94	275	12.61	0.453	0.01	9.05	6.0	0.007	0.0232	0.0020	0.134	0.0012	<0.0001	0.012	<0.0001	<0.0001	0.007	<0.0005	<0.0002	<0.0001	0.0240	0.00100	0.0021	0.002
95	100	17.88	0.013	0.01	####	4.2	<0.005	0.0025	0.0080	0.008	0.0011	<0.0001	0.004	<0.0001	0.002	0.001	0.0009	<0.0002	<0.0001	0.0890	<0.0005	0.0010	0.007
96	120	2.61	0.109	0.01	9.28	2.3	<0.005	0.0050	0.0060	0.019	<0.0005	<0.0001	<0.001	<0.0001	0.001	0.003	<0.0005	<0.0002	<0.0001	0.0600	<0.0005	0.0010	0.004
97	83	4.77	1.065	0.03	10.1	2.2	<0.005	0.0194	0.0100	0.253	0.0018	<0.0001	0.004	0.0001	<0.0001	0.009	<0.0005	<0.0002	<0.0001	0.0850	0.00060	0.0044	0.003
98	100	5.24	0.092	0.01	11.8	2.4	<0.005	0.0056	0.0050	0.019	0.0014	<0.0001	<0.001	<0.0001	<0.0001	0.002	0.0005	<0.0002	<0.0001	0.1000	<0.0005	0.0015	<0.001
99	95	10.36	0.014	0.52	9.83	2.6	<0.005	0.0005	0.0080	0.012	0.0015	<0.0001	0.005	0.0001	<0.001	<0.001	0.0025	<0.0002	<0.0001	0.0820	<0.0005	0.0010	0.006
100	64	2.74	0.061	0.01	####	4.2	<0.005	0.0034	0.0040	0.012	0.0007	<0.0001	<0.001	<0.0001	<0.001	0.002	<0.0005	<0.0002	<0.0001	0.0750	<0.0005	0.0029	0.004

Appendix G. Data including water sample ID, total metals and pathogens. (N=99)

Sample ID	Total Metals Ca	Fe	Mg	Mn	K	Si	Na	S	Al	As	Ba	B	Cd	Cr	Co	Cu	Pb	Li	Mo	Ni	Se	Ag	Sr	Ti	V	Zn	Pathogen TC (# /100mL)
1	27.7	<0.1	8.4	0.053	11.7	17.50	254.0	20.8	0.007	0.0430	0.027	0.445		0.001	<0.0002	<0.001	<0.0002	0.004	0.03	0.001	<0.0004	<0.0002	0.269	0.0026	0.0008	0.008	<1
2	26	0.4	24.3	0.076	14	11.40	483.0	46.2	<0.01	0.0377	0.049	0.443		0.001	<0.0002	<0.002	<0.0002	0.003	0.028	0.001	<0.0004	<0.0002	0.387	0.0043	0.0003	0.010	<1
3	<0.4	<0.2	0.2	<0.01	3	11.10	575.0	46	<0.01	0.0365	<0.002	0.458		0.001	<0.0002	0.003	<0.0002	<0.002	0.028	0.0021	0.0004	<0.0002	0.004	0.004	0.0003	0.010	<1
4	31.9	<0.2	15	0.066	13	12.10	342.0	31	<0.01	0.0310	0.063	0.31		<0.001	<0.0002	0.034	0.0345	0.003	0.024	0.0033	<0.0004	<0.0002	0.364	0.0028	0.0002	0.038	8.6
5	13	<0.1	5.5	0.03	10.5	19.00	156.0	7.5	<0.001	0.0371	0.018	0.306		<0.001	<0.0002	<0.001	<0.0001	0.003	0.01	<0.0005	<0.0004	<0.0002	0.120	0.0007	0.0005	0.006	1.0
6	18.6	<0.1	6.7	0.032	3	10.80	11.8	3.6	0.006	0.0008	0.006	0.024		<0.001	<0.0002	0.003	<0.0001	0.001	0.002	<0.0005	<0.0004	<0.0002	0.092	<0.0005	<0.0001	0.008	139.6
7	32.6	1.1	12.8	0.087	10.8	8.08	276.0	30.5	<0.005	0.0124	0.027	0.376		0.0006	<0.0002	<0.001	<0.0001	0.002	0.039	0.0024	<0.0002	<0.0002	0.332	0.0021	0.0001	0.007	>2419.2
8	9.9	<0.1	3.3	0.012	7.2	13.40	204.0	11.4	<0.005	0.0481	0.015	0.469		0.0006	<0.0002	0.002	<0.0001	0.002	0.021	0.0015	<0.0002	<0.0002	0.105	0.0013	0.0012	0.016	2.0
9	20.1	<0.1	7.1	0.028	4.6	14.30	11.4	3	<0.005	0.0139	0.012	0.026		<0.0005	<0.0002	0.023	0.0116	0.001	0.002	<0.0005	<0.0002	<0.0002	0.106	<0.0005	0.0001	0.016	47.9
10	34.8	<0.1	15.6	<0.005	2.4	15.10	12.4	7.7	<0.005	0.0010	0.007	0.012		0.0007	<0.0002	0.029	<0.0001	0.003	<0.001	<0.0005	<0.0002	<0.0002	0.192	0.001	0.002	0.016	45.7
11	60.5	0.6	20.2	0.091	7.2	6.89	494.0	43	<0.010	0.0190	0.047	0.324		0.0062	<0.0002	<0.002	<0.0001	0.002	0.042	<0.001	<0.0002	<0.0002	0.614	0.0035	<0.0002	0.020	<1
12	26.1	<0.1	9.4	0.012	13	15.60	262.0	23.6	<0.005	0.0347	0.027	0.378		0.0041	<0.0002	0.007	<0.0001	0.004	0.021	0.0006	<0.0002	<0.0002	0.281	0.0019	0.0004	0.020	260.2
13	11.4	<0.1	4.2	0.024	8.4	14.10	188.0	10.7	<0.005	0.0471	0.014	0.436		<0.0005	<0.0002	0.022	0.0002	0.003	0.02	0.0013	<0.0002	<0.0002	0.114	0.0011	0.001	0.007	45.7
14	42.2	<0.1	21	0.075	14	11.60	389.0	37.7	0.064	0.0204	0.044	0.334		<0.001	<0.0002	0.003	<0.0002	0.003	0.028	<0.001	<0.0002	<0.0002	0.504	0.0062	<0.0002	0.010	<1
15	18	<0.1	5.9	0.02	5.5	5.72	6.2	2.5	<0.005	0.0142	0.007	0.024		<0.0005	<0.0002	0.002	0.0001	0.001	<0.001	<0.0005	<0.0002	<0.0002	0.085	<0.0005	<0.0001	0.008	<1
16	0.9	<0.1	<0.1	<0.005	<0.4	0.88	4.4	<0.3	0.071	0.0003	0.003	0.003		<0.0005	<0.0002	0.159	0.0008	<0.001	<0.001	<0.0005	<0.0002	<0.0002	0.004	<0.0005	0.0001	0.013	<1
17	2.6	<0.1	1.2	0.008	1.9	9.59	104.0	5.5	0.007	0.0159	0.002	0.29		0.0006	<0.0002	0.006	<0.0001	0.001	0.006	0.001	<0.0002	<0.0002	0.022	0.0013	0.0014	0.007	344.8
18	8	<0.1	3.9	0.011	5.7	8.88	227.0	11.6	<0.005	0.0188	0.013	0.33		0.0032	<0.0002	0.035	0.0004	0.002	0.021	0.0008	<0.0002	<0.0002	0.093	0.0014	0.0009	0.013	50.4
19										0.0242																	
20	11	<0.1	4	0.033	8.6	12.80	111.0	5.5	0.051	0.0296	0.014	0.253		0.0008	<0.0002	<0.001	<0.0001	0.002	0.022	0.0008	<0.0002	<0.0002	0.103	0.0033	0.0009	0.008	<1
21	7.5	<0.1	2.3	0.019	6.8	12.00	77.9	1.6	<0.005	0.0264	0.006	0.217		<0.0005	<0.0002	<0.001	0.0001	0.002	0.008	<0.0005	<0.0002	<0.0002	0.064	<0.0005	0.0007	0.008	<1
23	4.4	<0.1	1.6	0.033	3	8.72	110.0	1	<0.005	0.0163	0.004	0.285		<0.0005	<0.0002	0.007	0.0003	<0.001	0.012	0.0007	<0.0002	<0.0002	0.036	<0.0005	0.0005	0.010	<1
24	10.2	0.3	1.9	0.083	0.9	6.84	6.6	1	0.012	<0.0002	0.017	0.005		<0.0005	<0.0002	0.11	0.001	<0.001	<0.001	0.0022	<0.0002	<0.0002	0.101	0.0008	<0.0001	0.014	1119.9
25	11.8	<0.1	4.8	0.032	3.5	7.23	42.4	<0.3	<0.005	0.0137	0.005	0.111		<0.0005	<0.0002	0.004	0.0001	<0.001	0.005	<0.0005	<0.0002	<0.0002	0.067	<0.0005	0.0003	0.007	12.2
26	11.7	0.2	2.7	0.154	0.5	11.50	9.0	1	0.011	0.0003	0.021	0.004		0.0013	<0.0002	0.249	0.0004	<0.001	<0.001	0.0017	<0.0002	<0.0002	0.158	<0.0005	0.0003	0.012	179.3
27	11	<0.1	3.5	0.015	3.7	6.70	103.0	0.7	0.006	0.0189	0.004	0.23		0.0005	<0.0002	<0.001	<0.0001	<0.001	0.039	0.0006	<0.0002	<0.0002	0.071	<0.0005	0.0008	0.006	<1
28	11.9	0.2	5.6	0.043	1.4	11.40	7.5	0.6	0.006	0.0018	0.005	0.011		<0.0005	<0.0002	0.002	<0.0001	<0.001	0.001	<0.0005	<0.0002	<0.0002	0.067	<0.0005	0.0021	0.013	<1
29	1.3	<0.1	0.9	0.007	5.0	7.40	131.0	6	0.015	0.0278	0.002	0.4		<0.0005	<0.0002	0.007	0.0009	<0.001	0.014	0.0005	<0.0002	<0.0002	0.016	0.0023	0.0005	0.014	<1
30	11.6	0.2	5.1	0.075	2.4	11.30	21.6	0.7	<0.005	0.0021	0.024	0.048		<0.0005	<0.0002	<0.001	<0.0001	<0.001	0.002	<0.0005	<0.0002	<0.0002	0.073	<0.0005	0.0002	0.008	1119.9
31	18.2	<0.1	4.9	0.02	2.2	8.10	8.1	2.9	<0.005	0.0074	0.01	0.012		<0.0005	<0.0002	0.001	<0.0001	<0.001	0.001	<0.0005	<0.0002	<0.0002	0.076	<0.0005	0.0003	0.007	<1
32	11	0.3	4.8	0.071	2.4	11.40	23.6	0.7	<0.005	0.0027	0.026	0.054		<0.0005	<0.0002	<0.001	<0.0001	<0.001	0.002	<0.0005	<0.0002	<0.0002	0.070	<0.0005	0.0002	0.006	<1
33	18.5	<0.1	5.0	<0.005	0.9	10.00	6.6	3.4	<0.005	<0.0002	0.005	0.015		0.0013	<0.0002	0.006	0.0006	<0.001	<0.001	0.0044	<0.0002	<0.0002	0.130	<0.0005	0.0008	0.008	<1
34	10.8	1.3	5.8	0.039	5.8	9.96	37.0	2.3	0.016	0.0184	0.010	0.095		<0.0005	<0.0002	1.59	0.0306	<0.001	0.005	<0.0005	<0.0002	<0.0002	0.076	0.0009	0.0001	0.025	235.9
35	9.4	0.1	4.5	0.082	2.2	11.90	20.4	0.7	<0.005	0.0056	0.011	0.054		<0.0005	<0.0002	<0.001	<0.0001	<0.001	0.002	<0.0005	<0.0002	<0.0002	0.055	<0.0005	0.0001	0.007	35.0
36	5.4	<0.1	0.8	0.022	0.8	5.52	5.2	4.7	0.007	0.0002	0.004	0.019		<0.0005	<0.0002	0.036	0.0008	<0.001	<0.001	<0.0005	<0.0002	<0.0002	0.061	<0.0005	<0.0001	0.018	261.3
37	3.8	<0.1	2.9	0.025	4.8	10.60	123.0	<0.3	<0.005	0.0022	0.006	0.612		0.0006	<0.0002	0.009	0.0003	<0.001	0.017	0.0005	<0.0002	<0.0002	0.043	0.0023	0.002	0.008	5.1
38	16.3	0.3	3.8	0.065	2.6	15.00	15.8	1.5	0.018	0.0038	0.008	0.018		<0.0005	<0.0002	<0.001	<0.0001	<0.001	0.002	<0.0005	<0.0002	<0.0002	0.073	0.0012	0.0001	0.006	8.6
39	37.6	1.6	17	0.011	2.1	11.30	46.5	1.6	<0.005	<0.0002	0.017	0.082		0.0022	<0.0002	0.006	0.0003	0.002	<0.001	<0.0005	<0.0002	<0.0002	0.276	<0.0005	0.0001	0.020	<1
40	17.3	<0.1	3.8	<0.005	0.7	11.10	5.5	1.8	<0.005	<0.0002	0.006	0.023		0.0005	<0.0002	0.065	0.0028	<0.001	<0.001	0.003	<0.0002	<0.0002	0.101	<0.0005	0.0004	0.077	<1
41	2	<0.1	1.3	0.01	3.3	10.60	108.0	0.8	0.024	0.0160	0.004	0.425		0.0009	<0.0002	0.018	0.0006	0.017	0.012	0.0016	<0.0002	<0.0002	0.023	0.005	0.0022	0.012	57.6
42	17.4	0.1	9.6	0.340	3.4	12.60	22.3	6.1	<0.005	0.0034	0.008	0.048		<0.0005	<0.0002	0.013	0.0004	0.002	0.002	<0.0005	<0.0002	<0.0002	0.116	<0.0005	0.0098	0.008	<1
43	14.3	1.7	8.2	0.127	2.2	8.40	13.1	5.3	<0.005	0.0011	0.015	0.030		<0.0005	<0.0002	0.003	0.0003	0.001	<0.001	<0.0005	<0.0002	<0.0002	0.066	<0.0005	<0.0001	0.009	3.1
44	6.3	<0.1	1.2	0.012	0.4	5.96	4.8	1.8	0.007	0.0002	0.002	0.011		<0.0005	<0.0002	0.047	0.0091	<0.001	<0.001	0.0007	0.0005	<0.0002	0.065	<0.0005	0.0002	0.013	1.0
45	11.7	<0.1	4.6	<0.005	0.8	7.83	8.7	2.6	0.011	<0.0002	0.033	0.008		<0.0005	<0.0002	0.106	0.0005	<0.001	<0.001	<0.0005	0.0003	<0.0002	0.094	<0.0005	0.0005	0.010	920.8
46	15.9	<0.1	8.9	<0.005	1.4	11.00	6.1	4.3	<0.005	0.0008	0.007	0.005		<0.0005	<0.0002	0.010	0.0002	<0.001	<0.001	<0.0005	0.0007	<0.0002	0.081	<0.0005	0.0044	0.013	88.2
47	2.1	0.3	2	0.029	4.9	7.86	283.0	0.6	0.018	0.0293	0.008	1.24	8E-05	0.0028	<0.0002	0.002	0.0003	<0.001	0.02	0.0008	<0.0002	<0.0002	0.036	0.0138	0.0082	0.022	<1
48	22.4	<0.1	5.3	<0.005	1.3	6.23	3.4	3.3	<0.005	0.0044	0.007	0.007		0.0015	<0.0002	0.002	<0.0001	0.002	<0.001	<0.0005	<0.0002	<0.0002	0.068	<0.0005	0.0021	0.010	<1
49	18.6	0.2	8.9	<0.005	1.6	9.33	5.8	3.9	<0.005	0.0010	0.005	0.015		<0.0005	<0.0002	0.009	0.0012	0.002	<0.001	0.0005	<0.0002	<0.0002	0.078	<0.0005	0.0013	0.209	17.5
50	10.7	<0.1	4.3	<0.005	1.8	6.24	6.6	2.3	0.011	<0.0002	0.009	0.02		<0.0005	<0.0002	0.11	0.0201	<0.001	<0.001	0.00121	<0.0002	<0.0002	0.130	<0.0005	0.0002	0.020	1.0

Sample ID	Ca	Fe	Mg	Mn	K	Si	Na	S	Al	As	Ba	B	Cd	Cr	Co	Cu	Pb	Li	Mo	Ni	Se	Ag	Sr	Ti	V	Zn	TC (# /100mL)
51	20.3	<0.1	7.5	0.007	0.7	12.00	7.7	2.6	0.007	<0.0002	0.006	0.012		0.0014	<0.0002	0.067	0.0014	<0.001	<0.001	0.0017	<0.0002	<0.0002	0.158	<0.0005	0.0006	0.035	<1
52	10.2	<0.1	5.5	0.046	5.3	13.40	84.5	3.9	<0.005	0.0170	0.01	0.231		<0.0005	<0.0002	0.001	<0.0001	0.001	0.012	<0.0005	<0.0002	<0.0002	0.078	0.0008	0.0008	0.004	<1
53	11.8	0.4	7.4	0.038	1.5	9.53	8.5	1.8	<0.005	0.0006	0.014	0.016		<0.0005	<0.0002	0.002	0.0002	<0.001	<0.001	<0.0005	<0.0002	<0.0002	0.067	<0.0005	0.0014	0.007	770.1
54	15.7	0.3	5.7	0.007	1.2	7.42	5.7	2.6	0.017	<0.0002	0.005	0.01		0.0008	<0.0002	0.071	0.0002	0.001	<0.001	0.0007	<0.0002	<0.0002	0.074	0.001	0.0001	0.018	14.6
55	4.0	<0.1	2.0	0.016	5.4	10.80	106.0	2.9	<0.005	0.0600	0.004	0.189		0.0008	<0.0002	0.006	<0.0001	0.002	0.013	0.0006	<0.0002	<0.0002	0.040	0.0006	0.0011	0.006	12.2
56	13.1	0.1	6.0	0.044	6.2	10.10	150.0	8.4	0.005	0.0058	0.013	0.234		0.0021	<0.0002	0.004	<0.0001	<0.001	0.015	<0.0005	<0.0002	<0.0002	0.120	0.0011	0.0017	0.015	3.1
57	15.8	<0.1	6.5	0.007	3.6	13.10	9.3	2.5	<0.005	0.0097	0.008	0.016		<0.0005	<0.0002	0.003	<0.0001	<0.001	0.001	<0.0005	<0.0002	<0.0002	0.090	<0.0005	0.0001	0.007	24.6
58	17.1	<0.1	4.3	0.052	4.9	12.10	64.7	6.8	<0.005	0.0160	0.015	0.167		<0.0005	<0.0002	0.007	0.0002	0.001	0.026	0.0008	0.0004	<0.0002	0.109	0.0007	0.0006	0.011	137.6
59	16.4	<0.1	4.7	0.084	5.5	14.00	81.3	8.4	<0.005	0.0005	0.012	0.160		0.0011	<0.0002	<0.001	<0.0001	<0.001	0.023	<0.0005	0.0005	<0.0002	0.100	0.0035	0.0014	0.005	1.0
60	18.7	<0.1	5.0	0.083	2.5	12.90	8.9	1.6	0.052	0.0042	0.019	0.014		<0.0005	<0.0002	0.002	<0.0001	<0.001	<0.001	<0.0005	<0.0002	<0.0002	0.070	<0.0005	0.0024	0.004	<1
61	9.1	<0.1	2.2	0.02	6.0	12.80	74.0	1.4	<0.005	0.0278	0.009	0.197		<0.0005	<0.0002	0.006	0.0002	0.002	0.008	<0.0005	0.0003	<0.0002	0.069	<0.0005	0.0004	0.005	<1
62	17.6	0.1	5.7	0.098	5.7	14.10	81.8	8.1	<0.005	0.0008	0.012	0.160		0.001	<0.0002	0.003	<0.0001	<0.001	0.023	<0.0005	0.0004	<0.0002	0.107	0.0033	0.0017	0.006	<1
63	20.4	0.1	5.4	0.058	2.6	12.90	6.5	1.8	0.009	0.0036	0.014	0.010		<0.0005	<0.0002	0.015	<0.0001	<0.001	<0.001	<0.0005	<0.0002	<0.0002	0.078	0.0005	0.002	0.009	1553.1
64	80.4	<0.2	26.6	0.130	21.9	12.50	519.0	46.2	<0.005	0.0324	0.043	0.388		<0.0005	<0.0002	0.01	<0.0001	0.007	0.032	0.0076	0.001	<0.0002	0.735	0.0048	<0.0001	0.020	>2419.2
65	16.2	0.3	5.5	0.027	5.7	15.50	12.5	<0.3	<0.005	0.0006	0.002	0.039		<0.0005	<0.0002	0.005	<0.0001	0.002	0.002	<0.0005	<0.0002	<0.0002	0.082	<0.0005	0.0002	0.004	5.2
66	11.7	<0.1	5.2	0.006	0.6	8.25	3.4	0.5	<0.005	<0.0002	0.003	0.004	0.00001	0.0022	<0.0002	0.012	0.0004	<0.001	<0.001	<0.0005	<0.0002	<0.0002	0.054	<0.0005	0.0009	0.006	51.2
67	19.2	<0.1	8.5	<0.005	0.6	7.35	3.8	9.4	<0.005	0.0004	0.004	0.004	0.00001	<0.0005	<0.0002	0.003	<0.0001	0.001	<0.001	<0.0005	<0.0002	<0.0002	0.097	<0.0005	0.0015	0.004	<1
68	16.7	0.4	4.1	1.02	0.6	9.28	9.8	7.5	0.158	<0.0002	0.146	0.029	0.00001	0.0009	<0.0002	0.196	0.0022	<0.001	<0.001	0.0304	<0.0002	<0.0002	0.212	0.0082	0.0005	0.114	2419.2
69	25.7	<0.1	7.2	<0.005	0.8	12.00	6.8	5.4	<0.005	0.0003	0.007	0.023	0.00001	0.0025	<0.0002	0.042	0.0005	0.001	<0.001	0.0013	<0.0002	<0.0002	0.172	<0.0005	0.0007	0.020	<1
70	27.2	<0.1	9	<0.005	1.2	8.31	4.8	3.2	<0.005	0.0019	0.008	0.005	0.00001	0.0026	<0.0002	0.004	0.0002	0.003	<0.001	<0.0005	<0.0002	<0.0002	0.110	<0.0005	0.002	0.014	<1
71	11.8	<0.1	3.9	<0.005	0.6	7.62	5.4	1.3	0.013	<0.0002	0.005	0.011	0.00001	0.0008	<0.0002	0.187	0.0037	0.001	<0.001	0.0011	<0.0002	<0.0002	0.063	<0.0005	0.0004	0.042	1.0
72	18.7	<0.1	8.4	0.006	7.7	18.00	64.2	<0.3	<0.005	0.0154	0.01	0.155	0.00001	<0.0005	<0.0002	0.003	0.0002	0.001	<0.001	<0.0005	<0.0002	<0.0002	0.137	<0.0005	0.0003	0.014	2.0
73	15.3	<0.1	6.4	<0.005	0.7	11.60	4.6	1.1	<0.005	<0.0002	0.008	0.011	0.00001	0.002	<0.0002	0.018	0.0005	0.002	<0.001	0.0007	<0.0002	<0.0002	0.081	<0.0005	0.0009	0.023	51.2
74	10.1	<0.1	2.7	<0.005	0.5	8.14	4.0	0.7	<0.005	<0.0002	0.003	0.004	0.00001	0.0009	<0.0002	0.039	0.0011	<0.001	<0.001	<0.0005	<0.0002	<0.0002	0.101	<0.0005	0.0004	0.012	<1
75	20.9	<0.1	8.6	0.005	6.1	7.43	324.0	27.7	<0.005	0.0199	0.025	0.395	6E-05	0.0038	<0.0002	<0.001	<0.0001	0.002	0.0280	<0.0005	<0.0002	<0.0002	0.234	0.0021	<0.0001	0.086	59.1
76	12.1	<0.1	5.8	0.008	6.7	12.40	202.0	14.5	<0.005	0.0100	0.018	0.331	1E-05	0.003	<0.0002	0.004	0.0002	0.002	0.0160	0.0006	<0.0002	<0.0002	0.134	0.0014	0.0004	0.033	<1
77	8.6	<0.1	2.0	0.01	3.0	6.96	67.9	<0.3	<0.005	0.0130	0.005	0.201	0.00001	<0.0005	<0.0002	<0.001	<0.0001	<0.001	0.0100	0.0005	<0.0002	<0.0002	0.051	<0.0005	0.0014	0.004	4.1
78	28.5	2.7	18.0	0.074	3.4	17.90	9.6	13.7	<0.005	<0.0002	0.019	0.006	0.00001	0.001	<0.0002	0.056	0.0076	<0.001	<0.001	0.0006	<0.0002	<0.0002	0.123	0.0008	<0.0001	0.045	<1
79	6.3	<0.1	1.4	0.017	2.6	6.50	74.7	0.5	<0.005	0.0186	0.004	0.231	0.00001	<0.0005	<0.0002	0.002	<0.0001	<0.001	0.0100	0.0006	<0.0002	<0.0002	0.040	<0.0005	0.0007	0.005	5.2
80	13.0	0.1	4.7	0.034	1.6	12.60	10.6	1.5	0.011	<0.0002	0.014	0.016	0.00001	<0.0005	<0.0002	0.085	0.0005	<0.001	0.0010	0.0007	0.0004	<0.0002	0.061	<0.0005	0.0003	0.018	<1
81	44.8	0.6	20.2	0.006	1.9	12.20	28.2	2.1	<0.005	0.0005	0.013	0.063	2E-05	0.0012	<0.0002	0.005	0.0001	0.002	<0.001	0.0007	<0.0002	<0.0002	0.257	0.0007	0.0007	0.006	4.1
82	11.8	0.5	5.3	0.048	4.4	14.40	66.1	<0.3	0.006	0.0006	0.015	0.092	1E-05	0.0018	<0.0002	0.001	<0.0001	0.001	0.0020	<0.0005	0.0004	<0.0002	0.089	0.0012	0.0004	0.006	30.9
83	23.8	<0.1	6.2	0.032	2.3	7.95	8.8	4.4	<0.005	0.0063	0.017	0.016	1E-05	<0.0005	<0.0002	<0.001	<0.0001	0.002	0.0010	<0.0005	<0.0002	<0.0002	0.081	<0.0005	0.0006	0.004	15.6
84	29.2	0.1	8.3	0.014	1.4	8.33	5.0	8.7	<0.005	0.0014	0.004	0.006	0.00001	0.0016	<0.0002	0.021	0.0005	<0.001	<0.001	0.005	0.0003	<0.0002	0.105	0.0006	0.0014	0.020	8.5
85	13	<0.1	3.9	0.031	3.2	7.35	46.4	0.6	<0.005	0.0128	0.006	0.123	0.00001	<0.0005	<0.0002	0.008	<0.0001	<0.001	0.007	<0.0005	<0.0002	<0.0002	0.071	<0.0005	0.0005	0.005	4.1
86	6	0.2	2.4	0.035	1.7	10.60	94.1	3.2	0.006	0.0132	0.0	0.230	0.00001	<0.0005	<0.0002	0.001	0.0002	<0.001	0.007	<0.0005	<0.0002	<0.0002	0.038	0.0027	0.0015	0.011	<1
87	11.7	<0.1	4.7	0.029	3.4	7.40	43.4	<0.3	<0.005	0.0129	0.006	0.111	0.00001	<0.0005	<0.0002	<0.001	<0.0001	<0.001	0.005	<0.0005	<0.0002	<0.0002	0.066	<0.0005	0.0003	0.004	<1
88	19.2	<0.1	7.2	0.110	4	9.95	74.8	1.3	<0.005	0.0135	0.015	0.186	0.00001	<0.0005	<0.0002	0.01	0.0003	0.001	0.009	0.0006	<0.0002	<0.0002	0.105	<0.0005	0.0007	0.007	<1
89	9.4	<0.1	4.1	0.054	2.2	11.00	21.7	0.8	<0.005	0.0095	0.016	0.053	0.00001	<0.0005	<0.0002	0.002	0.0002	<0.001	0.003	<0.0005	0.0004	<0.0002	0.053	<0.0005	0.0001	0.007	<1
90	36.9	0.2	11.0	0.227	1.9	10.40	5.2	4.3	<0.005	0.0024	0.013	0.01	0.00001	<0.0005	<0.0002	<0.001	<0.0001	0.004	<0.001	<0.0005	<0.0002	<0.0002	0.131	<0.0005	<0.0001	0.005	12.1
91	2.3	0.2	3.7	0.035	6.9	13.5	282	<0.3	0.005	0.0340	0.01	1.32	0.00001	0.001	<0.0002	0.011	<0.0001	0.002	0.042	0.0006	0.0003	<0.0002	0.047	0.0033	0.0024	0.009	<1
92	10.3	<0.1	6.1	0.017	5.7	10.40	79.0	6.4	<0.005	0.0176	0.007	0.167	0.00001	<0.0005	<0.0002	0.002	<0.0001	0.001	0.010	<0.0005	<0.0002	<0.0002	0.087	<0.0005	0.0002	0.004	1.0
93	4.7	<0.1	1.8	0.032	3.1	10.20	95.8	1	<0.005	0.0141	0.005	0.231	0.00001	<0.0005	<0.0002	0.003	0.0001	<0.001	0.011	0.0006	<0.0002	<0.0002	0.039	<0.0005	0.0005	0.004	<1
94	3.3	<0.1	2.0	0.013	4	8.55	81.8	5.6	0.008	0.0182	0.002	0.139	0.00001	<0.0005	<0.0002	0.012	0.0002	<0.001	0.007	<0.0005	<0.0002	<0.0002	0.026	0.0007	0.0002	0.005	3.1
95	23.4	1.2	15.5	0.182	1.8	13.40	10.5	3.9	<0.005	0.0028	0.008	0.009	0.00001	<0.0005	<0.0002	0.024	0.0006	0.002	<0.001	0.0012	<0.0002	<0.0002	0.097	<0.0005	<0.0001	0.011	<1
96	11.6	<0.1	5.5	0.04	1.6	8.87	13.1	2.2	<0.005	0.0040	0.006	0.019	0.00001	<0.0005	<0.0002	0.001	<0.0001	<0.001	0.003	<0.0005	<0.0002	<0.0002	0.066	<0.0005	0.0004	0.004	<1
97	14.2	<0.1	5.0	0.052	4.3	9.47	71.3	2	<0.005	0.0142	0.009	0.245	0.00001	<0.0005	<0.0002	0.004	<0.0001	<0.001	0.009	<0.0005	<0.0002	<0.0002	0.091	0.0005	0.0008	0.004	32.7
98	21.1	0.2	10.5	0.071	3	11.30	10.1	2.2	<0.005	0.0046	0.005	0.02	0.00001	<0.0005	<0.0002	0.004	<0.0001	<0.001	0.002	<0.0005	<0.0002	<0.0002	0.110	<0.0005	<0.0001	0.004	1.0
99	15.5	<0.1	5.6	0.006	0.8	9.44	5.6	2.6	<0.005	0.0003	0.008	0.012	0.00001	0.0005	<0.0002	0.02	0.0002	0.001	<0.001	0.0028	<0.0002	<0.0002	0.082	<0.0005	0.0008	0.015	1.0
100	21.6	0.2	8.9	0.038	2.2	9.98	7.9	3.9	<0.005	0.0029	0.004	0.012	0.00001	<0.0005	<0.0002	0.001	-0.0003	<0.001	0.002	<0.0005	<0.0002	<0.0002	0.081	<0.0005	0.002	0.005	1.0

Appendix H. Relation between total arsenic and thickness of the thickest layer of clay in the sampled well profile.

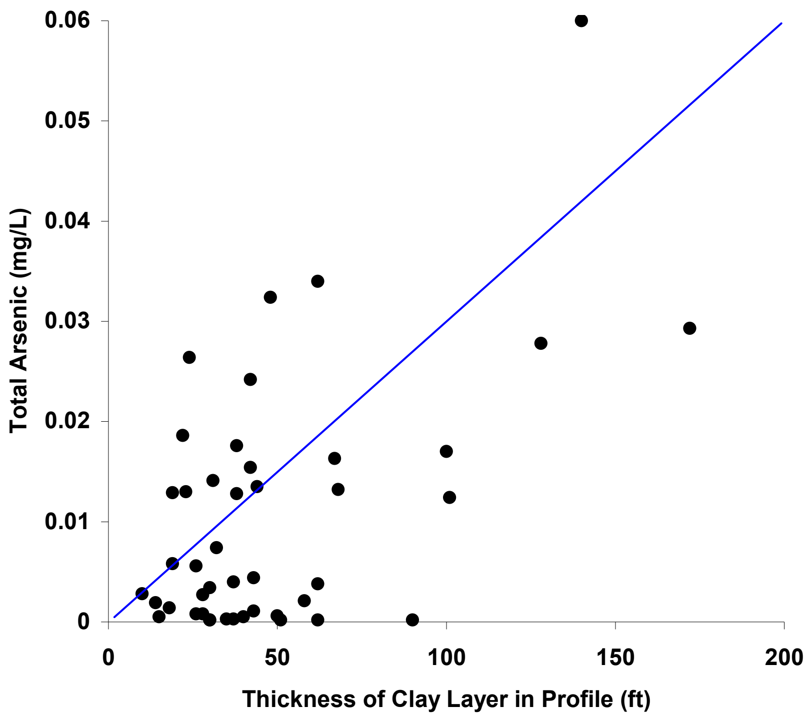

Figure. Total arsenic in well water vs. clay layer thickness in well profile. Well profile data was collected from borehole records from the MoE Water Well Application (BC MoE, 2007c). 1:1 line is included. (r=0.27, p=0.077, N=44)