Evaluation of Well Seal Integrity and Its Relative Importance in Assessing Groundwater Quality

By

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Abstract

Unlike municipal water supplies, provincial regulations do not require systematic testing of domestic well water, which may adversely impact local residents should contamination occur. Private wells are typically shallow relative to municipal wells, and thus, are particularly vulnerable to sources of surficial contamination if preferential recharge pathways such as natural fractures or faulty seals are present.

In order to determine the relative importance of well seal integrity as a preferential pathway, a practical detection method was developed based on infiltrometry. This method successfully detected faulty well seals in a wide range of geological settings across Canada, including: Hobbema, Alberta; Lindsay, Ontario; and Chelsea, Québec. It was most successful in areas of minimal heterogeneity and where the surficial geology is composed of fine-grained sediments.

The community of Chelsea (Québec) was also the primary study site to examine a range of factors affecting water quality including physical characteristics, faulty well seals, other anthropogenic activities and seasonality. Water samples were collected over a period of 14 months and analyzed for bacteria and major-ion chemistry. The results show that the consideration of physical features alone is not enough to predict vulnerability in the study area. Seasonal fluctuations in ionic concentrations (e.g. ionic strength, NO_3-N and Cl^-) and coliform bacteria are observed and result from disperse and rapid recharge events. Multivariate analysis techniques (e.g. principal components analysis and hierarchical cluster analysis) demonstrate that preferential recharge pathways and anthropogenic activities, such as domestic effluents affect the groundwater quality. The data and findings of this study were used to assist in the design of a probabilistic risk assessment model based on the Poisson distribution.

This study demonstrates the complexity and the challenges related to bacterial contamination in drilled wells. In spite of these challenges, this analysis was useful as a baseline to assess the impact of anthropogenic activities, and may be used in future studies to assist municipalities in the evaluation and protection of groundwater supplies.

Résumé

Les règlements provinciaux au Canada ne demandent pas un échantillonnage systématique des ouvrages de captage privés d'eau potable, contrairement aux ouvrages municipaux. Ceci peut avoir un impact sur la santé des utilisateurs advenant la contamination de l'ouvrage de captage. Les puits domestiques sont habituellement moins profonds que les puits municipaux, ce qui les rend vulnérables aux contaminants de surface en présence de chemins d'entrée directs, telles des fractures ou un scellement de tubage fautif de puits.

Une méthode de détection basée sur l'infiltrométrie fut développée dans le but de déterminer l'importance relative des scellements de tubage fautifs comme chemins d'entrée directs. La méthode détecta avec succès des scellements de tubage fautifs dans une grande variété d'environnements géologiques au Canada : Hobbema, Alberta; Lindsay, Ontario et Chelsea, Québec. Cependant, la méthode s'avère plus efficace lorsque l'hétérogénéité du terrain est minimale et que les dépôts meubles sont composés de sédiments fins.

La Municipalité de Chelsea (Québec) fut le site d'étude primaire pour investiguer l'impact d'une variété de facteurs, tels les caractéristiques physiques d'un site, les scellements fautifs, certaines activités anthropiques et les évènements climatiques sur la qualité de l'eau souterraine. L'échantillonnage se déroula sur une période de 14 mois et les échantillons furent analysés pour les indicateurs bactériens (coliforms totaux et fécaux) et chimiques. Les résultats démontrent que l'étude des facteurs physiques n'est pas suffisante afin d'évaluer la vulnérabilité d'un puits. Les fluctuations saisionnières observées dans les concentrations ioniques (e.g. force ionique, NO_3-N and Cl^-) et bactériologiques découlent d'épisodes de recharge dispersée et rapide. L'analyse des composantes principales et l'analyse hiérarchique de groupement démontrent que les chemins d'entrée directs ainsi que les activitées anthropiques, telle la présence de fosses septiques, influencent la qualité des eaux souterraines. Les résultats obtenus dans cette étude sont intégrés dans un modèle d'analyse probabilistique, basé sur la distribution de Poisson, pour la Municipalité de Chelsea (QC).

Cette étude démontre la complexité et les défis reliés à la contamination bactériologique des puits forés. En dépit de ces défis, cette recherche est utile pour établir des données de base pouvant servir à des études ultérieures permettant d'évaluer l'impact des activités anthropiques en plus d'assister les petites Municipalités, dépendantes des ouvrages de captage privés, à protéger leurs sources d' eau souterraine.

Dedication

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List of abbreviations

ANOVA :	Analysis of variance
CFU:	Colonie forming units
CLT:	Central Limit Theorem
CV:	Coefficient of variation
DIC:	Dissolved inorganic carbon
DWO:	Drinking water objective
EC:	Electric conductivity (μS/cm)
FC:	Faecal coliforms (CFU/100mL)
FQRNT:	Fond Québécois en Resources Naturelles et Technologies
HCA:	Hierarchical cluster analysis
ICP-AES:	Inductively coupled plasma atomic emission spectroscopy
K:	Hydraulic conductivity
LR:	Logistic regression
NSERC:	Natural Sciences and Engineering Research Council
PC:	Principal component
PCA:	Principal component analysis
RF:	Relative frequency
TC:	Total coliforms (CFU/100mL)
TOT:	Time of travel
WofE:	Weight-of-evidence

Chapter 1: Thesis introduction

1.1. Thesis rationale

Groundwater is the source of drinking water for approximately 30% of the Canadian population (Environment Canada, 2010a). Our awareness regarding the vulnerability of this resource has recently increased due to multiple breakout events of contamination at the Municipal level (e.g. Walkerton, Ontario in 2000). Protection of drinking water sources and the infrastructure that delivers our water is the focus of increased attention from governments and municipalities. Unfortunately, a disproportionate share of this attention has been prioritized towards municipal wells, whereas private wells are often ignored despite the fact that two thirds of rural Canada relies on groundwater (Environment Canada, 2010a). Unlike public water supply systems, regulations do not systematically require water testing for domestic private wells. Consequently, little is known on the proportion of wells that do not follow the jurisdiction guidelines and few research studies have been conducted on the contamination of private water wells in Canada. The Municipality of Chelsea (Québec) is such an example where minimal data has been collected to better understand the influence of natural and/or anthropogenic processes on groundwater quality.

Drilled wells are thought to be less vulnerable to contamination compared to shallow dug wells or bored wells. However, the quality of their drinking water may be affected if rapid surface water infiltration occurs in the unsealed or poorly-sealed annular space between the casing and the aquifer formation. The annular space is created during well construction and if it is not properly sealed, a preferential flow path is created, thereby enhancing the transport of surface waters to the aquifer system. The surface and runoff water often contains some bacteria that may negatively impact or even threaten human health. Proper sealing of the annular space is, therefore, an integral part of well construction. This was neglected in past water well drilling practices and is now legislated in many jurisdictions (Novakowsky et al., 2006). Although the annular space may be properly sealed, contamination with pathogenic organisms for example, still may occur if the local well-site settings enhance the creation of preferential pathways. It is often difficult to determine if the presence of bacteria in the well-water results from natural processes (i.e. bacteria in the aquifer) or anthropogenic activities (i.e. poor well construction) (Zimmerman et al., 2001). The actual extent of well seal problems are not well-documented because

there has been no practical method of testing the integrity of the surface seal, and as a result the relative importance of faulty well seals as a preferential pathway is poorly understood. Therefore, there is a need to evaluate the role of faulty well seals with respect to microbial contamination.

This Ph.D. research project contributes to the understanding of factors affecting rural water quality, from the relative importance of site-specific characteristics to climatic controls; and predicts the vulnerability to microbial contamination of wells in the Municipality of Chelsea, Québec. The first objective is to develop a practical method that allows the detection of faulty well seals and to characterize their importance as preferential pathways. The development of a relatively inexpensive and easy to implement method, based on infiltrometry, is an important contribution from this Ph.D. research. The well seal integrity component is unique; no one has used this simple technique to test well seals. This work has the potential for a significant impact in the monitoring of groundwater quality because it will quantify the degree to which preferential flow pathways, in particular poorly sealed wells, contribute to contamination. This study also characterizes the importance of faulty well seals relative to the local geology.

The second objective is to spatially and temporally characterize the groundwater quality in a test-community, Chelsea, Québec, over a 14 month period. This study is the first comprehensive study in the Municipality which determines the significance of natural and anthropogenic factors on groundwater quality and assesses the role of faulty seals on microbial contamination. Collection of monthly samples allowed the characterization of preferential recharge pathways and the influence of septic effluents on water quality in the test-community. Multivariate statistical analyses are employed in an attempt to further discriminate between extra-regional, regional, local and anthropogenic controls on the groundwater quality. This study employs multivariate analysis techniques as an alternative to more detailed studies (i.e. isotopic analysis) to identify significant factors that contribute to groundwater quality; and is also one of the few studies in the field of domestic well research that incorporates both coliform bacteria and water chemistry data into the multivariate statistical techniques. This dissertation aims to better understand the pathways and mechanisms which lead to the contamination of domestic wells, and to evaluate their spatial and seasonal variations in order to assess the vulnerability of domestic wells and assist in source water protection.

Lastly, the third objective is to assess the value of the collected data in the development a vulnerability model for microbial contamination in the Municipality of Chelsea, Québec. The vulnerability of domestic wells in Chelsea is assessed with a Poisson distribution which translates the study findings in terms of a probability of contamination. The application of this distribution towards the assessment of vulnerability in domestic wells is not well documented in the literature. The model also incorporates field data from preferential pathways, which are rarely considered in vulnerability assessment and had not been previously applied in domestic wells research. This simple model may help small municipalities to promote the importance of local groundwater monitoring and to effectively inform well owners about their well construction, the uniqueness of the local hydrogeological characteristics and the period of the year when their well may be more prone to contamination. This study has also contributed to increase of the knowledge and awareness of the 27 volunteers (well owners) regarding their well and water quality with the writing of reports addressing the water quality issues specific to their wells and recommendations to protect their source of drinking water.

1.2. Study sites

The development, feasibility and the applicability of the faulty seal detection method was investigated over three field seasons across Canada in the rural settings of Alberta, Ontario and Québec. The characterization of the groundwater quality and probabilistic model was specifically developed using the microbial and geochemical dataset obtained from the Municipality of Chelsea, Québec (site 3). This location was selected because of the availability of data on the occurrence of coliform bacteria over the Municipality, the willingness of volunteer well owners to participate in the study, the geological environment and the proximity to the University of Ottawa, which allowed for the collection of monthly samples for a period of 14 months.

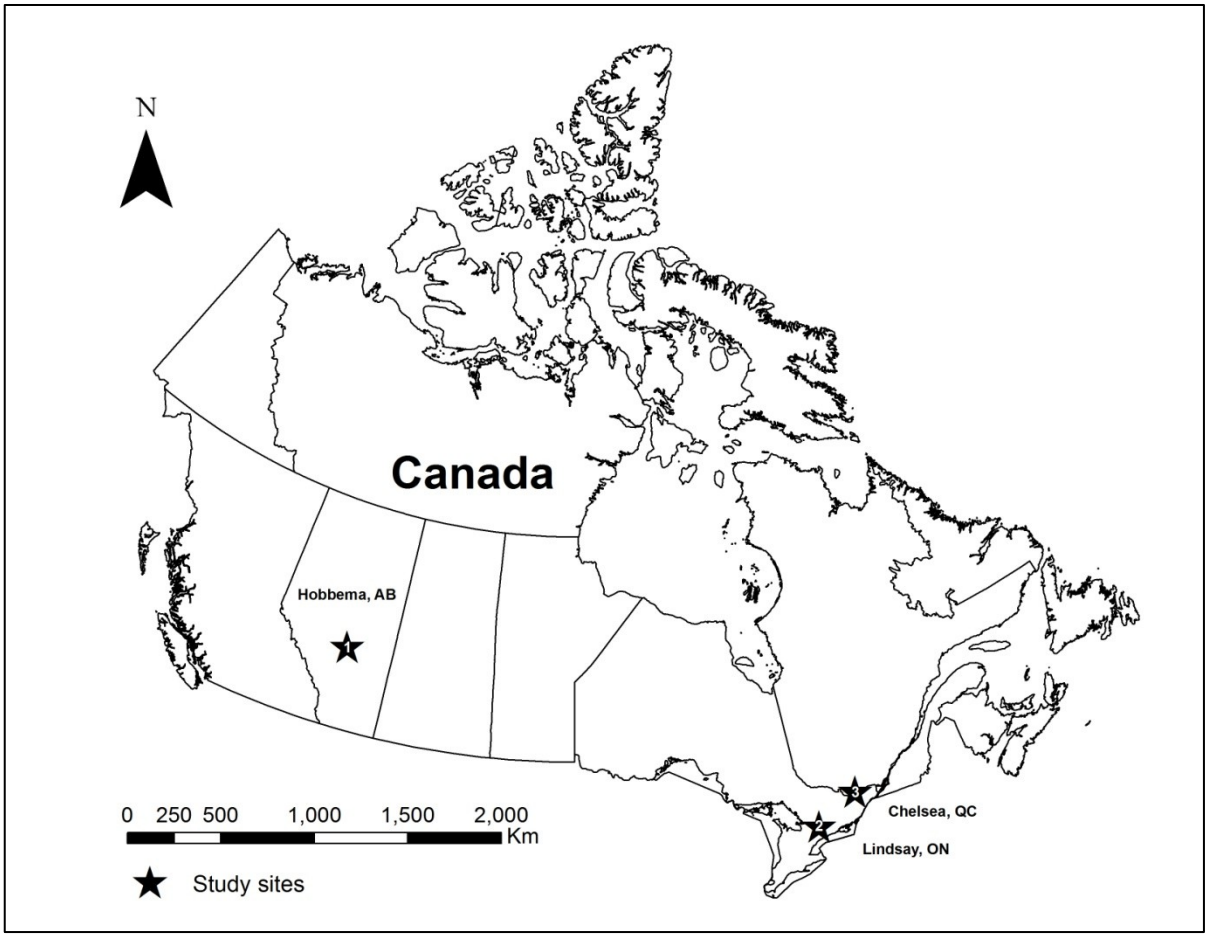


Figure 1.1: Geographic location of the study sites: site 1 is on the Hobbema First Nations Reserve (Alberta); site 2 is Lindsay (Ontario); and site 3 is Chelsea (Québec).

Hobbema First Nations, Alberta (Site 1)

The first summer of fieldwork tested four wells on the Hobbema First Nations Reserve, located between Edmonton and Red Deer, Alberta (Fig. 1.2). Limited information is available about the wells: the well logs are not obtainable for three of the four wells, and it is difficult to identify with certainty which aquifer supplies which well. Using an estimated depth of 50 m, the study wells are most likely drawing water from the Scollard Formation. This formation is approximately 100 m thick, and is composed of non-marine sandstones and mudstones. Surficial geology is composed mainly of till, sand and gravels (Ermineskin Tribal Enterprises, 2005).

Lindsay, Ontario (Site 2)

From June to August 2007, fieldwork was conducted on the Fleming College property in Lindsay, Ontario (Fig. 1.3). The surficial geology of the first 5 m consists of compact till, composed mainly of clay and silt (Bailey, personal communication, 2007). Underlying the till, karstic limestone is found from 5 to 6 m. The water table is located at a depth of approximately 5 m below the surface. Groundwater is flowing from northwest to southeast, towards the Scugog River.

Chelsea, Quebec (Site 3)

From April 2008 to May 2009, fieldwork was conducted in the Municipality of Chelsea, Québec. Figure 1.4 shows topographic elevations and locations of the sampling sites. Surface elevation ranges from 100 m (along Gatineau River) to 340 m (Precambrian hills). Most of the Municipality is located over the Canadian Shield, where the dominant bedrock geology consists of Precambrian crystalline igneous and metamorphic rocks (Fig. 1.5). The igneous rocks are composed mainly of syenite and monzonite whereas the metamorphic rocks consist of paragneiss, marble and quartzite (GSC, 2008). Bedrock frequently crops out in the study area. In the southern limits of the municipality, overlying the Precambrian bedrock are limestone and sandstone units of the Ordovician (Ottawa and Nepean formations). Main faults are oriented northwest-southeast and other structural lineaments (fold and faults) are east-west (Golder Associates, 1990). Most of the surficial deposits resulted from the last period of glacial melting, 12 000 years ago. In most areas, Precambrian bedrock is overlain by a thin veneer of till and/or glacio-fluvial deposits consisting of sand and pebbles, or thicker deposits of offshore marine silt and clay. These fine-grained marine units deposited from the Champlain Sea and are located along the Gatineau River and near the northern and southern boundaries of the municipality. The thickness of the surficial deposits varies from <1 (till on bedrock) up to 50 m (Champlain Sea deposits) (Golder Associates, 1990).

In fractured bedrock, the groundwater flow is mainly dictated by the topography and the direction of the fractures and joints (Boutt et al., 2010; Conboy and Goss, 2000; Novakowsky et al., 2006). In the municipality, the regional groundwater flow-trend is northwest to southeast, following the Gatineau River. Confining conditions (confined and

unconfined aquifers) are estimated from the surficial deposits map (Fig. 1.5). Clay and silt deposits provide an impermeable protective layer to the aquifer below. Aquifers under areas classified as offshore-marine deposits and landslide areas are therefore interpreted as confined. Even though some areas along the Gatineau River are classified as confined, the aquifer is thought to behave as semi-confined or unconfined because of the proximity to the recharge area. The areas covered by the other deposits (glaciofluvial sediments, organic deposits, till, Precambrian bedrock and near shore marine deposits) are not thought to be protected by an impermeable layer and the aquifer is defined as unconfined. The aquifer conditions are considered confined when the area was covered by the thick layer of silt and clay and unconfined where the surficial sediments were composed of till and glacio-fluvial deposits (Fig. 1.5).

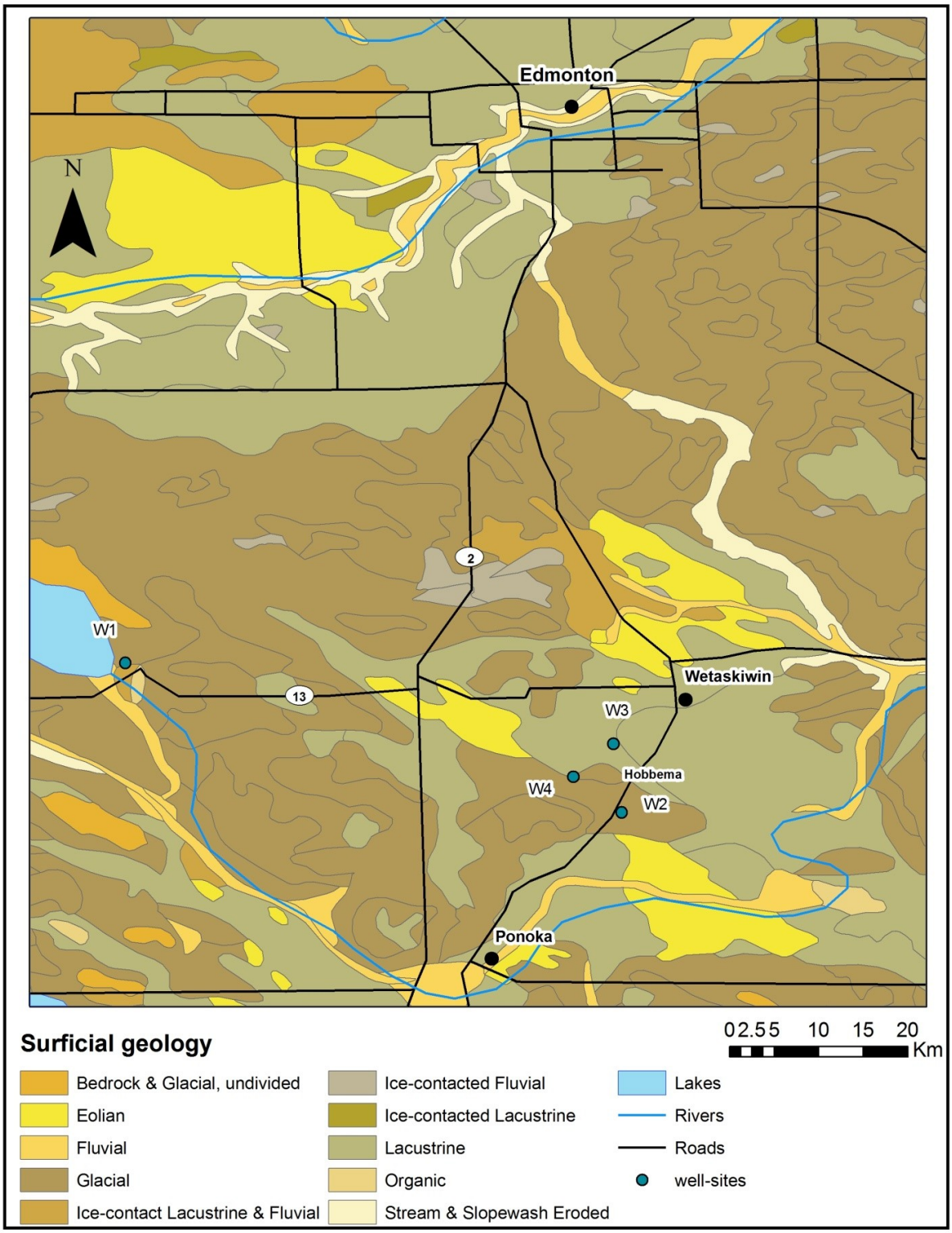


Figure 1.2: Surficial geology map of the Hobbema, Alberta are with locations of the four studied wells (Alberta Geological Survey, 2002).

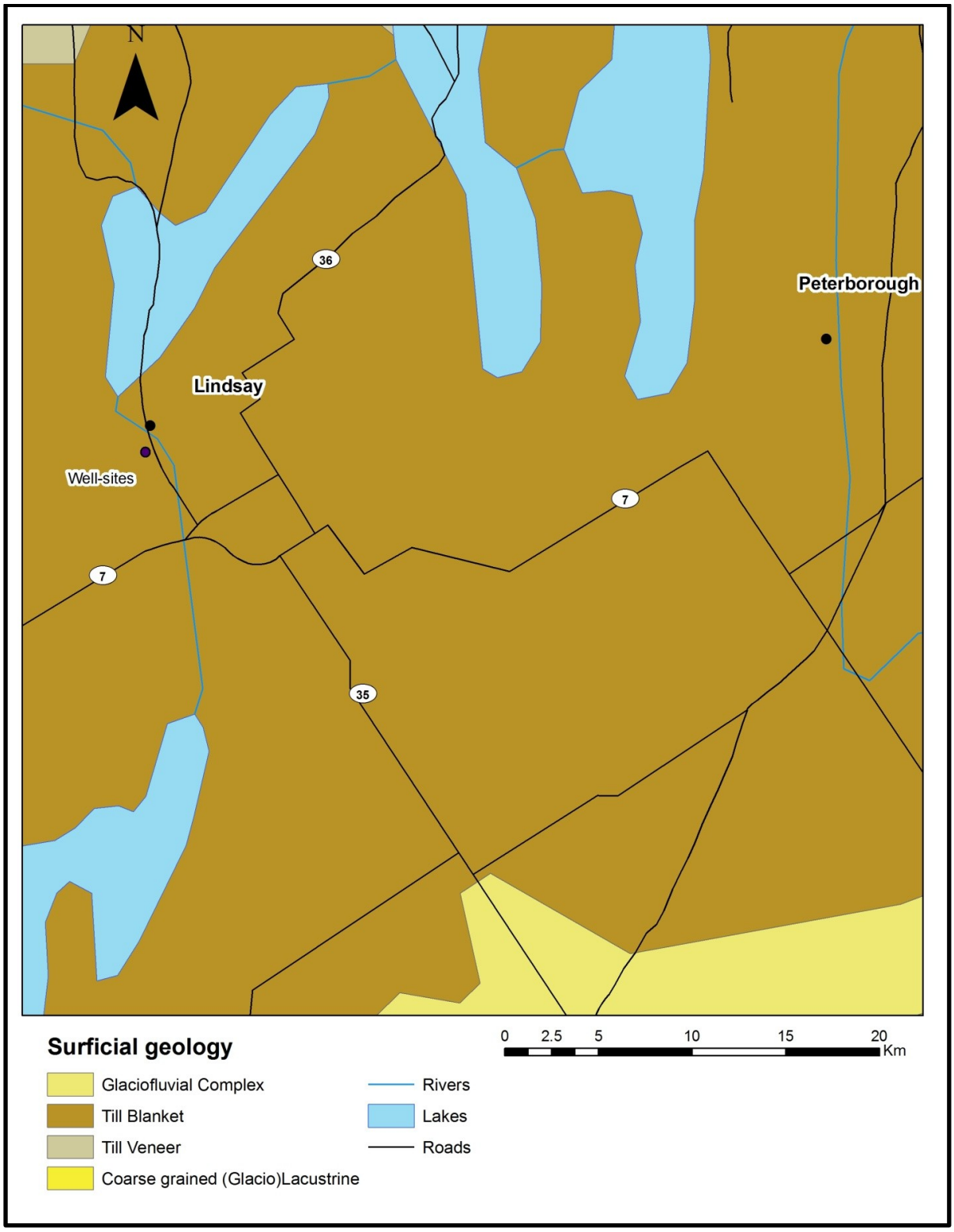


Figure 1.3: Surficial geology of the Peterborough, Ontario area with locations of the three studied wells (Geological Survey of Canada, Map1880A).

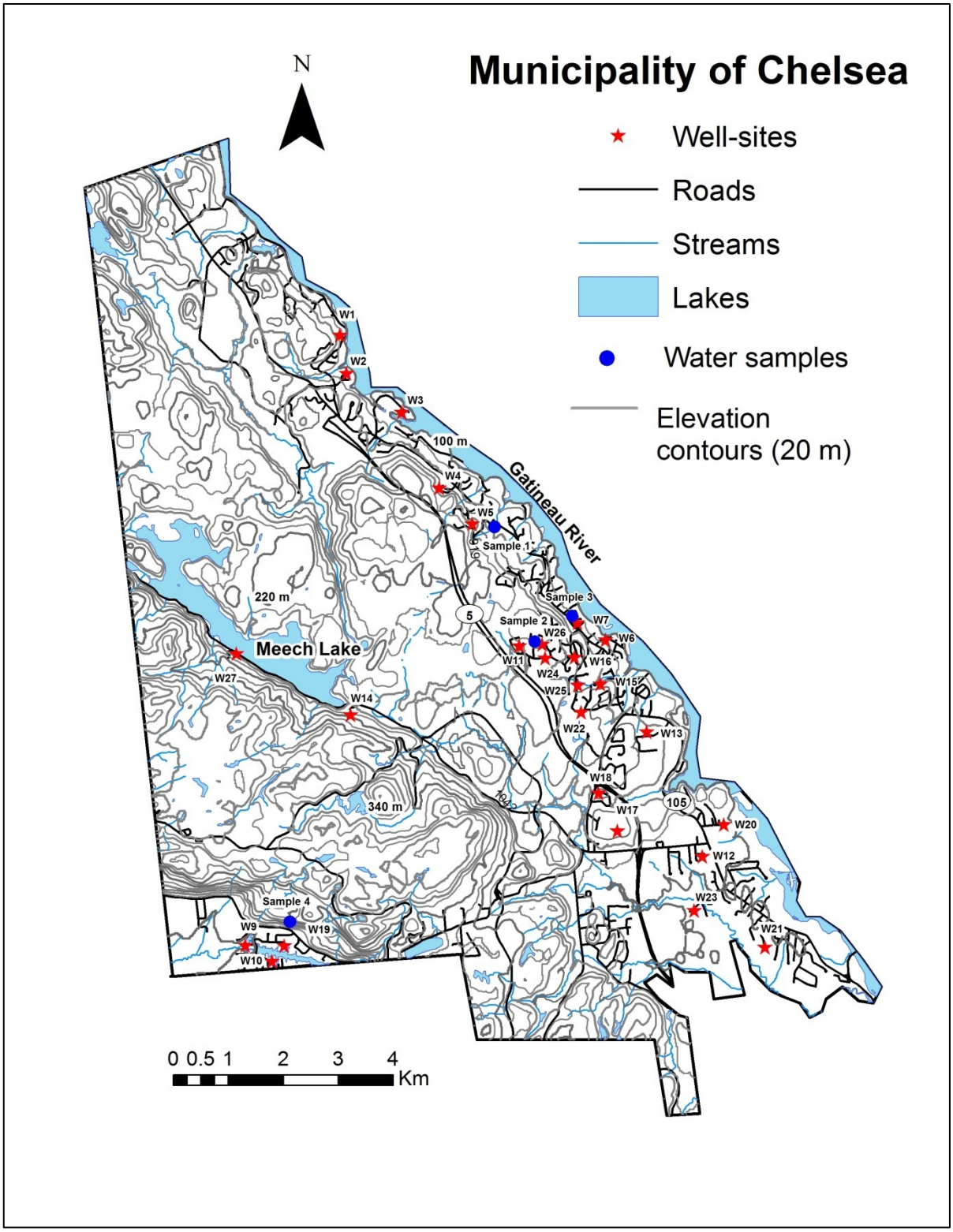


Figure 1.4: Study sites and sampling locations in Chelsea, Québec (site 3). Contour spacing is 20 m.

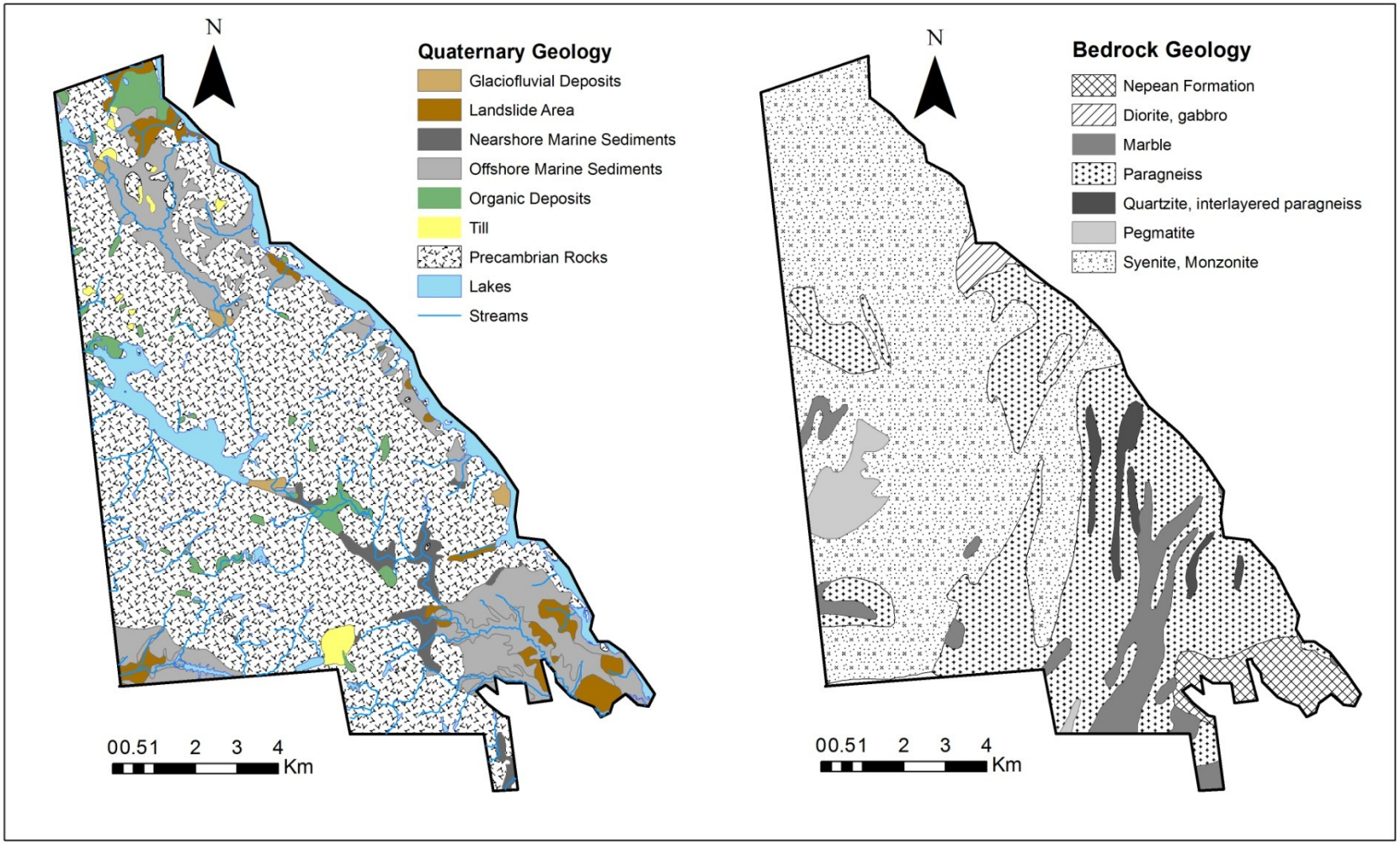


Figure 1.5: Surficial and bedrock geology of the Municipality of Chelsea (Geological Survey of Canada, 2008)

1.3. Groundwater quality

The groundwater quality in rural areas of Canada is affected by the presence of bacteria or chemicals that may cause contamination of domestic wells. Total coliforms (TC), faecal coliforms (FC) and Esherichia coli (*E.Coli)* are often used as bacteriological indicators to evaluate the quality of drinking water; however, many factors may contribute to bacterial contamination of domestic wells. These variables include: 1) well construction (well depth, type of well, age); 2) local environmental setting (soil thickness, surficial material, bedrock geology or proximity to a source of contamination); and/or 3) seasonal or temporal factors such as rainfall or temperature (Richardson et al., 2009). In most cases, it is difficult to determine if the presence of bacteria in the well-water results from natural processes (i.e. bacteria in the aquifer) or anthropogenic activities (i.e. poor well construction) (Zimmerman et al., 2001).

1.3.1. Faulty well seal

In confined and semi-confined aquifer systems, it is particularly important to insure a proper well seal at depth between the casing and the confining strata. Since the confining strata are a less permeable material that normally limits the movement of water between two aquifers, a preferential flow path created along the well, known as a hydraulic connection, may result in cross-contamination between aquifers even when the well is not pumped. When the well is pumped, however, water is drawn down from the upper aquifer by this hydraulic short-circuit, and the chemical composition of the lower aquifer water may be perturbed (Chesnaux and Chapuis, 2007). If the well seal integrity within the confining strata is compromised then the well head protection normally expected from the confining layers is also compromised at the well. Therefore, it is important to assess well seal integrity at depth.

A number of methods exist to evaluate the integrity of a well seal at depth. The methods range from the simple injection of a tracer into the water table (Meiri, 1989), to the analysis of recovery curves from pump tests (Chapuis and Chenaf, 1998). Chapuis and Sabourin (1989) showed that a falling head test is used to check if the seal of a monitoring well or a piezometer has been successfully installed. More recently, Chesnaux et al. (2006) were able to detect and characterize hydraulic short circuiting between aquifers by the injection of a tracer into a piezometer near a well, in the unconfined system, and by

recovering the tracer in pumped water. Step pumping tests are also performed to infer leakage, but the leakage may simply be indicative of the semi-permeable nature of the confining layer. While these techniques may detect faulty seals at depth, they are not used for well seals at, or near the ground surface, which is of equally great concern.

Another method, developed by Yesiller et al. (1997), is used along the entire length of a casing. This method employs a pulse-echo inspection technique using ultrasound to assess the integrity of annular seal at the outside surface of the casing. In essence, it consists of emitting ultrasounds at the interior wall of the casing and analyzing the reflected wave energy caused by the acoustic proprieties of the media touching the outside of the casing. Defective seals are detected by analyzing the difference in waveform. This technique has the advantage of detecting gaps between the casing and materials surrounding the casing without disturbing the immediate environment (seal, casing, and geological formation). However, it does not discriminate between the gaps that are hydraulically active and those that are not. The method will also not account for the possibility of grouts that swell upon wetting and shrink upon drying. Arguably, the main drawbacks are that the method requires that all piping and wires be removed from the well; that the data be processed by a highly qualified individual; and most importantly the required equipment is highly specialized and costly. These drawbacks make the technique impractical for routine detection of a large number of wells.

Glanville et al. (1998) also evaluated the integrity of the surface seal of shallow domestic wells. In their experiment, a sodium chloride (NaCl) solution was ponded over an 8-hour period around the casing of a pumping well and also of a nearby shallow monitoring well that was sealed with bentonite. Infiltration rates around the pumping well were then compared with the infiltration rates around the monitoring well. From these infiltration rates, the time of travel (TOT) through the soil was calculated and compared with the tracer arrival time, which represents the TOT through the potential preferential path. Three field trials were conducted. One trial was conclusive as the chloride concentration began to rise after 50 minutes, which indicated preferential flow of water. This was visually confirmed as water was seen seeping into the well after 15 minutes of tracer infiltration. The two others were less conclusive, either because the tracer reached the well within the TOT, or because the tracer was not found within the 8 hours of pumping. This methodology is fairly simple, but it does require the installation of monitoring equipment which can be costly and impractical in domestic applications.

Since the existing methodologies are not well-suited for private water wells, one of the objectives of this dissertation is to present a practical method to assess the integrity of a surface seal that is simple, inexpensive and arguably more applicable for routine investigations.

1.3.2. Bacterial contamination of domestic water wells

There are only a select number of studies that have focused on the influence of well characteristics and their impact on the contamination of water wells. For example, Goss et al. (1998) assessed the role of agricultural factors which affect groundwater quality and result in contamination. The study was based on approximately 1300 wells in Ontario and determined that 40% of wells exceeded the limit for one or more of the contaminants tested. From these contaminated wells 34% tested positive for bacteria, 14% for nitrate and 7% for both nitrate and bacteria. The study also identified that the type of well and well depth are important factors in the contamination of domestic wells. Also in Ontario, more comprehensive studies which examined a greater number of variables (Conboy and Goss, 1999; 2000) identified that one of the principal factors affecting contamination is well construction. Shallow dug or bored wells are constructed with a larger diameter of 0.6 to 2 m and are located in shallow soil with a high water table. Past construction practices may cause these wells to be prone to contamination from surface water due to deterioration of materials and lack of watertight annular sealants (Conboy and Smith, 2005). Conversely, drilled wells are generally smaller in diameter (0.06 to 0.15 m), and have a watertight casing. Because they are deeper, drilled wells have many layers of porous media which offers protection against direct infiltration of surface water into the well water column and thus, are less vulnerable to contamination compared to shallow bored wells. Conboy and Goss (2000) also found that for drilled wells in rural areas, surface water drainage toward the well, surficial geology and the first 9 m stratigraphy contribute to “unique information” in predicting differences in contamination between wells. In this context, “unique information” is information that is most predictive of the likelihood of a well to be contaminated. However, contamination of a drilled well will occur if the well is poorly constructed.

The variables related to the well construction include the type of well, well depth, length of the casing, presence of grout in the annular space and the installation of a proper sealed cap to prevent insects from entering the wellhead. Overall, shallower wells tend to

be more vulnerable to contamination (Goss et al., 1998; Conboy and Goss, 1999; Conboy and Goss 2000; Simpson, 2004) with Gonzales (2008) suggesting that the risk of bacterial contamination is higher if the well is less than 61 m deep. Zimmerman et al. (2001) looked at the effect of grouting the annular space on the occurrence of bacterial contamination in Pennsylvania, USA. They found that total coliforms were just as likely to be found in a grouted well as in a non-grouted well; however, *E.Coli* was more likely to be detected in non-grouted well. The authors also demonstrated that wells drilled into carbonate bedrock have a higher percentage of contamination and presence of *E.Coli* than wells drilled into non-carbonate bedrock. Also in Pennslyvania, Swistock and Sharpe (2005) evaluated the impact of large-scale aquifer contamination versus poor wellhead construction contamination. The study examined the incidence of contamination in drilled wells with grouted seals where insect-proof caps had been installed, after disinfecting the well. The results showed that installing a proper well cap was effective in a well having small counts of total coliforms and absence of *E.Coli*, but only for a short period after the installation. After one year, few wells remained free of bacterial contamination. The results also demonstrated that wells in carbonate bedrock are more vulnerable to the presence of bacteria than wells in non-carbonate settings corroborating the previous work by Zimmerman et al. (2001). The results from both studies suggest that direct contamination from the wellhead area appeared to be less important than the contamination occurring from the large-scale aquifer system.

Another aspect in the contamination of domestic wells involves the transport of bacteria into the water column. Bacteria are naturally present in surface water and soil and are transported to the groundwater system by infiltration processes (Conboy and Goss, 1999; Simpson, 2004). Different factors affect bacterial movement in soil such as the bacteria characteristics (type, size and population dynamic) or the soil properties (chemical, biological and physical) (Taylor et al., 2004). Usually, most of the bacteria are filtered through the upper soil profile, but water is able to transport bacteria deeper using larger pore structures (Conboy and Smith, 2005). These structures, called macro-pores, result from numerous processes, including earthworm movement, decayed roots, cracks in clayey soil or a bedrock fracture network. Macropores affect the efficiency of the soil to filter bacteria allowing them to travel deeper and faster (Cey et al., 2009). The soil cover usually offers natural protection against contamination by bacteria (Conboy and Goss, 2000), however, many bedrock aquifers are vulnerable to contamination because of a thin layer of

overburden (Levison and Novakowsky, 2009; Pronk et al., 2006). Consequently, the infiltrating water reaches the aquifer without significant filtration. Fractures in the bedrock also act as macro-pores and enhance the transport of surficial contamination.

1.3.3. Groundwater characterization

Water-rock interaction and dissolution processes are the main natural contributors to the chemical composition of groundwater (Tóth, 1999). Groundwater quality is also influenced by anthropogenic activities, such as agriculture, industry and residential development. Within the municipality of Chelsea, agricultural activity is relatively minor and is not thought to significantly impact groundwater quality. The primary anthropogenic sources are septic effluents, residential use of fertilizers and application of road salts on the nearby provincial highway. Previous work in the region is restricted to a report by Golder Associates (1990) which suggests that water samples in the various geological units have low alkalinity and hardness, with a relatively low Cl^- concentration (<10 mg/L). This overall paucity of comprehensive investigations in the region means there is little certainty with regards to the processes controlling the groundwater chemistry and evolution, and the impact of anthropogenic activities on the groundwater system.

Hydrogeochemical indices are used to ascertain the possible chemical reactions in the groundwater system, to characterize the groundwater evolution and to assess the possible impact of anthropogenic activities in the Chelsea, Québec. A piper diagram (Piper, 1944) is a graphical tool used to identify the main hydrogeochemical facies of the water by displaying the relative concentration of major anions and cations on trilinear plots. The points on the trilinear plot are projected on the central diamonds plot which is used to define the overall facies of the water (Güler et al., 2002). The major-ion chemistry of the groundwater in the Municipality of Chelsea is characterized using Piper diagrams. A classification of the wells based on hydrogeochemical facies is used to assist in the identification of the processes contributing to groundwater chemistry

In addition to graphical methods, multivariate analysis has been widely used for interpreting groundwater quality data in order to identify underlying factors controlling hydrogeological processes and to evaluate surface and groundwater interactions (Jiang et al., 2009; Menció and Mas-Pla, 2008; Valdes et al., 2007). Principal component analysis (PCA) and hierarchical cluster analysis (HCA) are the most commonly used multivariate

analysis techniques to understand and characterize groundwater processes (Litaor et al., 2010).

Principal component analysis (PCA) is a mathematical technique which consists of reducing the complexity of large datasets by determining new variables that account for the greater variance in the original variables (Davis, 2002; Jolliffe, 2002). The new variables reveal the simple underlying structure that is assumed to exist within a dataset and are known as principal (PC) components (Davis, 2002). PCA concentrates on the variance between the original variables and the first step in the analysis is to compute the variance-covariance matrix, or correlation matrix. The correlation matrix treats all variables as equal, whereas the covariance matrix is appropriate if all measurements are in the same unit, but will give more weight to larger and more variable measurements (Jolliffe, 2002). The matrix, which is an array of coefficients for all possible pair of variables, is symmetrical. The principal components are eigenvectors of the matrix which are orthogonal, uncorrelated and represent a weighted linear combination of the original variables. The original variables are transformed by diagonalization of the covariance or correlation matrix (Menció and Mas-Pla, 2008) to create the PC. The eigenvalues are a measure of the variance associated with each PC; the loadings represent the participation of the original variance whereas the combinations of PC loadings on the individual samples are called scores (Davis, 2002). The first component accounts for the greatest fraction of the variance which explains the largest amount of information in the dataset followed by each subsequent component explaining less information. A positive loading demonstrates a direct relationship between the component and the variable. The influence of the variable on the component is evaluated based on the absolute value of the loading, whereas the greatest influence is exerted by the strongest value. Plots of the PC scores are used to identify similarities and discrepancies between the samples, because samples with similar influencing processes will have the tendency to group together, whereas independent processes are identified by unrelated samples.

Hierarchical cluster analysis (HCA) is a data classification technique that assembles observations into more or less homogenous groups, distinct from other groups (Davis, 2002). There are many clustering techniques, but the hierarchical cluster analysis (HCA) which first merges the most similar observations then successively connects the next most similar to the first pair, is the most widely used in Earth Sciences (Davis, 2002) and in the classification of hydrogeochemical data (Cloutier et al., 2008, Güler et al., 2002). The first

step in the cluster analysis is to measure a distance between every pair of samples and then, to quantify the distance which identifies the cluster (Fowler et al., 1998). The distance between samples is used as a measure of similarity and to form clusters. A commonly used method to calculate the distance coefficient is the standardized Euclidian distance (Davis, 2002). Many linkage rules such as the complete linkage, single linkage, average, Centroid and the Ward's method are available, each with a different basis for merging into clusters (Fowler et al., 1998). The Ward's method uses the analysis of variance approach to evaluate the distance between clusters to minimize the within cluster sum of square (Davis, 2002; Fowler et al., 1998). Some studies found that the combination of the Euclidian distance with the Ward's linkage rule is a powerful tool to produce distinctive clusters (Güler et al., 2002; Cloutier et al. 2008; Menció and Mas-Pla, 2008).

Multivariate statistical analysis techniques have been shown to be a powerful tool in groundwater characterization and environmental studies. For instance, PCA has been successfully used by Cloutier et al. (2008) to identify processes controlling groundwater evolution of the Basses-Laurentides (Quebec, Canada) geographical region. The authors found that the integration of the classification method was useful and helped in refining the interpretation of the hydrogeochemical evolution of the groundwater system. Factor analysis has also been used by Jiang et al. (2009) to evaluate variables affecting groundwater quality in a karst underground river system in China. The factor analysis revealed that both natural and anthropogenic processes contributed to the groundwater quality, with the most important role played by human activities. PCA, in conjunction with HCA, was used to evaluate the origin of surface water and its interaction with groundwater (Menció and Mas-Pla, 2008). The joint analysis supported the hydrological observations and also characterized the significance of the interactions between streams and aquifers. To the author's knowledge, multivariate statistical studies combining microbial and geochemical data to assess groundwater quality are rare. For example, Korkka-Niemi (2005) evaluated the groundwater quality in domestic wells in Finland with PCA, and demonstrated that five factors contributed to the groundwater quality with extra-regional controls (geology, marine influence) as the strongest modifiers and site-specific factors (contamination, land uses, well construction, recharge) as a minor contributor on groundwater quality. The various studies demonstrate that the use of PCA and HCA assist in the determination of extra-regional, regional or local origins of the components, providing insight into the different variables controlling the hydrological processes.

1.3.4. Concept of well vulnerability

Groundwater vulnerability has become an important concept in assessing the risk of contaminating a groundwater resource (Worrall, 2005). The definitions of groundwater vulnerability and susceptibility are used interchangeably, depending on the author (Frind et al., 2006). For example, the USA Environmental Protection Agency (1993) defined the concept of "intrinsic susceptibility" based on the hydrogeological characteristics on the aquifer only, which was defined as "intrinsic vulnerability" by Vrba and Zoporozec (1994). In both cases, the definition does not consider the land use and the characteristics of the source (type of contaminant and loading). The National Research Council (1993) defined groundwater vulnerability as the likelihood of a contaminant to reach the aquifer system after its introduction at the surface; and the "specific vulnerability" refers to a particular type of contaminant whereas "intrinsic vulnerability" refers to any contaminant in general. Focazio et al. (2002) defined the vulnerability to contamination as an integration of the intrinsic properties of an aquifer (physical properties and flow system) as well as the characteristic of the source, the well location and the fate and transport of the contaminant. Within this Ph.D. dissertation the concept of groundwater vulnerability is defined as the ease with which water from the surface reaches an aquifer system (or a well), based on the intrinsic properties of the groundwater flow system, independent of the characteristic of the contaminant. This definition is selected because it recognizes that the vulnerability depends on the characteristics of the well-site, independent of the nature of the contaminant (Worrall, 2005).

Three main approaches are commonly used to evaluate vulnerability (NRC, 1993; Zhang et al., 1996). First, index methods such as DRASTIC (Aller et al., 1987) consist of overlaying various physical attributes of the system using GIS to produce vulnerability maps. These methods are relatively easy to implement, however, weighting factors are often arbitrarily selected and based on an expert opinion (Frind et al., 2006; Worrall, 2005). These methods are not based on observations or measurements and some studies (e.g., Frind et al., 2006) demonstrate that different methods applied to the same system yield different results. Moreover, the indices have to be interpreted against subjective classification schemes which are difficult to assess in the decision making process (Worrall, 2005). As a result, index overlay methods have been criticized by many authors (Frind et al., 2006). The second approach uses physical models to approximate contaminant transport. These tools are powerful, but a proper understanding of the groundwater system

is critical (Twarakavi and Kaluarachchi, 2005) and these data are not always available for a region or are costly to obtain. The last approach uses statistics to estimate the vulnerability occurrence based on the characteristics of the site. These methods have an advantage in their ability to accommodate for data uncertainty and provide a probability of occurrence (Twarakavi and Kaluarachchi, 2005; Worrall, 2005), which is helpful in the decision making process. Vulnerability assessment models are also characterized based on the source of the data and inputs: knowledge-driven models such as DRASTIC based on expert opinion whereas data-driven models are based on measured observations.

The first step in this dissertation is to demonstrate the association between the characteristics of the well-site, water chemistry and bacterial contamination. The applicability of logistic regression (LR) and weight-of evidence (WofE) as stochastic vulnerability assessment tools are first evaluated followed by the potential of a simple Poisson distribution to translate the study findings in terms of a probability of contamination. The model will attempt to answer simple questions that residential owners may have regarding spatial, temporal or site-specific characteristics that may increase the risk of contamination their drilled well.

1.4. Thesis organization

This Ph.D. thesis is organized in four main chapters, each as a standalone paper intended for publication in the near future. Chapter 2 outlines the faulty seal detection method, the results of the three field seasons, and a qualification of the relative importance of the well construction compared to the local environmental settings. Chapter 3 provides a general description of the bacterial and chemical groundwater quality in Chelsea, Québec with spatial identification of natural and anthropogenic contributors to the aquifer system. Chapter 4 expands on Chapter 3 with an examination of the seasonal variability of the water quality and outlines specific factors affecting the quality of the groundwater in Chelsea such as the effect of precipitation. Chapter 5 integrates the findings from the previous three chapters and presents the probabilistic model combining the effect of well construction and local environmental settings in the contamination of private water wells. A brief summary of the overall dissertation conclusions is presented in Chapter 6. Appendix A presents a summary report of the fieldwork conducted in Alberta provided to Health Canada, the funding agency for the project. Appendix B presents the first step in the development of a

retrofitting method for faulty well seals and the data collected during the fieldwork in Lindsay, Ontario. Appendix C contains individual well owner reports with a summary of the work performed, specific conclusions for their site and some suggestions on simple actions to maintain and improve water quality in their well. Additional data associated with chapter 4 are presented in appendix D.

1.5. Statement of contribution

The faulty seal detection method is the product of approximately 8 months of fieldwork over the summers of 2006 to 2008. Mudher Al-Kafaji (2006), Courtenay Brown (2007) and Christopher Moody (2008) provided field support by assisting and performing the various steps of the method.

The second component of the project involved monthly sampling at the 27 selected sites in Chelsea, Québec. The groundwater sampling in the municipality of Chelsea took place from April 2008 to May 2009. Both bacteria and geochemical water samples were collected monthly by the volunteer well owners following directions provided by the author. The samples were titrated, filtered and diluted by the author with assistance provided by Christopher Moody and Lisa Nikmo. At the University of Ottawa, the samples were analyzed for major cations and anions by Ping Zhang using ICP-AES and ions chromatography, respectively. The bacterial analyses were performed by the ACCUTEST laboratory staff, located in Ottawa, Ontario.

Chapters 2, 3, 4, 5 and 6, and Appendices A, B, and C were written by the author with assistance in the development of concepts and text editing by Dr. Michel J.L Robin (supervisor). Additional input for Chapters 2 and 3 was provided by Dr. Mary Jane Conboy. All graphic images were drafted by the author except where indicated by the original publication. Maps were drawn by the author with the ArcGIS software (9.2) from online government digital shapefiles on *Geogratis* (Natural Resources Canada), *Urban Geology of the Capital National Area* (Geological Survey of Canada) and Alberta Geological Survey.

Primary funding for this project was provided by a grant from Health Canada (Northern and Indian Affairs) to Dr. Michel Robin. Additional funding to the author was provided through University of Ottawa scholarships, the Natural Sciences and Engineering

Research Council of Canada (NSERC) and the “Fond Québécois en Resources Naturelles et Technologies” (FQRNT).

Chapter 2: Detection of faulty domestic well seals using hydraulic conductivity measurement and tracer test analysis

2.1. Introduction

Contamination of groundwater supply by pathogens occurs in a number of ways, but the main cause is thought to be via preferential flow through direct pathways from the ground surface to the aquifer (Novakowski et al., 2006). Preferential flow paths allow rapid movement of water and contaminants carried with rapidly infiltrating water to deep groundwater systems, without filtration through the soil (Cey et al., 2006). Preferential flow paths include root channels, bioturbation and other naturally present soil structures such as cracks in clayey soil. One of the most obvious anthropogenic preferential flow paths is along the well casing of poorly sealed wells (Simpson, 2004). When a well is constructed, a hole is drilled and a smaller casing installed. The casing, usually a steel pipe around 0.15 m in diameter, extends from the ground surface to the aquifer in sand or gravel; or to the depth where solid bedrock is encountered in a rock aquifer. During well construction, the annular space between the surrounding geologic material and the well casing must be sealed with a low permeability material. This provides protection against direct infiltration of surface water leading to contamination from the surface, and minimizes the vertical migration of water in the annular space (Dunnivant et al., 1997). Surface water is an issue because it may contain bacteria and pathogens. Even when properly installed during construction, the well seal tends to deteriorate over time, again providing a preferential flow path for surface water. The seal is an integral part of well construction and one that was commonly neglected in past water-well drilling practices, because the protection offered by an adequate seal was not understood (Novakowski et al., 2006).

In the past, the annular space was thought to be sufficiently sealed by the emplacement of drill cuttings which are small pieces of rock and soil created during the drilling process. At times, the seal would appear adequate at the surface, but poor at depth because cuttings bridge or leave large voids during emplacement. This resulted in preferential pathways along the casing that allowed surface water to enter into the well at the bottom of the casing, potentially causing contamination. Current regulations recognize that using cuttings to seal the area around the well is inadequate and there are restrictions on the use of cuttings to backfill the annular space. In the Province of Ontario, for example,

the annular space of the well must be made at least 0.076 m wider than the well casing to a minimum depth of 6 m. This space must be completely filled with a suitable sealant, such as bentonite (Ontario Ministry of the Environment, 2003). Figure 2.1 illustrates the difference between an efficient seal and faulty seal. An efficient seal forces the infiltrating water through the surrounding soil allowing contaminants to be sorbed or biodegraded, thereby reducing the potential for contamination. Once a well is constructed, it is difficult to verify if the seal was properly installed. The purpose of this work is to provide a simple diagnostic method to detect poorly sealed wells.

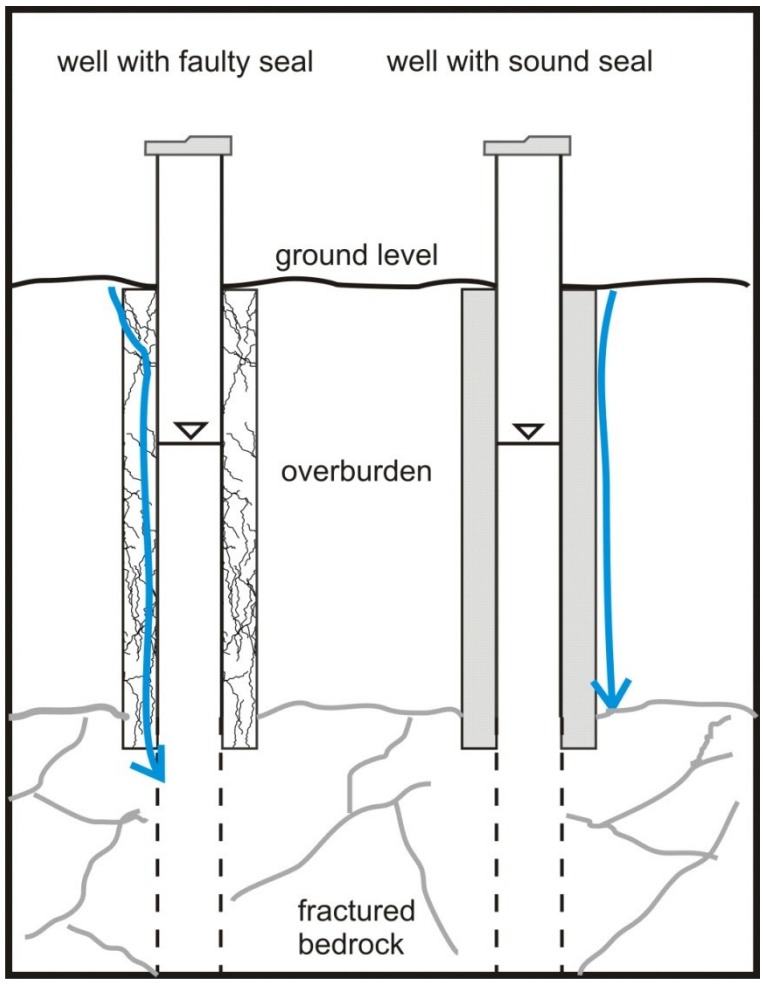


Figure 2.1: The left-hand side of the figure illustrates a rapid preferential pathway along the well casing in a faulty-seal situation; while the right-hand side illustrates that an sound well seal forces infiltrating water to slowly percolate away from the casing through the soil, thereby providing protection to the well.

2.2. Background

In confined and semi-confined systems, it is particularly important to insure a proper seal at depth between the casing and the confining strata. Since the confining strata are a less permeable material that normally limits the movement of water between two aquifers, a preferential flow path created along the well, known as a hydraulic short circuit, results in cross-contamination between aquifers even when the well is not pumped. When the well is pumped, however, water is drawn down from the upper aquifer through the faulty seal, and the chemical composition of the lower aquifer water may be perturbed (Chesnaux and Chapuis, 2007). If the well seal integrity of the confining strata is compromised then the well head protection normally expected from the confining layers is also compromised at the well. It is therefore important to assess well seal integrity at depth.

A number of methods exist to evaluate the integrity of well seal at depth. The methods range from the simple injection of a tracer into the water table (Meiri, 1989), to the analysis of recovery curves from pump tests (Chapuis and Chenaf, 1998). Chapuis and Sabourin (1989) demonstrated that a variable head permeability test is also used to check if the seal of a monitoring well or a piezometer has been successfully installed. The variable head permeability test detected a piezometric error (i.e. hydraulic perturbation induced by preferential seepage) that is related to the properties of the leakage zone. More recently, Chesnaux et al. (2006) were able to detect and characterize hydraulic short circuiting between aquifers by the injection of a tracer into a piezometer near a well in an unconfined system, and by recovering the tracer in pumping water. Step pumping tests are also performed to infer leakage but the leakage may simply be indicative of the semi-permeable nature of the confining layer. While these techniques may detect faulty seals at depth, they are not used for well seal at, or near the ground surface, which is of equally great concern.

Another method, developed by Yesiller et al. (1997), is used along the entire length of a casing. This method employs a pulse-echo inspection technique using ultrasound to assess the integrity of annular seal at the outside surface of the casing. In essence, it consists of emitting ultrasounds at the interior wall of the casing and analyzing the reflected wave energy caused by the acoustic proprieties of the media touching the outside of the casing. The method analyses the waveforms and uses the difference between them to infer intact or defective seals (Yesiller et al., 1997). This technique has the advantage of detecting gaps between the casing and materials surrounding the casing without disturbing the immediate environment (seal, casing, and geological formation). However, it does not

discriminate between the gaps that are hydraulically active and those that are not. The method will also not account for the possibility of grouts that swell upon wetting and shrink upon drying. Arguably, the main drawbacks are that the method requires that all piping and wires be removed from the well; that the data be processed by a highly qualified individual; and most importantly the required equipment is highly specialized and costly. These drawbacks make the technique impractical for routine detection of a large number of wells.

Glanville et al. (1998) evaluated the integrity of the surface seal of shallow domestic wells. In their experiment, a sodium chloride (NaCl) solution was ponded over an 8-hour period around the casing of a pumping well and also of a nearby shallow monitoring well that was sealed with bentonite. Infiltration rates around the pumping well were then compared with the infiltration rates around the monitoring well. From these infiltration rates, time of travel (TOT) through the soil was calculated and compared with the tracer arrival time, which represents the TOT through the potential preferential path. Three field trials were conducted. One trial was conclusive as the chloride concentrations began to rise after 50 minutes, which indicated preferential flow of water. This was visually confirmed as water was seen seeping into the well after 15 minutes of tracer infiltration. The two others were less conclusive either because the tracer reached the well within the TOT or because the tracer was not found within the 8 hours of pumping. This methodology is fairly simple, but it does require the installation of monitoring equipment which is costly and impractical for domestic application.

Since the existing methodologies are not well-suited for private water wells, the objective of this paper is to present a practical method to assess the integrity of a surface seal that is simple, inexpensive and arguably more applicable for routine investigations. Such a technique will also help evaluate the relative importance of faulty seals as preferential pathways in private water well contamination.

2.3. Study Areas

The feasibility and the applicability in different geological settings of this detection technique were investigated in three separate regions of Canada from 2006 to 2008. This section describes the general geological settings of the three study areas, whereas specific details regarding local geology are provided in the “Results” section. The locations of the study sites are shown in Figure 2.2.

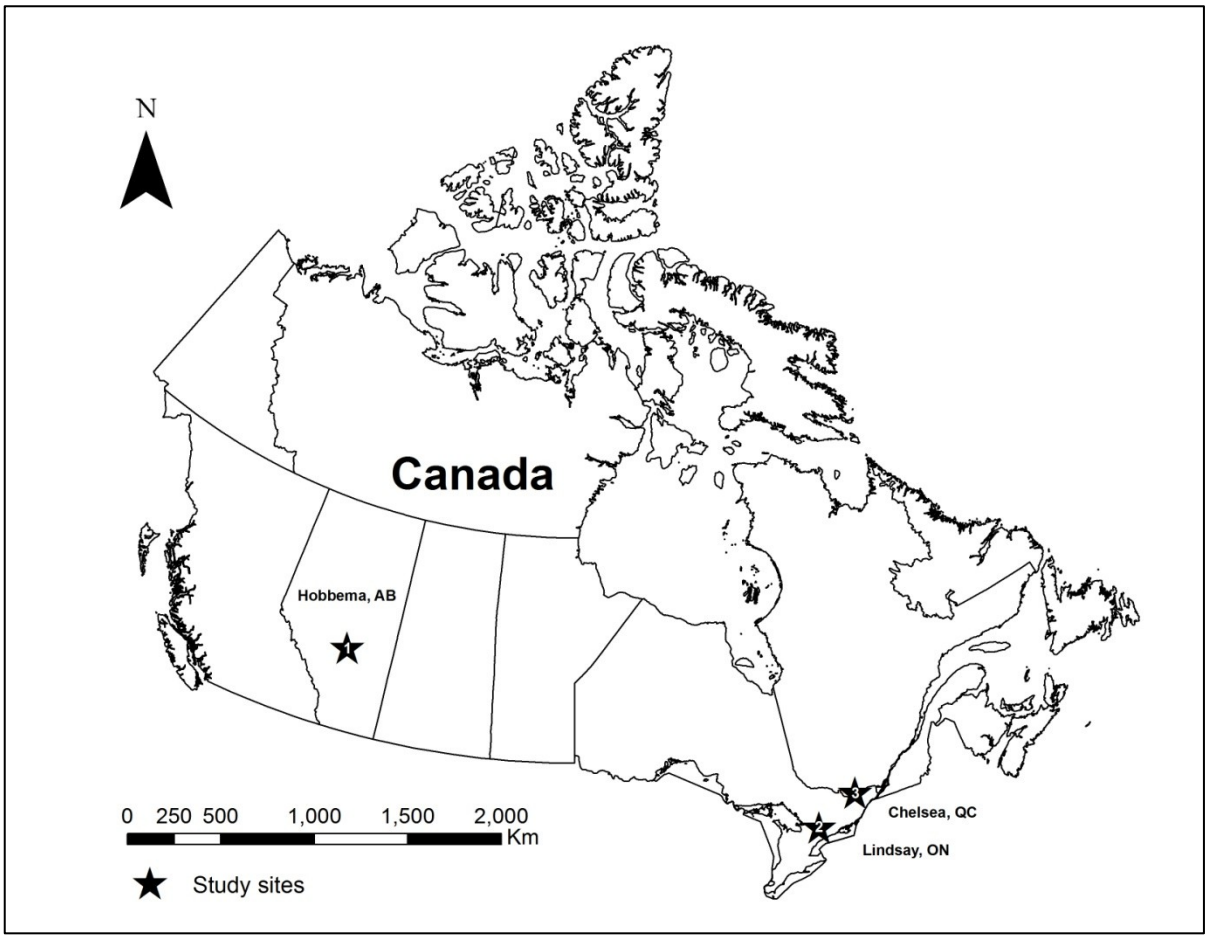


Figure 2.2: Geographic location of the study sites. The wells at site 1 are located on the Hobbema First Nations Reserve (Alberta), the wells at site 2 are located in Lindsay (Ontario) and the wells at site 3 are located in Chelsea (Québec).

2.3.1. Hobbema First Nations, Alberta (Site 1)

The Hobbema First Nations Reserve is located between Edmonton and Red Deer, Alberta. Limited information is available about the wells: the well logs are not obtainable for three of the four wells, and it is difficult to identify with confidence the aquifer supplying the wells. Using an estimated depth of 50 m, the study wells are most likely drawing water from the Scollard Formation. This formation is approximately 100 m thick, and is composed of non-marine sandstones and mudstones. Surficial geology is mainly composed of till, sand and gravels (Ermineskin Tribal Enterprises, 2005).

2.3.2. Lindsay, Ontario (Site 2)

This fieldwork was conducted on the Fleming College property in Lindsay, Ontario. The surficial geology of the first 5 m consists of compact till, mainly composed of clay and silt (Bailey, personal communication, 2007). Underlying the till, karstic limestone is found from 5 to 6 m. The water table is located at a depth of approximately 5 m below the surface. Groundwater is flowing from northwest to southeast, towards the Scugog River.

2.3.3. Chelsea, Quebec (Site 3)

Chelsea is a small rural community in Québec, located north of Ottawa. Most of the Municipality is underlain by the Precambrian bedrock of the Canadian Shield. The Precambrian bedrock is composed of igneous and metamorphic rocks. The surficial deposits vary in thickness over the territory and originate from the last period of glacial melting, 12 000 years ago. Groundwater flows regionally from the northwest to southeast, towards the Gatineau River. Locally, groundwater flow follows topography (Golder Associates, 1990).

2.4. Methodology

The procedure for testing seal integrity is based on the single ring infiltrometer approach developed in soil science for measuring vertical hydraulic conductivity. Briefly, the method consists of inserting a cylinder (the infiltrometer ring) into the soil and measuring the rate at which water infiltrates while maintaining a constant water level inside the cylinder. The constant head, single ring infiltrometer technique is described in detail by Reynolds (1993, 2007). The technique described by Reynolds (1993, 2007) is used to calculate the near-surface vertical hydraulic conductivity, K, based on the infiltration rate at steady-state and on the geometry of the system.

2.4.1. Hydraulic conductivity measurements

At each well site, single-ring infiltrometer tests were performed at the well using a large-ring infiltrometer and in the vicinity of the well, using small ring infiltrometers. The smaller rings were used because they are more practical: they utilize less water and, because a number of them are installed and operated simultaneously, they are therefore more time-efficient. Field tests show that the two ring sizes used in the study produce equivalent results within experimental error. The next sections describe the details of the infiltrometer tests around the well and the small ring infiltrometer tests. Figure 2.3a and b shows the overall system around the well using either a float-valve system or a Mariotte siphon system, while Figure 2.3c illustrates the small ring infiltrometers tests in the vicinity using a Mariotte siphon system.

2.4.1.1. Large ring infiltrometer tests

Two different sizes of large-ring infiltrometers were used during fieldwork. One large infiltrometer ring used for testing at the well was an open-ended cylinder cut from the wall of a large PVC barrel. It had an interior diameter of 0.66 m, wall thickness of approximately 0.01 m and had a height of the cylinder of 0.38 m. The other large-ring infiltrometer was made of stainless steel with a beveled lip at the base of the cylinder which facilitated insertion into the ground. It had an interior diameter of 0.405 m, wall thickness of approximately 0.003 m and had a height of 0.305 m. The large-ring infiltrometer was positioned on the ground with the well at its center. Prior to inserting the ring, and only when necessary, a shovel or a trowel was used to clear the ground surface around the well at the perimeter of the ring in order to facilitate ring insertion. This ensures a good seal between the ring and the soil. The soil surface was not altered to preserve the hydraulic proprieties of the soil (Reynolds, 1993). The ring was inserted by tapping with a sledge hammer against a plank of wood that was moved around the circumference. The ring was kept as level as possible (using a carpenter's level) during the insertion process. After ring insertion, the surface of the soil was compacted against the ring wall on the outside of the ring to minimize the possibility of "short-circuit" flow along the wall of the ring. The depth of penetration of the ring was then measured and averaged around the circumference. Typical ring depths of penetration varied from 0.035 to 0.065 m depending on the site and the ease of the ring insertion.

The water level was maintained constant inside the infiltrometer either by using a float valve system or a Mariotte siphon system. The float valve system (Fig. 2.3a) consists of two parts. The first part is a conical stopper made of flexible rubber that is glued to the top side of a piece of Styrofoam to ensure flotation. As the water level rises in the infiltrometer ring, the Styrofoam floats up and pushes the rubber stopper against the adapted outlet of a garden hose, thereby sealing the garden hose. The second part of the mechanism is the adapted hose outlet. It consists of a horizontal Plexiglas plate with two aluminum prongs (one at each end) that are inserted into the ground. A garden hose is attached to the top of the Plexiglas plate at the centre and connected through the plate to a machined Plexiglas fitting into which the rubber stopper fits snugly. The prongs hold the garden hose in place and force the Styrofoam to move up and down vertically to improve the seal against the outlet. The other end of the garden hose is connected to a valve attached to the bottom of a 190 L plastic barrel that is filled with the infiltration solution (NaCl tracer or water). The barrel was calibrated and the difference in the water level in the barrel is used to measure the flow rate. For high flow rates, two or more barrels are connected hydraulically through one or more siphons. While the hydraulic head in the barrel decreases as it empties, a constant head is maintained in the infiltrometer by the float valve. Figure 2.3b shows the overall system around the well using the Mariotte siphon system.

Different types of measurements were made during the infiltration test. The infiltration rates were monitored by recording the rate of descent of the water on the barrel as a function of time. Also, the pressure head in the ring was constantly checked to verify that the system was functioning. The measurement of the infiltration rate was important for determining when steady state was reached, i.e. the time when the infiltration rate became constant. The steady-state infiltration rate was used in Equation 1 to obtain the hydraulic conductivity. A tracer test was used to verify the measured K values. If the tracer was found in the well, this confirms a potential faulty annular seal by demonstrating the hydraulic connection between the water column and the surface.

2.4.1.2. Small-ring infiltrometer tests

Small-ring infiltrometers (Fig. 2.3c) were used to determine the hydraulic conductivity through the soil profile in the vicinity of the well. The small rings had a diameter

of 0.146 m and a length of 0.254 m. The wall thickness was approximately 0.005 m and the bottom lip was beveled to a sharp cutting edge to facilitate insertion into the ground. The ring was made of stainless steel. It was inserted using a block of wood and a small sledgehammer. The uniformity of penetration was measured regularly with a level to minimize tilt. The depth of penetration was then recorded. Again, the soil surface was not altered in order to preserve the hydraulic properties of the soil. The number of small-ring tests performed at each site varied between 8 and 16. An approximately equal number of tests were made “in the field” surrounding the well and “on the waterline”. The tests “on the waterline” were carried out where the waterline supplying the house from the well was buried. These tests were carried out separately because the waterline area is an environment that is considered to have been mechanically perturbed, and likely to resemble the soil surrounding the well. Conversely, the tests conducted “in the field”, away from the waterline and the well, were considered to have been carried out in an unperturbed area. In some cases, the location of the waterline was unknown and the small ring infiltration tests were done randomly in the vicinity of the well. The small ring infiltration tests were performed within a 25 m radius from the wellhead.

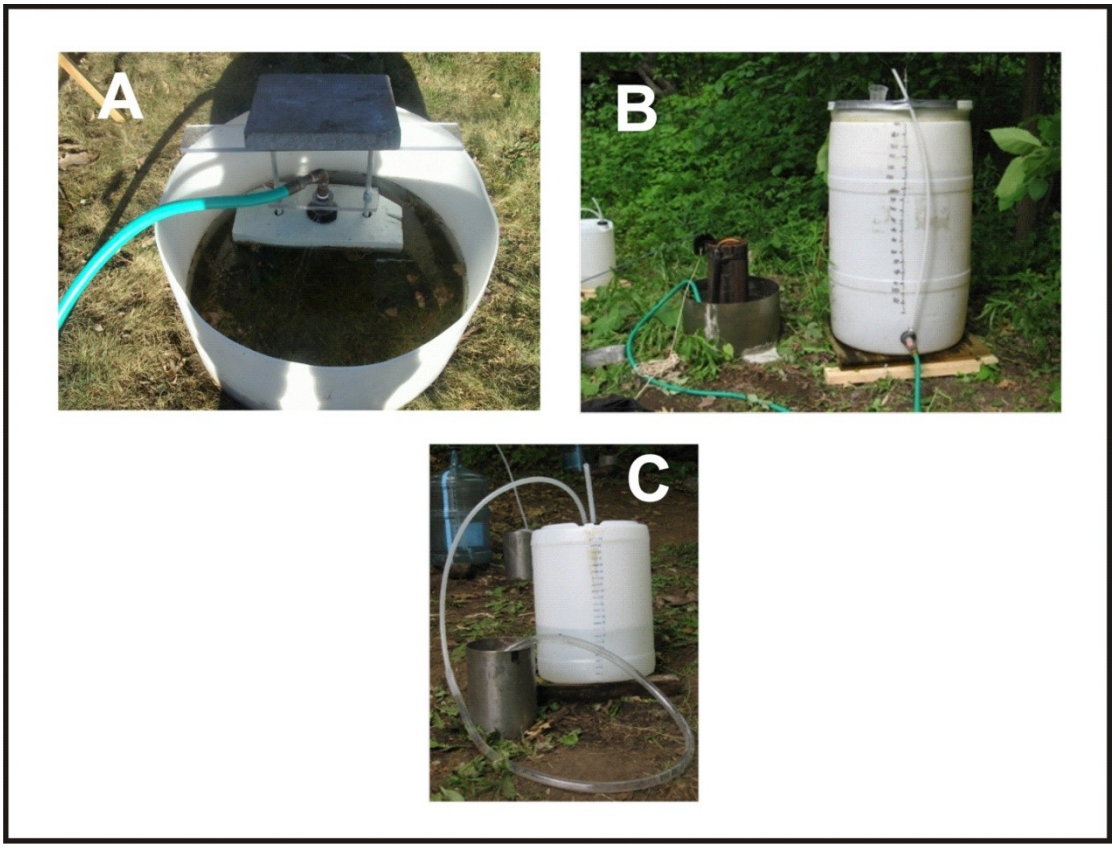


Figure 2.3: A) Float valve system used to maintain a constant water level B) Large-ring infiltrometer at the well; and C) small-ring infiltrometers in the vicinity of the well showing the Mariotte siphon system used to maintain a constant water level.

2.4.1.3. Calculation of the hydraulic conductivity

$$K = \frac{\alpha * GQ}{\left[a\left(\alpha * H_1 + 1\right) + G\alpha * \pi a^2\right]} \qquad [1]$$

Equation 1 shows the formula used to calculate the hydraulic conductivity (Reynolds, 1993). In this equation, α* (cm^{-1}) represents a soil texture/structure parameter; Q (cm^3s^{-1}) represents the steady state infiltration rate; a (cm) is the inside radius of the infiltrometer (Small ring = 0.073 m and Large ring = 0.33 m); H_1 (cm) is the steady pressure head on the infiltration surface; and G is a dimensionless shape factor obtained using:

$$G = 0.316\left(\frac{d}{a}\right) + 0.184 \qquad [2]$$

where d (cm) is the depth of the ring insertion into soil, and again a (cm), the inside radius of the infiltrometer.

At most of visited sites, α* was determined to be 0.04 or 0.12 cm^{-1}. These values were obtained from Table 2.1 (Reynolds, 1993). The choice of alpha is important when accurate measurements of K are necessary to compare values between soils of varying textures. The choice of alpha was somewhat arbitrary and assumed to be constant within a well-site. This approximation will have minimal impact on the interpretation because K values were compared only within well-sites. After the K values were obtained, the next step was to compare these values.

Table 2.1: Soil Texture/Structure Categories for site estimation of α* in the constant head pressure infiltrometer methods modified from Reynolds (1993).

Soil Texture/Structure Categories	α* (cm^{-1})
Compacted, Structureless, clayey materials	0.01
Soils which are both fine textured (clayey) and unstructured	0.04
Structured soils from clays through loams; also includes unstructured medium and fine sand	0.12
Coarse and gravelly sands; may also include some highly structured soils with large cracks and macropores	0.36

2.4.2. Statistical analysis

This technique is based upon the hypothesis that an effective seal is detected by showing that K at the well is significantly lower than in the vicinity of the well. The hydraulic conductivity is expected to vary over the well-site. For this reason, analysis of variance (ANOVA) is selected as a statistical test because it compares the variability within a group

to the variability between the groups (Davis, 2002). A series of one way ANOVAs are conducted to answer the following questions:

1) Are the hydraulic conductivities different in the disturbed material (along the waterline, from the well to the house) from the undisturbed material (vicinity)? If there is a difference then it suggests that the disturbed material is probably a better comparison for hydraulic conductivity value at the well. However, in most cases, the location of the water line is unknown and the placement of the small-ring tests was randomly selected in the vicinity.

2) Is the hydraulic conductivity at the well significantly different than the "vicinity" conductivity or the "waterline" conductivity?

The two-tailed ANOVA are performed with a significance level (α) of 0.05. The null hypothesis (H_0) is that there is no significant difference between the well K and the vicinity K. If the H_0 is rejected and the well K is significantly lower than the vicinity K, this suggests that the seal is sound; otherwise ($K_{well}>K_{vicinity}$) there are preferential pathways at the wellhead and the seal is inferred to be faulty. If there is no significant difference between the hydraulic conductivities, then we fail to reject H_0, which is inferred to indicate the absence of sealant material in the annular space or that the field variability is too large and/or the power of the test is too small to detect a significant difference. In these cases, there is a possibility that the well seals are faulty, which should be corroborated by other evidence, such as tracer tests.

2.4.3. Estimation of Time of Travel (TOT)

A simple time of travel (TOT) procedure is used to estimate the vertical TOT. The estimated time is then compared with tracer test results. The TOT is determined by dividing the hydraulic conductivity by an estimated effective porosity of the soil surrounding the casing. The hydraulic conductivity is used instead of the infiltration rate (expressed as a flux) because at steady-state, the infiltration rate is numerically equal to the unsaturated K (Jury et al. 1991). The effective porosity, in Alberta, is assumed to be 0.3, which is a typical value for sand. For the Lindsay and Chelsea's sites, the effective porosity used to calculate the TOT ranges from 0.1 to 0.7. An effective porosity of 0.7 is high and unlikely to be observed. The idea here is to calculate a range of effective porosity using extreme porosity

values. This gives an interval of TOT which is then used to compare with the measured TOT. This estimated TOT is an indication of the groundwater velocity through a soil matrix. Comparing this value with the tracer arrival time will help in providing evidence for a faulty seal. If the tracer TOT is significantly faster than the estimated TOT, then preferential pathways in the annular space or defects in the well seal may be inferred. If the estimated TOT is similar to the tracer TOT, then our method to calculate hydraulic conductivity is inferred to give a fair estimate of the average K in the annular space and is also representative of a preferential path. A faulty seal will then be assumed. A greater measured TOT indicates that the tracer travel path is slower than expected. This could result from a sound seal somewhere in the annular space, but not necessarily at the surface. It may also result from decreases in K with depth. However, the fast travel time of the tracer still needs to be considered in the final verdict. Short travel times may indicate a hydraulic connection, especially if the comparison of K inferred a faulty seal. Finally, if the estimated TOT is large enough and the tracer TOT does not reach the well within the elapsed time, it is interpreted that there is no hydraulic connection between the surface and the well seal provides an efficient barrier to surface water infiltration.

2.4.4. Tracer Test

The tracer tests were used to corroborate the data from the hydraulic conductivity tests. Infiltration experiments at the well consisted of injecting a tracer solution followed by a “chaser” of well water. The tracer injection consisted of two barrels (approximately 380 L in total) of a sodium chloride (NaCl) solution. The electrical conductivity of the tracer solutions varied between 5000 µS/cm and 15 000 µS/cm with concentrations ranging from approximately 1400 to 5500 mg/L of NaCl. The chaser water was obtained from barrels filled with well water while the infiltration test was running. Injection was terminated when the depth of penetration of the wetting front was estimated as deep enough to cover the length of the casing, or after infiltration of 2 to 4 barrels of chaser water where the casing was deeper than 10 m (some casings were as long as 50 m).

Prior to commencing the infiltration test, an electrical conductivity (EC) profile of the well water column was measured with a “*Solinst Reelloger*” probe model 2001. The precision of the instrument is ± 1%. This initial profile was used as the control for comparison with the subsequent EC profiles. Profiles were collected before and

immediately after the injection of the NaCl tracer solution; and a number of times during the days following the test. Increases of the water column EC is inferred to demonstrate a hydraulic connection to the surface, since the tracer is reaching the well water. The tracer advective time was estimated and compared to the TOT calculated from K around the well (as described previously).

The tracer technique was slightly modified for the Lindsay sites:

1. To saturate the upper soil profile and promote tracer infiltration prior to pumping, a pre-tracer was percolated in the soil surrounding the well for approximately two to three hours before tracer injection. Electrical conductivity profiles were measured before the pre-tracer infiltration and tracer injection.

2. During the tracer injection, water was pumped from the well using a Solinst peristaltic pump, with the intake near the casing shoe. Since no water was withdrawn from these wells, the purpose of pumping was to increase water flow into the well, thereby increasing the chances of tracer detection in the water column. The average pumping rates varied between 0.13 and 0.22 L/min, and the depth of pumping was approximately 5.5 to 6 m.

3. To verify the accuracy of the EC probe, water samples were collected and analyzed for major cations and anions. The samples were collected before the pre-tracer infiltration and tracer injection. Samples were also collected every 2 hours during pumping and every day after profiling the water column. The samples were immediately refrigerated in the field and were filtered and acidified in the laboratory.

Chloride (Cl^-) and sulfate (SO_4^{2-}) were used to distinguish between increases in Cl^- concentration related to the tracer arrival versus variations related to the water origin. Since Cl^- is conservative tracer (Fritz and Clark, 1997), a change in the Cl/SO_4 ratio indicates a modification in the source of water. An increase in the Cl/SO_4 ratio was an indication of a Cl^- rich source, most likely the tracer.

Most of these modifications were retained for the fieldwork in Chelsea, Québec. The domestic wells were frequently pumped during the tracer injection and during the monitoring period and there was no need for inducing flow into the well. Therefore, the wells were not pumped for a specific period of time during tracer injection. Samples were only collected before and after the injection in addition to during the monitoring days. At some sites, a Schlumberger CTD-Diver datalogger was used to detect tracer arrival in the water column. The accuracy of the instrument is ± 1% and the resolution is 0.1%.

2.5. Results

Nineteen well-sites were tested to evaluate the applicability of the faulty seal detection technique in different geological settings. Table 2.2 presents the data from the infiltration tests performed at each well-site and Table 2.3 shows the characteristics of the wells and local geology. Table 2.3 also provides the results of the tests conducted (comparison of K and tracer test) and the verdict regarding the status of individual well seals. An example of the detailed analysis is presented for one site (2C) following the results description. This well-site was chosen because it shows that even a newer well, where a proper seal should be present, may have a faulty seal. Complete analyses for all well-sites are located in Appendix A, B and C.

Four wells are located in Alberta; their depth varies from 30 to 49 m and the depth to water ranges from 16 to 44 m below ground surface. The well reports were not available, therefore the age of the wells and the presence of a well seal remains unknown. The wells are thought to be drawing water from the Upper or Lower Scollard Formation which consists of sandstone. The surficial geology is mainly composed of till. The thickness of the unconsolidated top layer is estimated to be approximately 20 m. At each well-site, hydraulic conductivity measurements and a tracer test were carried out. The results show that the null hypothesis (H_0) is rejected in one well-site (1A) indicating a faulty seal. At this site the tracer test corroborates the hydraulic conductivity test, also indicating the presence of a faulty seal, because the measured TOT for the tracer is lower than the estimated TOT. These two results demonstrate a faulty seal, which is the final verdict for well 1A. H_0 is not rejected for the three others well-sites (2A, 3A, 4A). Even though there are no significant differences between the hydraulic conductivity measurements, the possibility of a faulty seal

still needs to be considered. In one case, well 4A, the presence of a faulty seal is demonstrated by the lower measured TOT. For the other two wells (2A and 3A), the measured TOT is greater than the estimated TOT and a faulty seal is not inferred for these well-sites.

The three well-sites located in Ontario have depths varying from 8 to 61 m and the depth to water is 4.5 m below ground surface. The wells were drilled on the property of a community college that trains well drillers. The characteristics of the wells were obtained through personal communication with the coordinator of the drilling program (G. Bailey, 2007). The wells draw water from a Phanerozoic limestone aquifer (Singer et *al*., 2002) and the first metre of the bedrock is more fractured because of weathering. The surficial geology is composed a compact till with a thickness of 5 m. At each well-site, hydraulic conductivity measurements and a tracer test were carried out. The results show that the null hypothesis (H_0) is rejected in two well-sites (4F and 8F), indicating a faulty seal. The tracer test also indicates the presence of a faulty seal for well 8F because the measured TOT for the tracer is lower than the estimated TOT. These two results demonstrate a faulty seal, which is the final verdict for well 8F. At well 4F, the measured TOT is greater than the estimated TOT but the seal is still thought to be faulty because of the short travel time. H_0 is not rejected for the well-site 6F but the comparison of the TOT demonstrates the presence of a faulty seal because the measured TOT is within the range of the estimated TOT.

The twelve well-sites located in Québec were drilled and completed with a steel casing of 0.15 m in diameter. The depths vary from 30 to 80 m and the wells range in age from 1 to 30 years. In most cases, the well reports are not obtainable and some characteristics are estimated or remain unknown. The depth to water varies from 0.5 to 34 m from the ground surface. The aquifer consists of igneous/metamorphic rocks from the Precambrian. The overburden varies in grain size, composition and thickness. The results show that the null hypothesis (H_0) is rejected in five well-sites (2C, 7C, 24C, 26C and 27C) indicating a faulty seal. The tracer test also indicates the presence of a faulty seal for wells 2C and 7C because the measured TOT for the tracer is less than the estimated TOT. These two results demonstrate a faulty seal, which is the final verdict for these wells. For wells 25C, 26C and 27C, the measured TOT is greater than the estimated TOT but the seal is still interpreted as faulty because of the fast travel time. In one well-site (23C) the difference between the K measurements is marginally statistically significant. Unfortunately the tracer test is not conclusive because of cross-contamination into the water column.

Based on the K measurement only, the seal at this well is most likely to be faulty. Finally, H_0 is not rejected for the six others well-sites (3C, 10C, 11C, 15C, 16C and 24C). The comparison of the TOT demonstrates the presence of a faulty seal at three well-sites (11C, 16C and 24C). For the other well-sites (3C, 10C and 15C) the measured TOT is greater compared to the estimated TOT and the well seal is not likely faulty.

Table 2.2: Data from the infiltration tests performed at each well-site: A - Hobbema First Nations (Alberta); F - Lindsay (Ontario); and C - Chelsea (Québec)

	Large ring infiltrometre at the well				Small ring infiltrometre in the vicinity				
Well-site #	Test duration (hrs)	Depth of Insertion (m)	Head of water in ring (m)	K at the well (m/s)	Number of tests	Depth of Insertion (m)	Head of water in ring (m)	Average K in vicinity (m/s)	Standard deviation
1A	5.7	0.05	0.10	1.0E-05	13	0.08 - 0.18	0.01 - 0.05	3.4E-06	2.5E-06
2A	8.8	0.07	0.11	2.7E-05	12	0.11 - 0.15	0.02 - 0.04	2.9E-05	1.9E-05
3A	4.0	0.08	0.08	7.0E-05	12	0.10 - 0.15	0.02 - 0.05	5.1E-05	4.3E-05
4A	8.0	0.05	0.10	2.0E-05	12	0.09 - 0.13	0.03 - 0.05	2.6E-05	9.7E-06
4F	5.6	0.02	0.18	1.7E-05	16	0.06 - 0.14	0.02 - 0.13	5.2E-06	4.4E-06
6F	7.5	0.05	0.06	8.2E-06	16	0.06 - 0.14	0.02 - 0.13	5.2E-06	4.4E-06
8F	5.9	0.05	0.07	2.1E-05	16	0.06 - 0.14	0.02 - 0.13	5.2E-06	4.4E-06
2C	4.8	0.09	0.05	6.5E-05	12	0.04 - 0.09	0.05 - 0.13	4.4E-06	3.7E-06
3C	5.8	0.08	0.07	1.7E-05	12	0.05 - 0.11	0.07 - 0.14	1.8E-05	1.0E-05
7C	5.8	0.08	0.11	1.2E-04	10	0.06 - 0.13	0.02 - 0.11	7.8E-06	5.7E-06
10C	3.8	0.10	0.09	3.7E-05	10	0.05 - 0.10	0.03 - 0.08	2.0E-05	9.4E-06
11C	5.3	0.04	0.07	2.3E-05	11	0.05 - 0.11	0.02 - 0.13	2.9E-05	1.5E-05
15C	5.2	0.10	0.10	2.8E-05	12	0.05 - 0.13	0.03 - 0.12	4.3E-05	2.3E-05
16C	3.8	0.10	0.08	2.1E-05	8	0.04 - 0.08	0.01 - 0.10	4.9E-05	2.8E-05
23C	6.0	0.10	0.05	6.6E-05	11	0.07 - 0.13	0.02 - 0.12	2.3E-05	1.9E-05
24C	6.8	0.07	0.17	1.2E-05	12	0.08 - 0.12	0.03 - 0.12	9.7E-06	5.9E-06
25C	7.0	0.11	0.06	1.3E-04	8	0.07 - 0.10	0.05 - 0.12	4.0E-05	3.7E-05
26C	6.0	0.10	0.01	5.4E-05	10	0.08 - 0.11	0.06 - 0.12	1.5E-05	1.1E-05
27C	7.5	0.09	0.01	1.9E-04	10	0.05 - 0.09	0.10 - 0.15	9.1E-06	6.8E-06

Table 2.3: Summary of all well-sites, including well and site characteristics, the results of field measurements and the verdict regarding the seal status where, F= Faulty, NF= Not Faulty and P=Potentially Faulty

Well-site #	Well Characteristics					Site Characteristics			Field measurements					Final verdict
									K analysis Ho: $K_w=K_v$ Ha: $\mathbf{K_w>K_v}$; $K_w<K_v$		Time of Travel (hrs)			
	Well Location	Depth (m)	Age (yrs in 2008)	Depth to water (m)	Presence of a Sanitary Seal	Bedrock Gelogy	Surficial Geology	Estimated Soil Thickness (m)	p-value	Verdict	Calculated	Measured	Verdict	
1A	Alberta	30	?	16	?	sandstone	till	>5	**0.02**	F	242	192	F	F
2A	Alberta	49	?	36	?	sandstone	till	>5	0.92	P	155	240	NF	NF
3A	Alberta	48	?	44	?	sandstone	till	>5	0.69	P	60	120	NF	NF
4A	Alberta	45	?	21	?	sandstone	till	>5	0.55	P	206	170	F	F
4F	Ontario	61	9	4.5	cuttings	limestone	dense till	5	**1.50E-02**	F	10-68	175	NF	F
6F	Ontario	40	8	4.5	bentonite	limestone	dense till	5	0.51	P	20-143	120	F	F
8F	Ontario	8	1	4.5	cuttings	limestone	dense till	5	**3.00E-03**	F	8-55	48	F	F
2C	Québec	70	4	25	bentonite	syenite, monzonite	clay	>5	**4.50E-10**	F	3-20	5	F	F
3C	Québec	80	20	3	?	diorite, gabbro	till	<1	0.94	P	10-73	160	NF	NF
7C	Québec	70	15	9	?	quartzite	clay	>5	**1.40E-08**	F	2-12	6	F	F
10C	Québec	35	20	6	?	syenite, monzonite	clay	>5	0.11	P	5-32	234	NF	NF
11C	Québec	70	20	5	?	paragneiss	till	<1	0.7	P	8-58	24	F	F
15C	Québec	35	6	3	bentonite ring	paragneiss	silt	<1	0.68	P	78-53	Not detected	NF	NF
16C	Québec	78	15-20	16	?	paragneiss	silt	<1	0.38	P	13-88	24	F	F
23C	Québec	50	30	34	?	paragneiss	clay	>5	**0.04**	F	3-20	n/a	n/a	most likely
24C	Québec	35	6	0.5	?	paragneiss	silt	<2	0.67	P	27-194	137	F	F
25C	Québec	80	18	0.5	?	paragneiss	till	<2	**0.05**	F	1-9	139	NF	F
26C	Québec	45	20	2	?	paragneiss	silt	<2	**0.009**	F	3-23	77	NF	F
27C	Québec	30	1	6	bentonite	pegmatite	sand	<5	**1.00E-09**	F	2-11	19	NF	F

2.5.1. Detailed analysis, Well 2, Chelsea (Québec)

2.5.1.1. Description

The selected site is located in the Gatineau Hills, about 30 km north of Ottawa, Ontario. Roughly 5 m of clayey soil lie above the Precambrian bedrock, which consists of syenite and monzonite. The Gatineau River is located approximately 120 m east of the well. The river elevation is 98 m.a.s.l. and regional groundwater flows northwest to southeast. The well at this site was drilled in 2004, one year after the enforcement of Québec's regulation on water well construction. Therefore, a proper sealant material should be in place in the annular space. The elevation of the ground surface at the well is 124 m.a.s.l, the depth is 70 m and the static water level is at 25 m below ground surface. This well has recurrent contamination problems, with both faecal and total coliforms.

The infiltration tests were conducted over two consecutive days. A total of twelve small ring tests were done in the vicinity of the well. The near-surface hydraulic conductivity value at the well is $6x10^{-5}$ m/s, which is significantly higher than the average of the nearby values, $4x10^{-6}$ m/s.

The tracer injection at the well was carried out over one day, which is considered "Day zero" in the analysis. A total of 380L of NaCl solution, with an electrical conductivity (EC) of 10 500 µS/cm, was injected following the infiltration of 380L of well water (EC around 500 µS/cm), which acted as the pre-tracer in this case. After the injection of the tracer, additional well water was infiltrated, acting as chaser water. The well was used for domestic purposes after the tracer test, which induced renewal of the water into the water column. The tracer in the water column was monitored for 12 days following its injection. To verify if the observed EC increases of the water are related to the tracer, water samples were collected daily. The water was sampled immediately after profiling the water column. The well was purged for fifteen minutes before sampling. The samples were obtained from an outside water tap because of the technical complexity of sampling directly from the water interface of the well. The samples were analysed for Cl^- and SO_4^{2-} and the Cl/SO_4 ratio was calculated. Water samples were collected for 12 days following the tracer injection.

2.5.1.2. Results

Figure 2.4 displays the electrical conductivity profiles of the water column in the open borehole. Representative EC profiles are shown in the figure for clarity. The profile *before tracer injection* represents the background profile of the water column. The electrical conductivity increases with depth, with a sharp increase of about 50µS/cm, at a depth of 35 m. This increase is considered a boundary between the upper and the lower section of profile, which may represent the boundary between the shallow and deep aquifers. The upper section of the profile has a gentle slope compared to the steeper slope of the lower section. The range of the daily variations between the upper and lower section also fluctuate. And lastly, the range of the EC values of the upper profile is somewhat wider compared to the range in the lower profile.

The tracer was injected at the ground surface and the water level is located below the casing shoe. As a result, the tracer is expected to reach the water column in the upper section of the profile. The tracer arrival in the well is observed on the EC profile of the water column (Fig. 2.4) with the tracer detected 5 hours following the injection. This is observed in the *immediately after tracer injection* profile. The EC values increase through the water column, but the increase is more noticeable in the upper section of the profile. The EC profiles return to a background value after the injection and remain relatively stable until *8 days*, when a decrease of the EC values starts to occur and is observed at *9 days*.

The tracer arrival is corroborated by the increase in the Cl/SO_4 ratio, calculated from the chemical analysis of the samples (Fig. 2.5). In general, the background concentration ratio is near 1.5 throughout the period of analysis. At *2 days*, the Cl/SO_4 ratio increases, which indicates a source enriched in chloride. The ratio remains consistent until *8 days*, when the Cl/SO_4 ratio returns to the background value. At *12 days*, the ratio increases slightly, however, the reason for this increase is unclear.

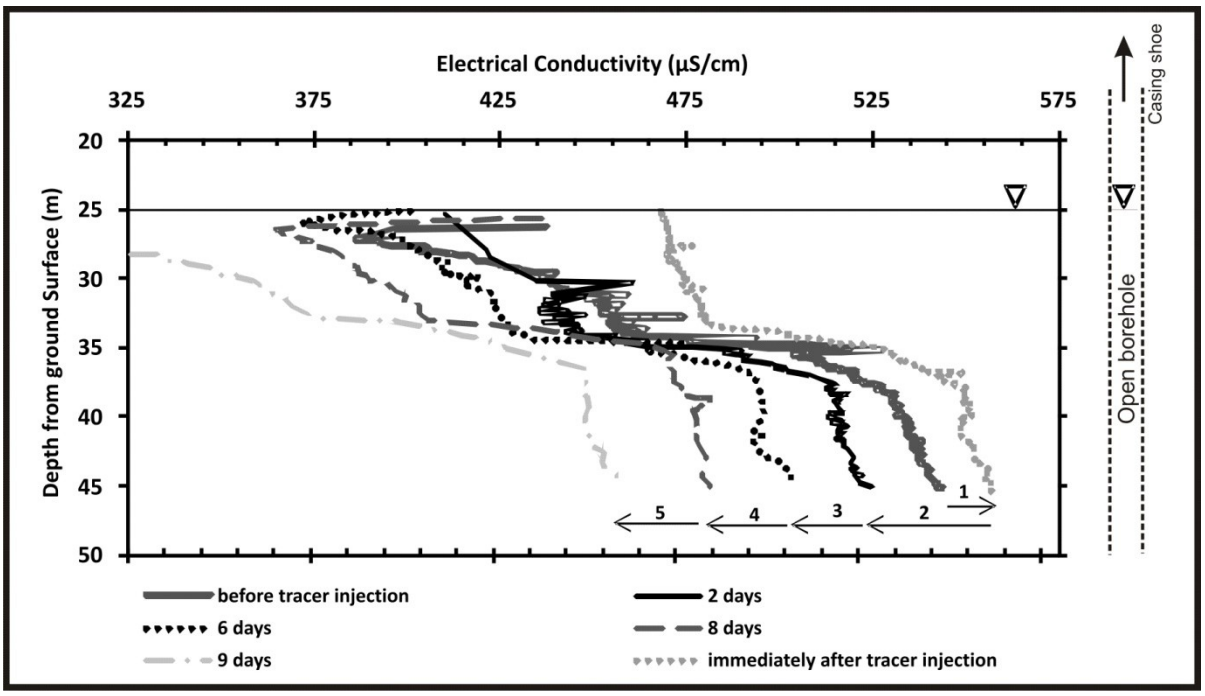


Figure 2.4: EC profiles of the water column at Well 2C. The tracer monitoring is performed in a open borehole since the casing shoe is located 6 m from the ground surface. The shift in the *immediately after tracer injection* profile is interpreted to represent the tracer arrival into the well.

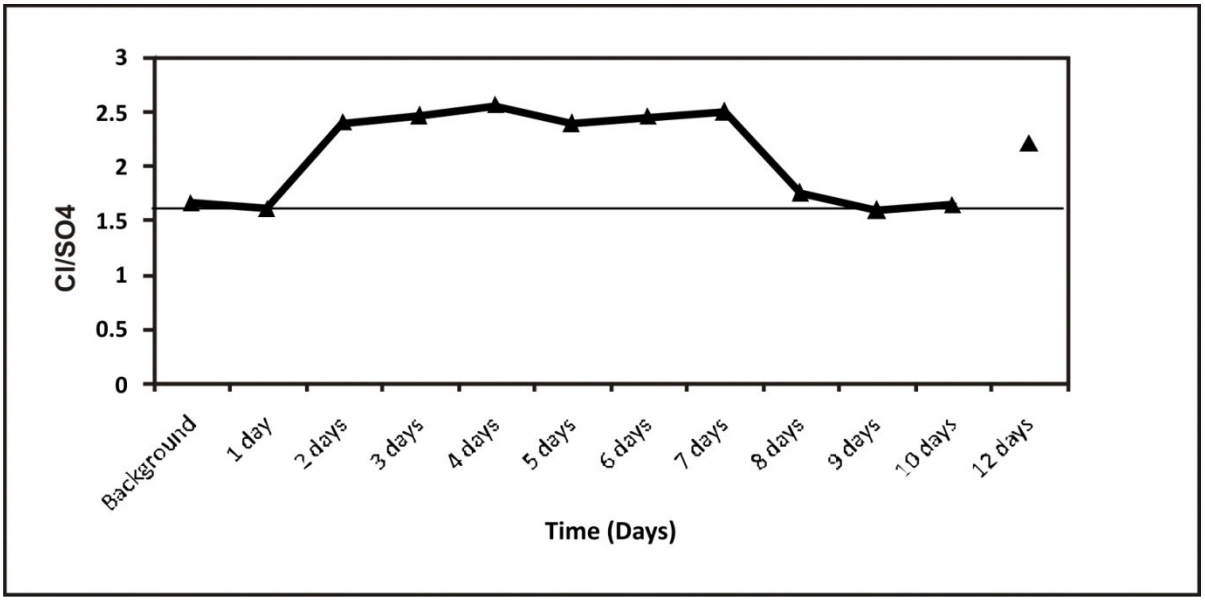


Figure 2.5: Cl/SO_4 concentration ratio from the geochemical analysis of the water samples. An increase is observed 2 days after the tracer injection and it is attributed to the tracer arrival, in detectable concentrations, into the house water distribution system.

2.5.1.3. Interpretation

Well 2C (Figure 2.4) shows a stratification of the water column, with a sharp boundary at a depth of 35 m below ground surface. The boundary is thought to represent changes in the origin of water reaching the well resulting from variations in the fracture network. The upper section of the profile may characterize a shallower groundwater system, whereas the lower section may be more representative of a deeper groundwater system. This would explain the variation in the range of the EC values observed in the lower and upper profile.

The tracer reaches the water column within five hours after the injection. The increase in the upper section of the profile is more noticeable than the increase in the lower section. These variations result from the dilution of the tracer while seeping into the water column. As mentioned earlier, the well was used for domestic purposes after the tracer test, which induced renewal of the water into the water column. This would explain why the EC values in water column return to values similar to the background values in the days following the injection. Figure 2.4 also illustrates another decrease of the EC values of the water column. This decrease is observed in the *8 days* profile but is more obvious in the *9 days* profile. This decrease is explained by the occurrence of an important rainfall event six days after the injection of the tracer. Accordingly, the decrease observed in the *8 days* and *9 days* profiles may result from surface water reaching the water column. This would correspond to a two to three day lag time between a rain event and the recharge in the well. This lag time is relatively fast and may contribute to the presence of coliforms in the well.

The tracer is also detected in the water samples collected during the monitoring period. An increase in the Cl/SO_4 ratio is interpreted as the result of mixing between the water column and the tracer water, which is richer in chloride. The increase of the ratio (Fig. 2.5) is interpreted as tracer arrival into the house piping systems. Even if the tracer reached the well within 5 hours it would have arrived in concentrations detectable by the water analysis after two days. This may result from the different degree of mixing through the water column and because there is approximately 50 m of water in the water column. The ratio returns to the background value of about 1.5 eight days following the injection. This decrease in the ratio corresponds roughly to the decrease observed in the EC profile of *8 days* and *9 days* (Fig. 2.4). The further increase of the ratio on day 12 (Fig. 2.5) is interpreted as more mixing with the tracer after the rainfall event.

2.5.1.4. Summary for well-site 2C, Chelsea, Québec

The near-surface vertical hydraulic conductivity at the well is significantly higher than in the vicinity and the tracer is detected in the well using both EC profiles and chemical analysis. The early tracer arrival time in the water column is supported by the estimated time of travel (TOT). The calculated TOT varies between 3 and 20 hours based on the K measurement at the well and the effective porosities which range from 0.1 and 0.7, respectively. These TOT values correspond well with the time at which the tracer is detected in the water column (less than 5 hours). In their totality, the results indicate that the seal of this well is faulty, which is further corroborated by the chronic recurrence of pathogen contamination in this particular well.

2.6. Discussion

The statistical comparison of near-surface hydraulic conductivities alone is successful at detecting a faulty seal ($K_{well}>K_{vicinity}$) at eight well-sites. At the other ten well-sites, the null hypothesis is not rejected ($K_{well}\approx K_{vicinity}$). The non-detect (when H_0 not rejected) are at least in part, due to the large variability in the K which reduces the statistical resolution of the analysis and which, in turn, makes statistical inference more difficult. When this occurs, the use of the tracer is necessary to confirm or deny the presence of a preferential pathway into the annular space, because the potential exists for a faulty seal. The use of a tracer increases the complexity of the analysis because the results need to be integrated with the statistical analysis, increasing the range of interpretation. Table 2.4 summarizes the different scenarios when combining the measurement of the K and the tracer test results. These scenarios help evaluate the relative importance of the well construction versus the importance of the local geology leading to the well contamination.

Scenarios 1 and 2 are similar because the comparison of the hydraulic conductivity shows a K significantly greater at the well than in the vicinity (p-value<0.05). Five sites are classified into the first scenario where the p-value is lower than 0.05 and the tracer is detected in the water column within the range of estimated TOT. This indicates the presence of preferential pathways in the annular space and at the wellhead, leading to surface water infiltration into the water column. Most of these sites have a similar surficial geology composed mainly of dense till, clayey material and fine-grained sediments. Lower hydraulic conductivities were measured on-site. The soil is also thicker compared to the

other sites (approximately 5 m). The second scenario consists of a significant p-value and a measured TOT greater than the estimated TOT. Three well-sites fall within this category. The seal is still considered faulty because the measured TOT is relatively fast (less than 6 days). The differences in the TOTs could result from a possible decrease of the K of the annular seal with depth which reduces the velocity of the tracer. When the K p-values are statistically significant, the infiltration technique alone is sufficient to detect a faulty seal which is demonstrated with the tracer test. Therefore, for the wells classified into categories 1 and 2, the relative impact of the well construction as a preferential infiltration pathway is potentially greater than the local characteristics regarding the potential for bacterial contamination.

The p-values for the third and fourth scenarios are not statistically significant indicating no meaningful differences between the K values. Six sites are classified into the third scenario where the measured TOT is equal or smaller compared to the estimated TOT. This suggests the presence of preferential pathways into the well annular space, and therefore a faulty seal. The soil thickness for these sites is variable, ranging from less than one meter (3 sites) to over 5 m (3 sites). Four sites are classified into the fourth category where the measured TOT is greater than estimated one which is the fourth possibility. Three out of four sites have soil thicknesses greater than 5 m with a lower hydraulic conductivity material. When the p-values are not statistically significant, there is no clear correlation between the soil type, the thickness and the failure to reject H_0 and/or to detect the tracer into the well. The ability of the technique to detect faulty seal is reduced because local heterogeneity overshadows the statistical resolution. The hydraulic conductivities alone are not sufficient and a tracer test is required to deduce the well seal status. Even if the annular space acts as a preferential pathway, the local characteristics may be an important contributor to contamination events.

Table 2.4: Summary of the scenarios and integration of the field measurements. The scenarios help evaluate the relative importance of the well construction versus the importance of the local geology leading to the well contamination.

P-value	Scenario	TOT	Wells ID	Status of the seal	Rationale behind decision	Relative importance of well construction to the local characteristics
<0.05	1	$TOT_m \leq TOT_e$	1A 8F 2C 7C 27C	Faulty	Presence of a preferential pathway was detected in the well annular space	Well Construction > Local Characteristics
	2	$TOT_m > TOT_e$	4F 25C 26C	Faulty	High near-surface K but it decreases with depth. The tracer still reaches the well within a few days, which is relatively fast	Well Construction > Local Characteristics
>0.05	3	$TOT_m \leq TOT_e$	2A 4A 6F 11C 16C 24C	Faulty	Presence of a preferential pathway was detected at the well, but there is also a potential for preferential pathways in the local geology	Well Construction ≈ Local Characteristics
	4	$TOT_m > TOT_e$	3A 3C 10C 15C	Not faulty	Lower risk of faulty seal. The tracer reaches the well from natural seepage through the overburden matrix surrounding the well	Well Construction < Local Characteristics

2.7. Conclusions

The technique for detecting faulty well seals presented here uses a comparison of near-surface vertical hydraulic conductivities (K) measurements and the injection of a sodium chloride solution at the wellhead. Hydraulic conductivity measurements, using single ring infiltrometers, were performed around the well and in its surroundings. The K values were statistically compared using single-factor ANOVAs. The seal in the annular space should be characterized by a lower K than the soil surrounding it (Lutenegger and DeGroot, 1994). Therefore, a good seal through the annular space is inferred if the K at the well is significantly lower than the average of the K in vicinity area. An estimate of the TOT is calculated using the K value at the well and is then compared to the measured TOT, obtained from the tracer arrival time.

The following conclusions are drawn regarding the applicability of the technique and the interpretations of the results in determining the relative importance of the well construction and the local characteristics leading to the infiltration of surface water:

1. The technique was tested in different geological settings across Canada to evaluate its widespread applicability. The technique successfully detected faulty well seals in different geological settings, however, it is most successful where local heterogeneity is minimal and the surficial geology is composed of fine-grained sediments.

2. When the K measurements from the well are significantly higher than the surrounding area, a faulty seal is inferred. The results show that every time the p-value was statistically significant, the tracer is detected in the well water column within a short period of time. This is interpreted as evidence for a preferential pathway through the annular space. In these cases, it is argued that the impact of the well construction is greater than the local characteristics of the geological system for contamination events.

3. When there is no significant difference between the well and the surrounding K, a tracer test is necessary to evaluate the possible connection between the surface and the water column. In most cases, no statistically significant difference is interpreted as evidence for a preferential pathway into the annular space or close to the wellhead. This hydraulic connection is demonstrated with the tracer test. The well construction and the

local characteristics are equally important potential contributors to contamination resulting from the infiltration of surface water.

4. When the K measurement at the well is significantly smaller than the values from the surrounding area, the well seal is interpreted as sound. There is no well-site in this study where the K value at the well is significantly smaller than the K values in the surrounding area. Therefore, the ability of the technique to detect a proper seal is not tested.

The infiltration technique alone offers the advantage that it is simple, cost effective and requires, in most cases, limited expertise and equipment. The tracer technique used to verify the infiltration method is successful at detecting rapid pathways to the well, which are inferred to result from a faulty seal. The infiltration and tracer techniques offer two independent tests that lead to the better identification of a faulty seal. Without the infiltration test, it would be difficult to evaluate if the tracer travels through the soil matrix or a preferential pathway in the annular space. The downside of this technique is the time involved in performing the infiltration tests and during the monitoring of the tracer. Before applying this technique, an evaluation of the potential contamination sources should be conducted to eliminate the most probable sources and then, proceed to the seal evaluation to further investigate the site. This simple, but effective detection technique for source water protection will aid in the determination of key indicator variables in domestic well contamination because the results give an indication of the relative importance of well construction in contamination events and eventually, to calculate the probability of having a faulty seal.

Chapter 3: Groundwater characterization and identification of spatial factors influencing water quality of a crystalline bedrock aquifer in Chelsea, Québec, Canada

3.1. Introduction

Groundwater is an important source of water for Canada as 30% of its population relies on it as a source of drinking water (Environment Canada, 2010a). In many rural municipalities, such as Chelsea, Québec (Canada), the entire population is dependent on groundwater supplied by private water wells for domestic usage. Some of these wells are shallow dug or bored wells, whereas the majority are drilled wells. Shallow dug or bored wells are constructed with a larger diameter (of 0.6 to 2 m) and are located in shallow soil with a high water table. Past construction practices may cause these wells to be prone to contamination from surface water due to deterioration of materials and lack of watertight annular sealants (Conboy and Smith, 2005). Conversely, drilled wells are generally deeper, smaller in diameter (0.06 to 0.15 m), have a watertight casing, and technically less vulnerable to contamination. The quality of the water in private wells is affected by the presence of pathogens and by concentrations of solutes. With increasing use of groundwater resources, it is critical to understand how the quality of groundwater is influenced by both natural and anthropogenic activities.

The concentration of solutes in groundwater is driven mainly by natural processes, precipitation inputs and anthropogenic activities (Tòth, 1999). The composition of the water is governed primarily by the interactions between the rocks and the water in the aquifer. As water travels in the subsurface, a series of geochemical and biological reactions control its geochemical evolution. These reactions include the degradation of organic matter, nitrification-denitrification, mineral dissolution and/or precipitation, reduction-oxidation reactions, cation exchange processes, sorption and mixing (Appelo and Postma, 2005; Edmunds et al., 2003; Clark and Fritz, 1997; Tòth, 1999). As the groundwater moves from the recharge area to discharge area, the concentration of major-ions generally increase, unless mixing with a less concentrated source of water occurs along the flow path. Anthropogenic activities also have the potential to contribute to the chemical composition of the groundwater (Appelo and Postma, 2005).

In rural areas, private water wells are exposed to contamination from diverse sources of pathogens and surficial contaminants (Goss et al., 1998). Presence of livestock and septic fields increases the risk of pathogen contamination, whereas agricultural fields, septic fields, exercise yards, and manure or fertilizer application and storage may increase the risk of nitrate contamination (Rudolph et al., 1998). In a small rural municipality such as Chelsea, agricultural activities and the presence of livestock are relatively minor. The presence of septic systems (tank and field), the application of fertilizers (at small scale), usage of road salts in driveways and household development are examples of potential sources that may affect the water quality in the area. These sources increase the concentration of nitrates, sulphates, chloride, sodium, potassium, calcium and bicarbonates in the groundwater system (Barrett et al., 1998; Jiang et al., 2009; Jiang and Yan 2010; Mencio and Mas-Pla, 2008; Valdes et al., 2007).

The presence of pathogens in the water is arguably one of the most important aspects of groundwater quality. Many studies have found that the presence of micro-organisms in private water wells is affected by the local setting, the well construction and nearby anthropogenic activities (Conboy and Goss, 2000; Goss et al., 1998). Rock type and topography affect the transport of pathogens and contaminants from the surface or near the surface towards a drinking water well. Depending on their type and thickness, surficial deposits offer some natural protection to the resource through attenuation processes, which consequently, reduce the concentration of pathogens and contaminants reaching a drinking water well (Conboy and Goss, 2000). The presence of macro-pores or preferential pathways affect this natural protection and the aquifer may become more vulnerable to surface contaminants (Cey et al., 2006; Levison and Novakowski, 2009). Crystalline bedrock and karst aquifers are particularly vulnerable to contamination because the primary porosity is often minimal and the flow largely depends on secondary porosity created by fractures and weathering. These fractures act as macro-pores and offer little potential for filtration and sorption. This allows the surface contaminants or pathogens to travel faster and deeper into the aquifer (Conboy and Smith, 2005).

Preferential pathways are naturally present in the overburden and in the aquifer, but are also the consequence of poor well construction (NRC, 1993; Simpson, 2004). Potential issues may arise from the well type, the well depth, the length of the casing, the presence of grout in the annular space and the installation of a proper vented sealed cap which prevents insects from entering the well through the wellhead (Simpson, 2004). It is widely

recognized that dug or bored wells are more vulnerable to contamination because these types of wells tend to be shallower and less protection is offered from the surrounding soil (Conboy and Goss, 2000; Goss et al., 1998). Well depth and the length of the casing have also been shown to influence the presence of bacteria in water wells. Gonzales (2008) suggested that the risk of bacterial contamination of water well is higher if the well is less than 61 m deep. Zimmerman et al. (2001) and Swistock and Sharpe (2005) examined the effect of grouting the annular space on the occurrence of bacterial contamination in Pennsylvania. The authors found that total coliforms were as likely to be found in a grouted well as in a non-grouted well, however, the presence of Esherichia coli (*E.Coli.)* was most likely to be detected in non-grouted wells. The authors also demonstrated that wells drilled into carbonate bedrock have higher percentages of contamination and increased presence of *E.Coli.* than wells drilled in non-carbonate bedrock. Therefore, the quality of well construction and subsequent maintenance may affect the presence of micro-organisms and contaminants from the surface in the water column.

Hydrogeochemical studies provide important insights into the relationship between groundwater composition and the geological or hydrogeological setting. One difficulty in evaluating the groundwater quality is to distinguish between the contribution from weathering processes versus anthropogenic inputs in the chemical composition of the groundwater (e.g. Jiang et al., 2009). For this purpose, multivariate analysis has been widely used to help the interpretation of groundwater data to identify hydrogeological processes affecting the groundwater, or to investigate the interaction between surface water and groundwater (Jiang et al., 2009; Mencio and Mas-Pla, 2008; Valdes et al., 2007). For example, principal component analysis (PCA) was successfully used by Cloutier et al. (2008) to identify processes controlling groundwater evolution of the Basses-Laurentides (Québec, Canada) geographical region. The authors found that the integration of the classification method was useful and helped in refining the interpretation of the hydrogeochemical evolution of the groundwater system. Factor analysis have also been used by Jiang et al. (2009) to evaluate factors affecting groundwater quality in a karst underground river system in China. The factor analysis reveals that both natural and anthropogenic processes contributed to the groundwater quality, with the most important role played by human activities. Korkka-Niemi (2005) evaluated the groundwater quality in domestic wells in Finland with PCA, and demonstrated that five factors contributed to the groundwater quality with extra-regional (geology, marine influence) as the strongest

modifier with site-specific factors (contamination, land uses, well construction, recharge) a minor contributor to groundwater quality. Also, studies have used multivariate analysis techniques to classify large datasets based on similarities between samples. Cloutier et al. (2008) used hierarchical cluster analysis (HCA) to discriminate between the geological and hydrogeological process affecting groundwater evolution. The results recognized the importance of the hydrogeological condition and bedrock geology on trace elements. The various studies demonstrate that the use of PCA and HCA is a powerful tool to group water samples into geochemical facies, assist in the determination of extra-regional, regional or local origins of the components, and provide insights into the different variables controlling the hydrogeological evolution of groundwater.

A large proportion the groundwater in Chelsea, Québec is drawn from unconfined crystalline bedrock aquifers with variable overburden thickness. In areas of thin overburden, the water quality is more susceptible to contamination because the fractures are potentially acting as preferential pathways. The thin soil cover may lead to poor filtration and rapid infiltration of surface water, and thus, widespread contaminant migration (Cey et al., 2006; Levison and Novakowsky, 2009). Most residential lots within the Municipality of Chelsea are greater than an acre (0.004 km^2) to ensure proper distance between wells and septic systems. However, in some areas, residences and their wells tend to be clustered near the roads or the Gatineau River, and are sometimes downgradient from each other. Where contamination occurs, the potential sources of contamination are not always clearly identifiable because the distance between households varies.

Understanding the pathways and the factors affecting contamination of domestic wells is important for source water protection. This paper presents the analytical results from a study carried-out from spring 2008 to spring 2009 on a crystalline bedrock aquifer located in Chelsea, Québec, a municipality located 15 km north of Ottawa, Ontario (Canada). The objectives of this study are to evaluate factors affecting spatial variability of groundwater quality and to describe the evolution of groundwater chemistry. The study investigates the spatial variability of bacterial (total and faecal coliforms) contamination in drinking water wells; characterizes the groundwater chemistry; and uses the geochemistry of the water as a natural tracer along with multivariate statistical analysis (HCA and PCA) to identify the natural (extra-regional or regional) and anthropogenic (local) components affecting the groundwater quality.

3.2. Study area

The Municipality of Chelsea is located 15 km north of Ottawa, ON (Canada). The surface area of the Municipality is approximately 110 km^2 in a roughly triangular shape (Figure 3.1). The study site is composed of a mix of flat areas and small hills with local areas of more abrupt topography. The eastern boundary is the Gatineau River, which flows from northwest to southeast. The average daily temperature ranges from -11.5°C in January to 20.7°C in July. The average annual precipitation for the Chelsea area is 987.1 mm per year including 214.8 mm water equivalent in the form of snow (Environment Canada, 2010b). Recharge occurs primarily after the spring snowmelt and in late fall, when evapotranspiration is minimal (Golder Associates, 1990). During the summer, recharge is minimal because the water available for infiltration is limited by evapotranspiration, but it may occur after a long rainy period. Minimal infiltration occurs during the winter months due to the frozen soil.

Figure 3.1 shows topographic elevations and locations of the sampling sites. Surface elevation ranges from 100 m (along Gatineau River) to 340 m (Precambrian hills). Most of the Municipality is located over the Canadian Shield, where the dominant bedrock geology consists of Precambrian crystalline igneous and metamorphic rocks (Fig. 3.2). The igneous rocks are composed mainly of syenite and monzonite whereas the metamorphic rocks consist of paragneiss, marble and quartzite (GSC, 2008). Bedrock frequently crops out in the study area. In the southern limits of the municipality, overlying the Precambrian bedrock are limestone and sandstone units of the Ordovician (Ottawa and Nepean formations). Main faults are oriented northwest-southeast and other structural lineaments (fold and faults) are east-west (Golder Associates, 1990). Most of the surficial deposits resulted from the last period of glacial melting, 12 000 years ago. In most areas, Precambrian bedrock is overlain by a thin veneer of till and/or glacio-fluvial deposits consisting of sand and pebbles, or thicker deposits of offshore marine silt and clay. These fine-grained marine units deposited from the Champlain Sea and are located along the Gatineau River and near the northern and southern boundaries of the municipality. The thickness of the surficial deposits varies from <1 (till on bedrock) up to 50 m (Champlain Sea deposits) (Golder Associates, 1990).

In fractured bedrock, the groundwater flow is mainly dictated by the topography and the direction of the fractures and joints (Boutt et al., 2010; Conboy and Goss, 2000; Novakowsky et al., 2006). In the municipality, the regional groundwater flow-trend is

northwest to southeast, following the Gatineau River. Confining conditions (confined and unconfined aquifers) are estimated from the surficial deposits map (Fig. 3.2). Clay and silt deposits provide an impermeable protective layer to the aquifer below. Areas classified as offshore-marine deposits and landslide areas are therefore interpreted as confined. Even though some areas along the Gatineau River are classified as confined, the aquifer is thought to behave as semi-confined or unconfined because of the proximity to the recharge area. The areas covered by the other deposits (glaciofluvial sediments, organic deposits, till, Precambrian bedrock and near shore marine deposits) are not thought to be protected by an impermeable layer and the aquifer is defined as unconfined. The aquifer conditions are considered confined when the area was covered by the thick layer of silt and clay and unconfined where the surficial sediments were composed of till and glacio-fluvial deposits (Fig. 3.2).

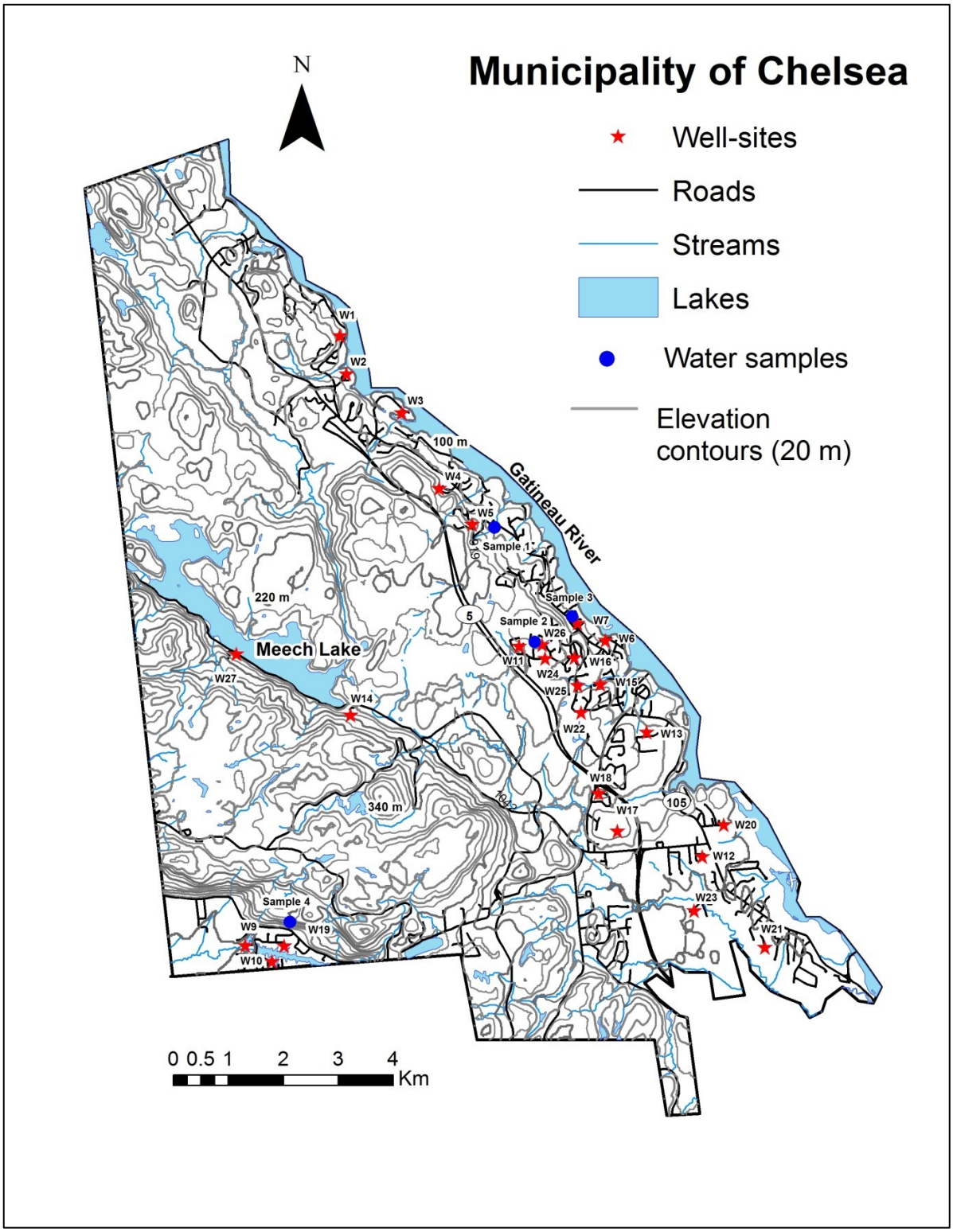


Figure 3.1: Study area of the Municipality of Chelsea, Québec showing sites examined and location of water samples. Contour spacing is 20 m.

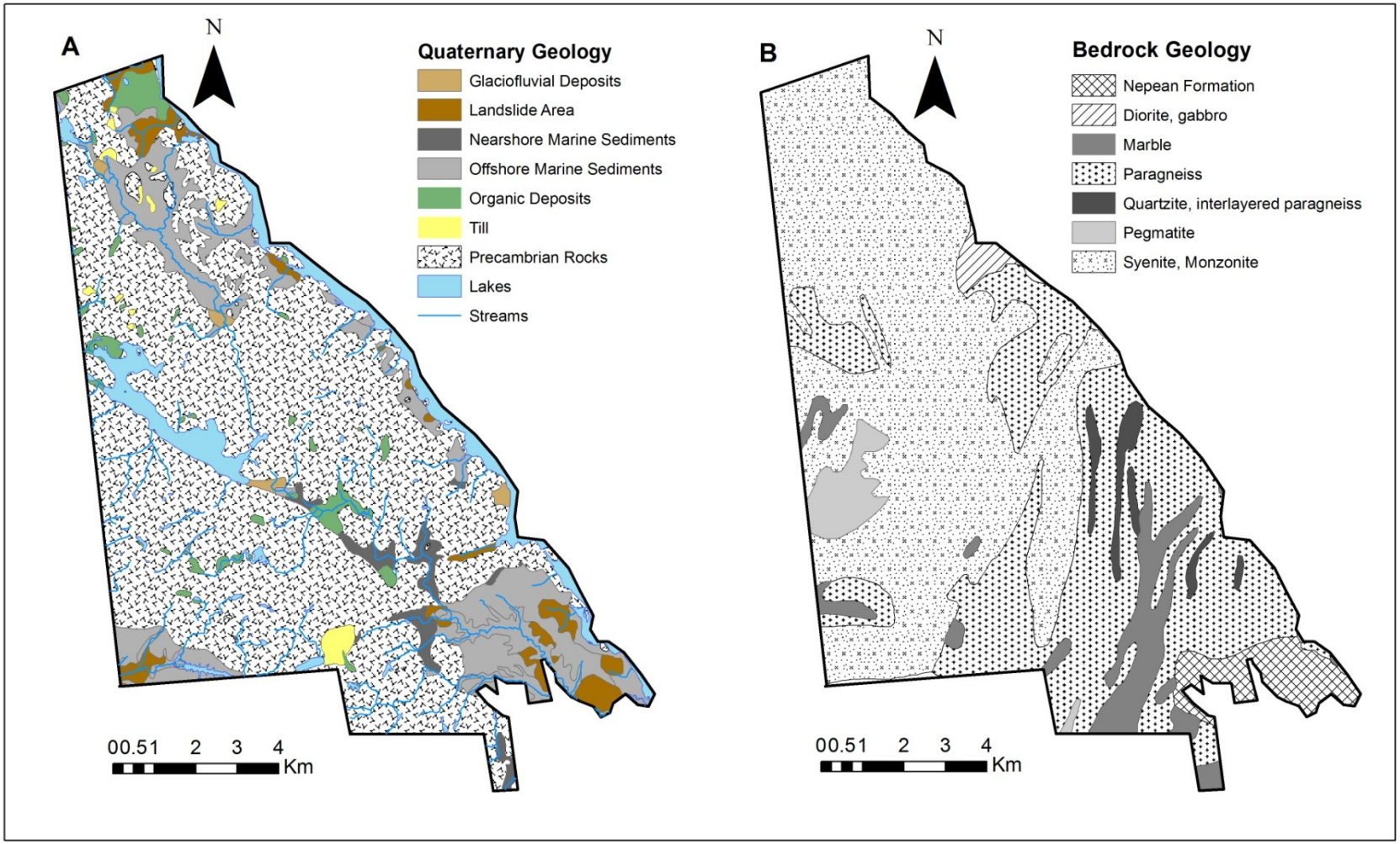


Figure 3.2: A) Geological map of the surficial deposits of the Municipality of Chelsea, Québec. Precambrian rocks indicate the presence of thin surficial deposits. B) Bedrock geological map of the study area (Geological Survey of Canada, 2008).

3.3. Methods

3.3.1. Sampling and analytical procedures

A total of 27 sites were selected for the well survey. All wells are drilled wells, but local characteristics of the site are variable. The sites were selected based on their relative elevation and the confining conditions at the site. The history of contamination of the well was also considered in the selection process, but to a lesser extent. The selection provides a representative dataset of the various combinations of well depth, soil thickness and the geographic location within the Municipality. From the suite of 27 wells, 9 are located in clayey surficial (confined conditions) deposits, whereas the other 18 are in areas with minimal (<1 to 2 m) thickness of surficial deposits.

Four surface water samples were collected in May 2009 at different locations within the Municipality. The purpose of these samples was to provide an estimate of the contribution from the surface water and runoff to the groundwater system. Sample 1 was collected on the side of Municipal Road 105 and is interpreted as representing runoff from the Gatineau Hills. Sample 2 was collected in a wetland by a gravel road at a higher elevation and is interpreted as runoff from the recharge area. Sample 3 was collected in a creek in the lowland area (down from the Gatineau Hills). It could be a mixture of groundwater discharge in the creek and runoff from the hill. Lastly, sample 4 was collected from a spring in the Hallow Glen area. It represents runoff through the Gatineau Park (forest and protected land). The locations of the runoff/surface water samples are indicated in Figure 3.1.

Wells were sampled every month, from April 2008 to May 2009, and analysed for total coliforms, faecal coliforms and ion chemistry. Both water samples (bacteria and chemistry analysis) were collected at the same location inside the house. The well owners (volunteers) had the responsibility to collect the water samples on a specific date. At each site, the samples were consistently collected by the same volunteer. This reduced the uncertainty introduced during water sampling and ensured that it remained the same throughout the sampling period. The volunteers were given directions to remove any aerator from the tap, to let the water run for five minutes before sample collection, and to reduce the flow while collecting the water samples. Instructions were also given to take extra care to avoid touching any component of the bottle opening and to keep the samples

cold (with icepacks) until collection. It is assumed that water samples were collected properly and that the error introduced from collecting the water sample is minimal. The samples were collected in sterile 250 mL bottles containing sodium thiosulphate furnished by a certified laboratory in Ottawa, Ontario. The samples were then picked up, stored in a cooler with ice packs and dropped-off at the laboratory where they were analysed within 24 hours. The private laboratory used the methods 9222B (total coliforms) and 9222D (faecal coliforms) for coliforms enumeration from the protocol: Standard Methods for the Examination of Water and Wasterwater, 21st edition, 2005.

The samples analysed for ion chemistry were collected in 250 mL plastic bottles with a screw cap. The samples were collected immediately after the sample for the bacterial analysis. The volunteers were instructed to leave minimal headspace and to reduce the flow rate while collecting the sample in order to avoid disturbance of the water. The samples were refrigerated until transported to the lab. Samples were filtered and acidified in the laboratory shortly after arrival at the lab. Chemical analysis was completed by a technician at the geochemistry laboratory at the University of Ottawa. Cations ($Ca^{2+,}$ K^{+}, Mg^{2+} and Na^{+}) were analyzed using ICP-AES, whereas anions (F^{-}, Cl^{-}, $SO_4^{2-,}$ NO_3^{-}) were analyzed using ion chromatography. Bicarbonate concentration (HCO_3^{-}) was determined using a portable Hatch titration system in the laboratory shortly after the collection of the water samples. The analytical error on the chemical analysis was within 10%. Samples with errors above this value were not considered for further analysis. Duplicates on the chemical analysis were within 5%.

3.3.2. Statistical Data Analysis

The wells were sampled monthly for a total of 14 months. For each ion, an average of the monthly concentration is calculated and used for statistical analysis. A total of 256 samples from 25 wells are used to describe the geochemistry of the groundwater in the Municipality of Chelsea. Descriptive statistics, box plots, statistical tests (ANOVA and t-test), principal component analysis (PCA) and cluster analysis were performed using Microsoft Excel, PAST software (Hommer et al. 2001) and S-Plus software version 8.0.

PCA is a multivariate statistical analysis used to reduce the complexity in large datasets and provide insights on the structure of the dataset (Davis, 2002; Jolliffe, 2002). PCA was used to identify which of the measured components provide the greatest variation

on the quality of the water. The analysis was applied to the average value for each variable. Censored data were replaced by the detection limits. PCA was applied to 12 variables (Ca^{2+}, $Mg^{2+,}$ Na^{+}, K^{+}, F^{-}, Cl^{-}, NO_3-N, SO_4^{2-}, HCO_3^{-}, pH as well as the relative frequency of contamination for total and faecal coliforms). Log transforms and normalization are commonly used in multivariate analysis (Cloutier et al., 2008; Güler et al., 2002; Moore et al., 2009) and were applied to the chemical dataset of this study. The distributions of the chemical variables are non-normal (Figs 3.5 and 3.6) therefore they were log-transformed and normalized before performing the analysis. The normalized data were obtained by subtracting the distribution mean from the measured values for individual samples and by dividing by the standard deviation of the distribution (Cloutier et al., 2008; Güler et al., 2002; Moore et al., 2009).

Cluster analysis is used to classify samples into geochemical facies based on their similarity (Cloutier et al., 2008; Güler et al., 2002; Mencio and Mas-Pla, 2008). The log-transformed and normalized datasets were used for the cluster analysis. The cluster analysis consists of using a linkage rule which links nearby points by the use of a similarity matrix. Different linkage rules such as complete linkage, average linkage and the Ward's methods are commonly used in HCA (Güler et al., 2002; Mencio and Mas-Pla, 2008). Ward's method differs from the other clustering method because it uses analysis of variance to evaluate the distances between clusters (Güler et al., 2002). Ward's linkage rule combined with the Euclidean distance as the measure of similarity has been shown to form more or less homogeneous and more distinct clusters (Güler et al., 2002; Mencio and Mas-Pla 2008; Cloutier et al., 2008) where each member is more similar than any member from another cluster. For these reasons, Ward's method using the Euclidean distance was selected for the cluster analysis.

3.4. Results and interpretations

3.4.1. Site characteristics

The 27 sampling sites located in Chelsea (Québec, Canada) are representative of the various local settings found on the Municipality and are presented in Table 3.1. The ages of the wells (in 2008) varies from 1 to 40 years. The depth of the wells range from 18

to 108 m and the static water level varies from less <1 to 34 m below ground surface. Most wells are located in the Gatineau Hills where the thickness of the overburden is <2 m. The composition of the surficial material depends on the location of the well. The soil for the sites located near the Gatineau River and in the southwest area of the municipality is composed mainly of clay. The soils at higher elevations are composed mainly of fine-grained material such as silt and fine-grained sand. The wells are also classified according to the confining condition at the site, which was largely determined by the presence or absence of a clayey layer. Nine wells are under confined conditions whereas the other 18 are unconfined. Finally, the wells are classified according to their location relative to the Gatineau Hills or to the Gatineau River. The relative locations are defined as highland, meaning they are the highest residence on the hill; midland indicates the presence of neighbour uphill from the well; and lowland means that the well is located in a flat area near the Gatineau River or the St-Laurence lowlands.

3.4.2. Bacterial quality of groundwater in Chelsea

The results indicate that 86% (23/27) of the wells show the presence of TC at least once and that in 41% (10/27) of the wells, the relative frequency of detection exceeds 50% (Table 3.1). FC are detected less frequently than TC with thirty-seven percent (37%) of the wells testing positive for FC at least once during the sampling period. It is important to note that that 67% of the wells exceeded the Québec drinking water objective of 10 CFU/100mL for TC at least once during the sampling period.

When considered individually, each well characteristic is not found to have a significant impact on the incidence of coliform bacterial over the entire Municipality. For statistical purposes, the wells are classified into categories based on the characteristics of the well and the site location. The categories tested are the well depth, the water level, the presence of grout, the thickness of the surficial deposits, the ground surface grading (or “drainage towards the well”), and the presence or absence of confining conditions at the well. Statistical tests (student-t and ANOVA) were performed to determine which variables contributed to the presence of coliforms in domestic wells. The hypothesis of the tests is that there is no difference between the incidence of TC (TC>0 CFU/100mL and TC≥10 CFU/100mL) or FC (FC>0 CFU/100mL) for the various site characteristics. P-values less than 0.05 are considered significant while p-values between 0.05 and 0.1 are considered

marginally significant (weak relationship). The results of the t-tests and ANOVA show that the only significant variable is the “drainage towards the well” (Table 3.2). This variable is marginally significant only when comparing relative frequency of TC >0 CFU/ 100mL, whereas all the other characteristics of the site show no significant trends.

Figure 3.3 illustrates the spatial distribution of the relative frequency of samples that tested positive for TC. The median value for the relative frequency of detection of TC is 45.8%. The relative frequency of detection is not significantly affected by any variable. Shallower wells have a slightly higher (45 vs. 30%) relative frequency of detection compared to deeper wells (>61 m). The presence of grout in the annular space influences slightly the median value with a relative frequency of TC detection of 29 and 43% for grouted and non-grouted wells, respectively. Moreover, the average frequency of detection is slightly higher when the well is located in the highland (52%) compared to wells located in the midland (38%) and lowland (32%). Wells with an unconfined condition have a slightly lower average relative frequency of detection (34%) compared to wells in a confined condition (40%) and the position of the water level shows that wells with a lower water level have a slightly higher median (48 vs. 29%).

Figure 3.4 illustrates the spatial distribution of the relative frequency of samples contaminated with TC (exceeding the provincial drinking water objective ≥10 CFU/100mL). Again, it is not clear which variables most influence the presence of coliform bacteria. When comparing relative frequencies of samples which exceed the drinking water objective (TC≥10 CFU/100mL), the median is slightly higher for shallower drilled wells (15%) compared to deeper wells (8%). The presence of grout in the annular space, the position of the water level and the confining conditions do not show any significant differences. Finally, when comparing the median values for samples tested positive for FC, no obvious trends are observed (Fig 3.5). The medians are similar irrespective of well depth, of the presence of grout, of the position of the water level and of the confining conditions at the well.

Table 3.1: Characteristics of the wells and site locations.

Well #	Well age (yrs)	Well depth (m)	Water level (m)	Soil thickness (m)	Surficial geology	Hydrogeological conditions	Bedrock geology	Relative location	Total coliforms	Faecal coliforms
W1	40	50	27	<2	sandy silt	unconfined	syenite, monzonite	midland	9/14	1/14
W2	2	45	25	>5	clay	confined	Syenite, Monzonite	lowland	8/11	4/11
W3	30	77	3.3	<1	till	unconfined	syenite, monzonite	lowland	4/14	3/14
W4	22	50	11	<1	till	unconfined	syenite, monzonite	midland	8/14	0/14
W5	15	74	24	<1	till	unconfined	paragneiss	highland	8/14	1/14
W6	12	47.5	7	<1	clayey fine sand	unconfined	paragneiss	lowland	6/14	0/14
W7	15	75	10	>5	clay	confined	quartzite/paragneiss	midland	1/13	0/13
W9	20	50	7.7	>5	clay	confined	syenite, monzonite	lowland	6/13	0/13
W10	20	30	6	>5	clay	confined	syenite, monzonite	lowland	7/12	1/12
W11	20	65	5	<1	till	unconfined	paragneiss	midland	10/14	1/14
W12	20	58	24.5	>5	clay	confined	paragneiss	lowland	5/14	0/14
W13	4	90	5.4	<2	silty fine sand	Unconfined	paragneiss	midland	0/14	0/14
W14	20	67	16	<1	sandy silt	unconfined	syenite, monzonite	highland	1/13	0/13
W15	6	35.1	2.5	<1	fine grain sand	unconfined	paragneiss	midland	0/14	0/14
W16	15	77	16	<1	silty fine sand	unconfined	quartzite/paragneiss	highland	11/12	4/12
W17	2	93.5	17.8	<1	silty fine sand	unconfined	paragneiss	highland	4/14	0/14
W18	1	108	10.7	<2	fine sand	unconfined	Marble	highland	6/12	0/12
W19	20	56	3	>5	clay	confined	syenite, monzonite	lowland	4/14	0/14
W20	10	35	29	>5	clay	confined	quartzite/paragneiss	lowland	0/13	0/13
W21	15	84	10.6	>5	clay	confined	sandstone	lowland	3/14	0/14
W22	15	35.5	3	<1	sandy silt	unconfined	quartzite/paragneiss	midland	0/14	0/14
W23	20	54	34	<5	sandy silt	confined	paragneiss	highland	7/13	0/13
W24	6	60	0.5	<2	clayey sand	unconfined	paragneiss	midland	3/14	0/14
W25	18	80	0.5	<2	till	unconfined	quartzite/paragneiss	midland	5/13	1/13
W26	15	41.22	2.6	<2	fine sand	unconfined	paragneiss	midland	6/11	1/11
W27	1	18	6	>5	medium/coarse sand	unconfined	pegmatite	lowland	4/14	1/14

Notes:

Well age:	in 2008
Water level:	m below ground surface
Location:	relative emplacement of the well to the Gatineau Hills
Value given as fraction:	positive samples/total number of samples
Hydrogeological condition:	at the well

Table 3.2: Results of the statistical tests performed on the 13 characteristics of the sites.

Characteristics of the well-site	Categories tested (N of samples)	Statistical test	p-value (TC>0)	p-value (TC≥10)	p-value (FC>0)
Vented-sealed cap	Y (6) N(21)	t-test (unequal var)	0.80	0.88	0.56
Insects inside the well	Y (13) N(11) (2 unknown)	t-test (unequal var)	0.41	0.78	0.23
Presence of tree/flowers within 2 feet	Y (13) N(14)	t-test (unequal var)	0.12	0.74	0.42
Area sunk around the well	Y (4) N(23)	t-test (unequal var)	0.85	0.87	0.50
Drainage towards the well	Y (19) N(8)	t-test (unequal var)	0.06	0.11	0.79
Distance to septic	>31 (14), <30 (12) (1 no septic)	t-test (unequal var)	0.86	0.71	0.82
Relative location	lowland (10), midland (11), highland (6)	ANOVA	0.58	0.16	0.34
Surficial geology	clay (8), fine graine (12), till (7)	ANOVA	0.40	0.96	0.97
Estimate soil thickness	>5 (10), <5 (8), <1(9)	ANOVA	0.72	0.93	0.46
Water level	above (10)/ below (17) casing show	t-test (unequal var)	0.22	0.42	0.69
Well depth	<60.9, >61	t-test (unequal var)	0.79	0.82	0.47
Well age	> 10 (08), 10-20 (8), <20 (11)	ANOVA	0.19	0.86	0.36
Presence of grout	Y (6) N(21)	t-test (unequal var)	0.43	0.74	0.24

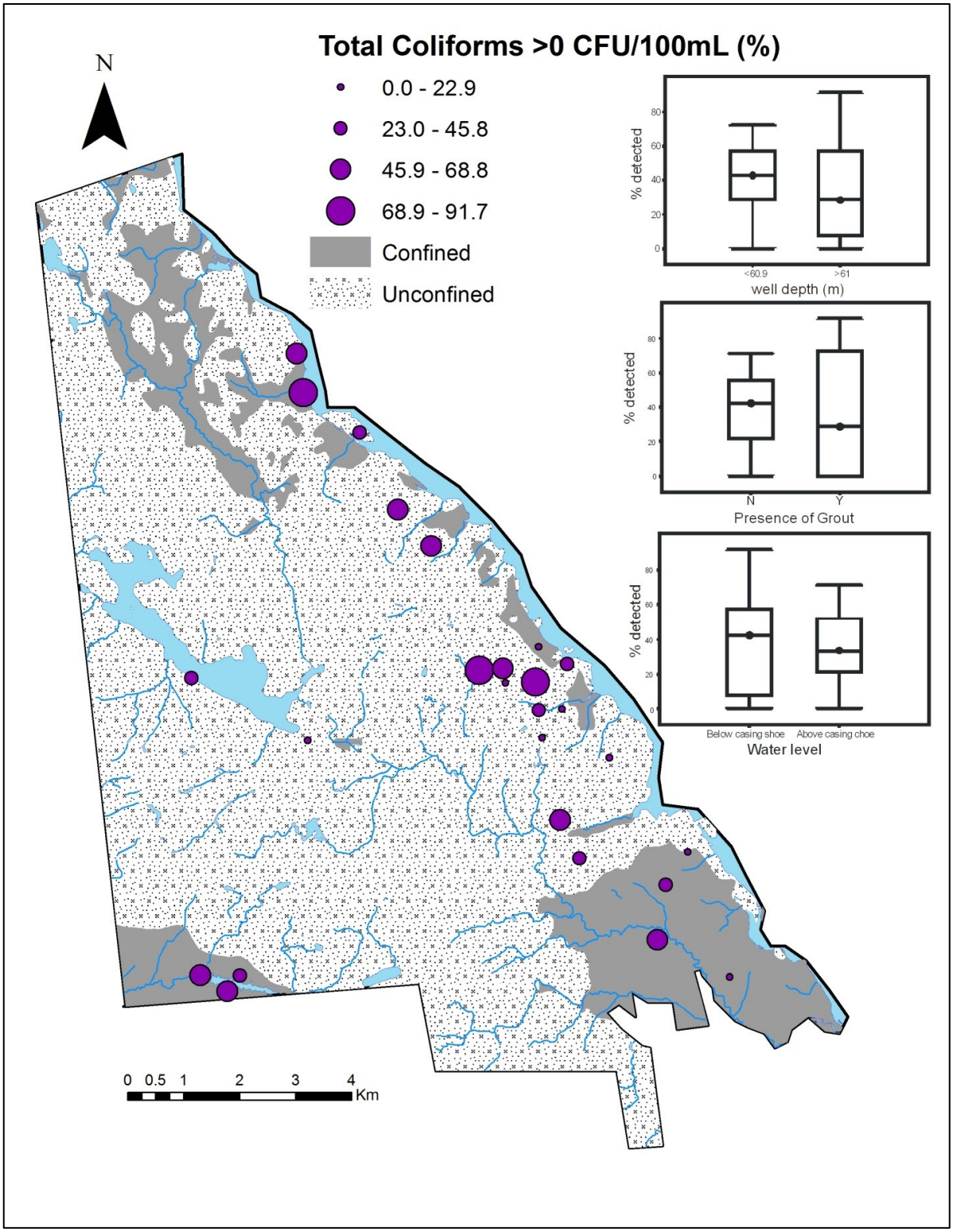


Figure 3.3: Spatial distribution of total coliforms (% of sampling events where TC>0 CFU/100mL).

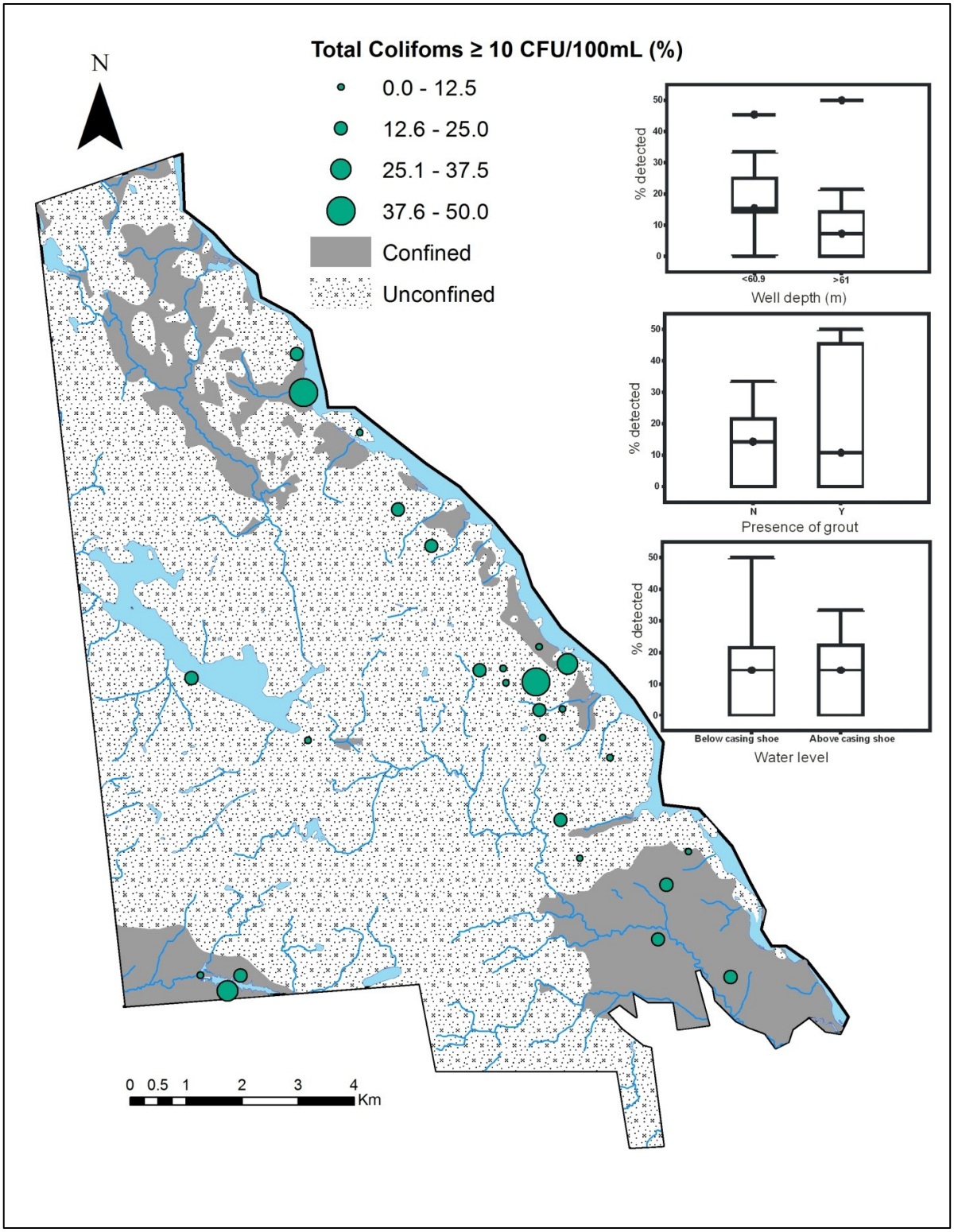


Figure 3.4: Spatial distribution of total coliforms (% of sampling events where TC ≥ 10 CFU/100mL).

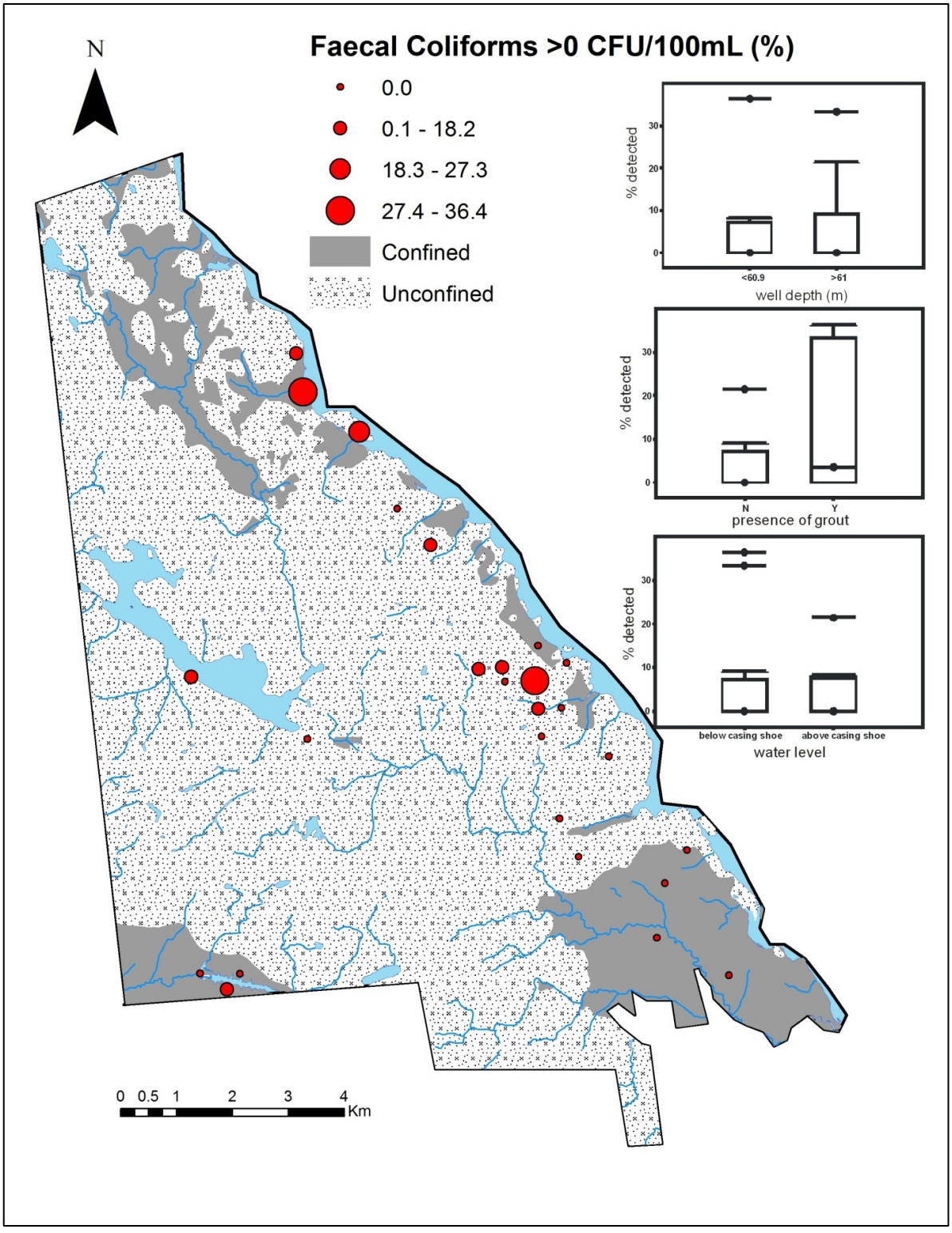


Figure 3.5: Spatial distribution of faecal coliforms (% of sampling events where FC > 0 CFU/100mL).

Table 3.3: Results of the chemical analysis and groundwater facies of the water wells in Chelsea.

Well ID	Concentrations (mg/L)										Piper Diagram
	Ca	K	Mg	Na	F	Cl	NO_3-N	SO_4	HCO_3	pH	Groundwater Facies
W1	68.58	2.00	25.57	26.26	0.74	30.34	0.51	42.85	284.40	7.18	Ca-HCO_3
W4	56.56	1.55	5.81	2.12	bdl	3.90	0.45	10.50	160.78	7.17	Ca-HCO_3
W5	49.51	2.06	8.92	12.66	bdl	18.94	1.22	22.11	150.20	6.78	Ca-HCO_3
W7	75.48	1.95	11.33	16.03	0.58	55.87	0.71	29.67	184.14	7.11	Ca-HCO_3
W11	37.57	1.12	8.28	6.95	bdl	13.34	0.11	15.85	123.02	6.68	Ca-HCO_3
W13	111.33	2.27	10.54	23.50	bdl	57.49	2.35	106.45	214.69	7.15	Ca-HCO_3
W14	37.30	1.25	5.35	6.12	1.57	3.25	0.14	16.33	131.25	7.19	Ca-HCO_3
W15	121.57	1.54	8.54	47.34	0.85	91.44	0.55	99.86	249.81	7.09	Ca-HCO_3
W17	47.02	0.53	4.65	36.16	1.33	1.32	bdl	65.61	181.76	7.30	Ca-HCO_3
W20	52.13	3.51	12.72	27.67	bdl	66.42	bdl	29.60	144.35	7.42	Ca-HCO_3
W22	64.11	1.36	8.58	7.61	1.26	20.52	bdl	25.91	167.45	7.14	Ca-HCO_3
W24	56.64	2.29	10.37	11.94	0.69	32.05	0.12	16.06	171.03	6.90	Ca-HCO_3
W27	30.15	1.15	2.86	1.27	bdl	1.14	0.72	13.24	83.72	6.65	Ca-HCO_3
W9	7.85	2.20	3.98	86.71	1.64	17.31	bdl	41.40	178.59	8.18	Na-HCO_3
W10	24.21	4.13	11.32	53.41	0.78	27.40	bdl	35.39	169.78	7.77	Na-HCO_3
W23	8.48	4.01	7.21	113.83	2.40	10.66	bdl	20.95	306.40	8.00	Na-HCO_3
W25	43.03	2.11	7.17	57.51	1.33	29.40	bdl	79.31	157.05	7.42	Na-HCO_3
W26	48.32	1.64	6.28	18.22	0.50	89.59	bdl	22.69	65.80	6.24	Ca-Cl
W16	71.57	10.87	14.19	20.50	bdl	97.38	0.48	33.71	151.62	6.70	Ca-Mixed anions
W6	82.07	2.94	60.98	54.93	bdl	191.55	0.73	36.55	291.54	6.91	Mixed Cations-Cl
W3	54.37	3.17	10.70	39.06	1.52	8.14	bdl	32.81	237.96	7.19	Mixed Cations-HCO_3
W2	28.00	14.32	27.13	75.32	1.06	46.97	0.17	24.08	343.10	7.99	Mixed Cations-HCO_3
W12	17.51	3.37	5.67	109.23	0.98	67.86	0.11	129.70	110.74	7.96	Na-Mixed Anions
W18	70.10	3.12	11.25	158.94	0.47	167.79	0.74	91.99	303.14	7.20	Na-Mixed Anions
W19	13.75	5.08	7.55	123.46	1.96	59.99	bdl	101.49	175.79	7.69	Na-Mixed Anions
Mean	51.09	3.18	11.88	45.47	1.16	48.40	0.61	45.76	189.52	7.24	
StDev	28.76	3.07	11.72	43.12	0.54	49.34	0.58	34.75	72.23	0.48	
Min	7.85	0.53	2.86	1.27	0.47	1.14	0.11	10.50	65.80	6.24	
Max	121.57	14.32	60.98	158.94	2.40	191.55	2.35	129.70	343.10	8.18	
CV(%)	56.29	96.58	98.65	94.82	46.96	101.93	95.12	75.94	38.11	6.66	
Skewness	0.72	2.97	3.35	1.92	1.09	1.57	3.14	1.21	0.59	-0.03	

3.4.3. Chemical characteristics of the groundwater in Chelsea

Chemical analyses show that both cations and anions are spatially variable and that a number of different groundwater facies are identified over the study area (Table 3.3, Figs. 3.6 – 3.9). Although local bedrock geology is the primary control for much of the displayed variation, other factors such as recharge in preferential recharge areas, aquifer conditions (i.e. confined vs. unconfined) or anthropogenic factors (i.e. proximity to other residences) appear to be important as well. Table 3.3 presents the complete descriptive statistics of the 10 chemical variables monitored during the monthly sampling period from April 2008 to May 2009, including the coefficient of variation (CV), the coefficient of skewness and

classification of the groundwater facies on a Piper diagram. The CV describes the variability between sample locations for a given component as a relative standard deviation; and the coefficient of skewness gives the degree of skewness of the distribution relative to a normal distribution. From the dataset, chloride (Cl^-) shows the highest variability (as CV) followed by Mg^{2+}, K^+ , Na^+, NO_3-N, SO_4^{2-}, Ca^{2+}, F^- and HCO_3^-. The pH is the component showing the lowest variability with all samples characterized by circum neutral values for pH in the range of 6.24 to 8.18 with an average of 7.23.

Figures 3.6 and 3.7 illustrate the spatial distribution of the major-ions based on the bedrock geology. The concentrations of the cations and anions are classified based on the 25th, 50th, 75th and 100th percentiles. The concentration of Ca^{2+} (Fig. 3.6a) ranges from 7.85 to 121.57 mg/L with a median of 49.51 mg/L. The lower concentrations (< 49.51 mg/L) are located in the central portion of the Municipality, near Meech Lake and the Gatineau River (W2). Some wells (W11, W17, W26 and W25), located at higher elevations in the Gatineau Hills also show a lower concentration of Ca^{2+}. Most wells located within igneous bedrock show a concentration of Ca^{2+} below the median value. Only the wells W1 and W4 show a concentration above the median in this type of bedrock. The highest concentration of Ca^{2+} is found in the eastern part of the Municipality. The bedrock in this area is composed mainly of metamorphic rock (paragneiss, marble and quartzite). The concentration of Mg^{2+} varies from 2.86 to 60.98 mg/L with a median value of 8.58 mg/L (Fig. 3.6b). The concentration Mg^{2+} appears to increase towards the discharging areas with concentrations of K^+ and Na^+ following similar spatial trends. The concentration of K^+ varies from 0.53 to 14.32 mg/L whereas the concentration of Na^+ ranges from 1.27 to 158.94 mg/L. The median values are 2.20 and 27.67, respectively. The distribution of K^+ and Na^+ do not appear to be related to the bedrock geology (Fig. 3.6 c and d). The highest concentrations of these cations are found along the Gatineau River and in the southern portion of the Municipality, mainly in the vicinity of discharge areas.

The concentrations of anions also show spatial variability in the Municipality. Figure 3.7 illustrates the spatial variability of HCO_3^-, Cl^-, SO_4^{2-} and F^- and the relationship with the bedrock geology. The concentration of HCO_3^- varies from 65.8 to 343.3 mg/L with a median of 171 mg/L. The distribution of HCO_3^- does not appear to correlate to the bedrock geology, but shows a lower concentration in the recharge areas with increases towards discharge areas (Fig. 3.7a). A similar trend is observed for SO_4^{2-} (Fig. 3.7b). The concentration of SO_4^{2-} ranges from 10.5 to 129.7mg/L with a median of 32.8 mg/L. There is no clear

relationship between the distribution of Cl^- and bedrock geology. The concentration varies from 1.14 to 191.6 mg/L, and is relatively lower in the recharge areas whereas it increases towards the discharge areas. The concentration of F^- ranges from below the detection limit (<0.5) to 2.40 mg/L. The distribution of F^- appears to be related to the bedrock geology since the samples with the highest concentrations are mostly found where groundwater flows through the igneous rocks. In most cases, the NO_3-N values are below the limit of detection, however, when detected, the average concentration for NO_3-N ranges from 0.12 to 2.35 mg/L.

Figure 3.8 shows the chemical composition of the samples on a Piper diagram (Piper 1944), which illustrates the variability of ion chemistry over the Municipality. The Piper diagram shows the dispersion of the major cation and anion concentrations in groundwater samples based on confining conditions (confined or unconfined). Most wells in an unconfined aquifer plot near the runoff and surface water samples, which are also displayed on the Piper diagram. Hydrogeochemical facies of the Chelsea area vary broadly from Ca-HCO_3, Na-HCO_3 or mixed cations-HCO_3 type to Ca (or mixed cations)-Cl or Ca-mixed anions. The facies of the runoff/surface water samples are classified as Ca-HCO_3 water type. The wells under confined condition are distributed more broadly in the various zones of the diagram. Some wells are located along the lower right side of the diamond shape of the diagram in the Na-HCO_3 and Ca-Cl zones and whereas others in the Ca-HCO_3 zone.

The spatial distribution of the groundwater facies varies across the municipality (Fig. 3.9); but the predominant groundwater type is Ca-HCO_3 and the wells characterized by this facies are located mainly within Precambrian bedrock where the thickness of the overburden is minimal. In general, wells exhibiting the Ca-HCO_3 facies are located in the highland of the Gatineau Hills or where there is minimal clustering of residences. The Na-HCO_3 (or mixed anions) type is located mainly in the southern section of the municipality, on the St-Laurence lowland. The mixed groundwater types are clustered in an area of the Municipality with a high density of residences (Fig. 3.9).

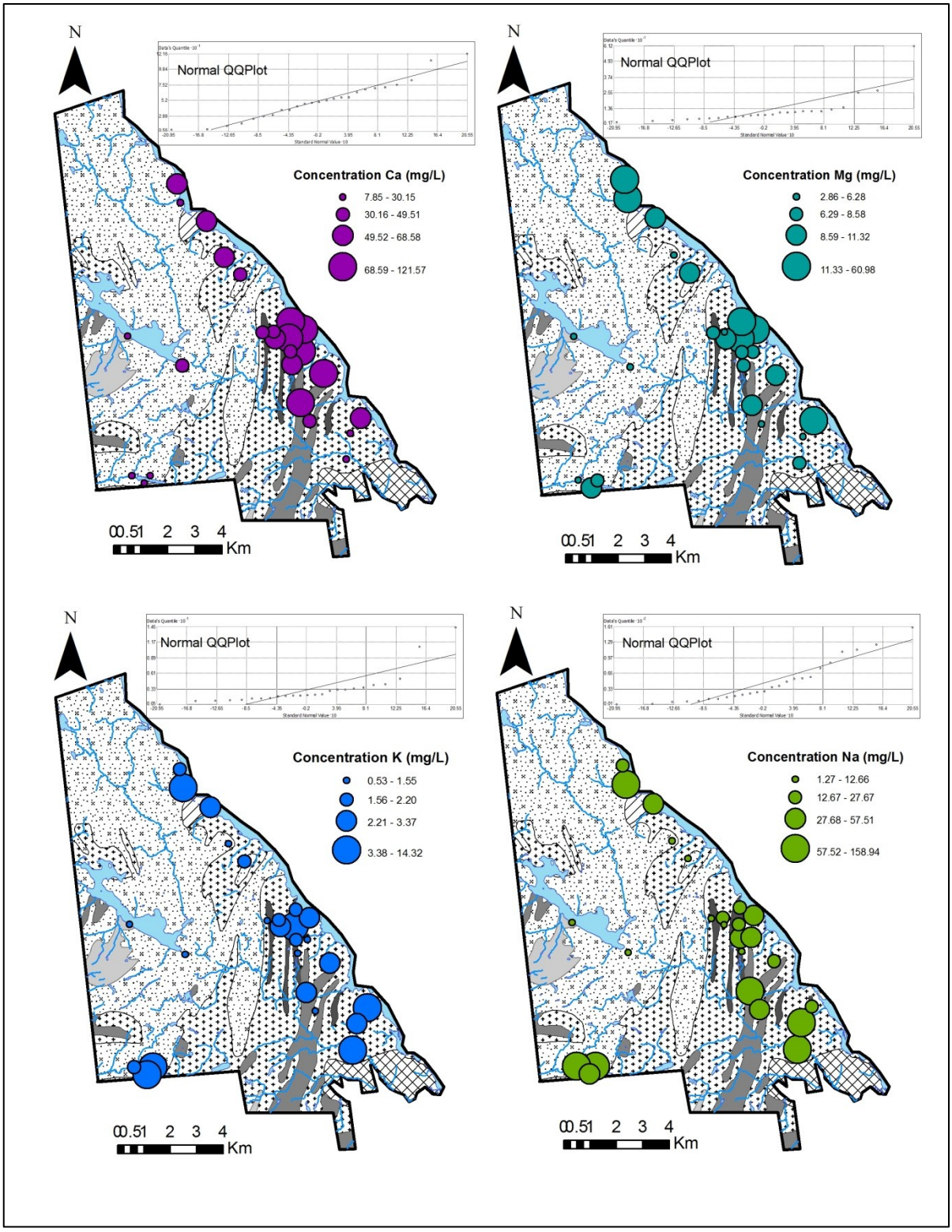


Figure 3.6: Distribution of the major cation species within the Municipality limits (percentiles 25, 50, 75, 100). Legend for bedrock geology is the same as in Figure 3.2.

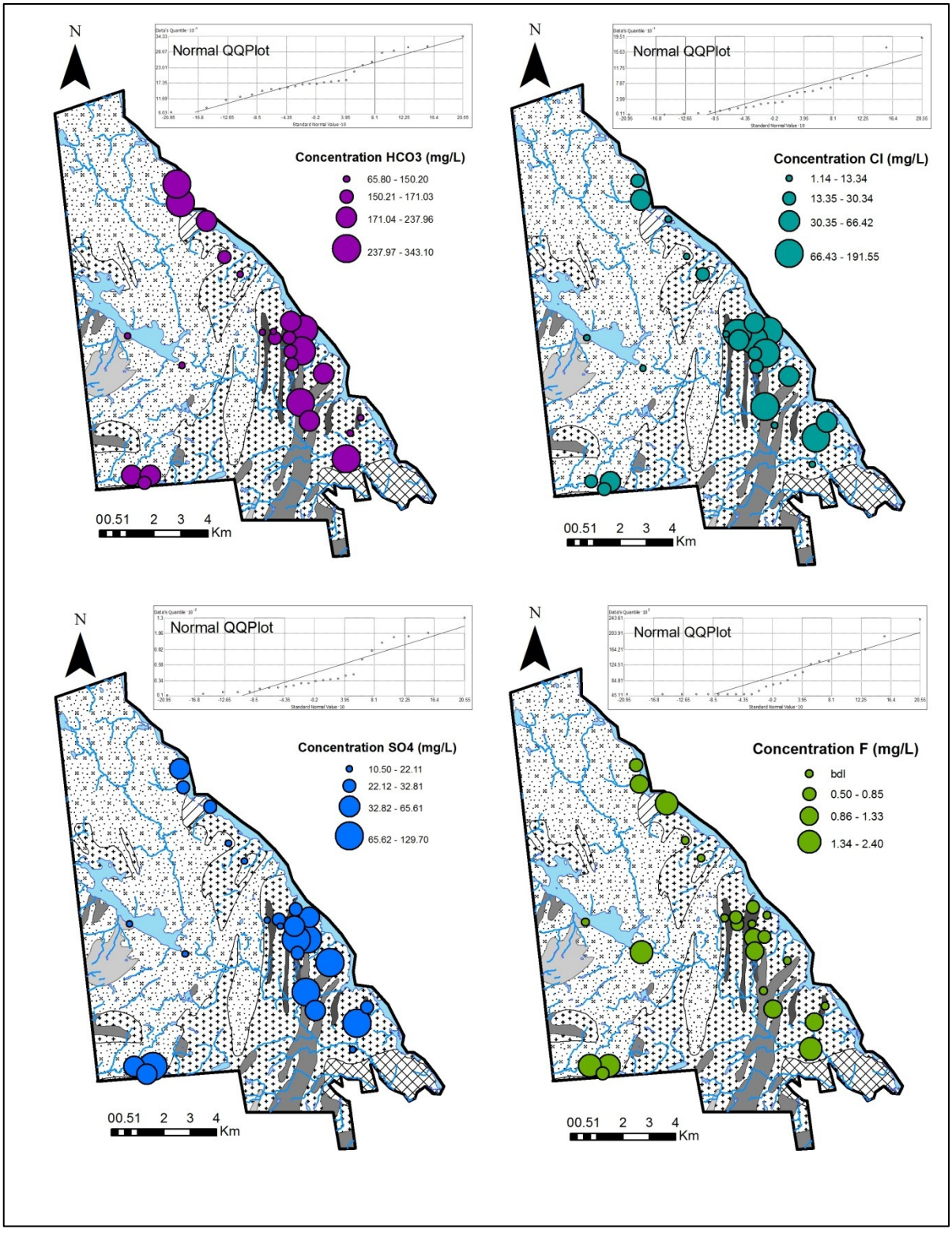


Figure 3.7: Distribution of the major cation species within the Municipality limits (percentiles 25, 50, 75, 100). Legend for bedrock geology is the same as in Figure 3.2.

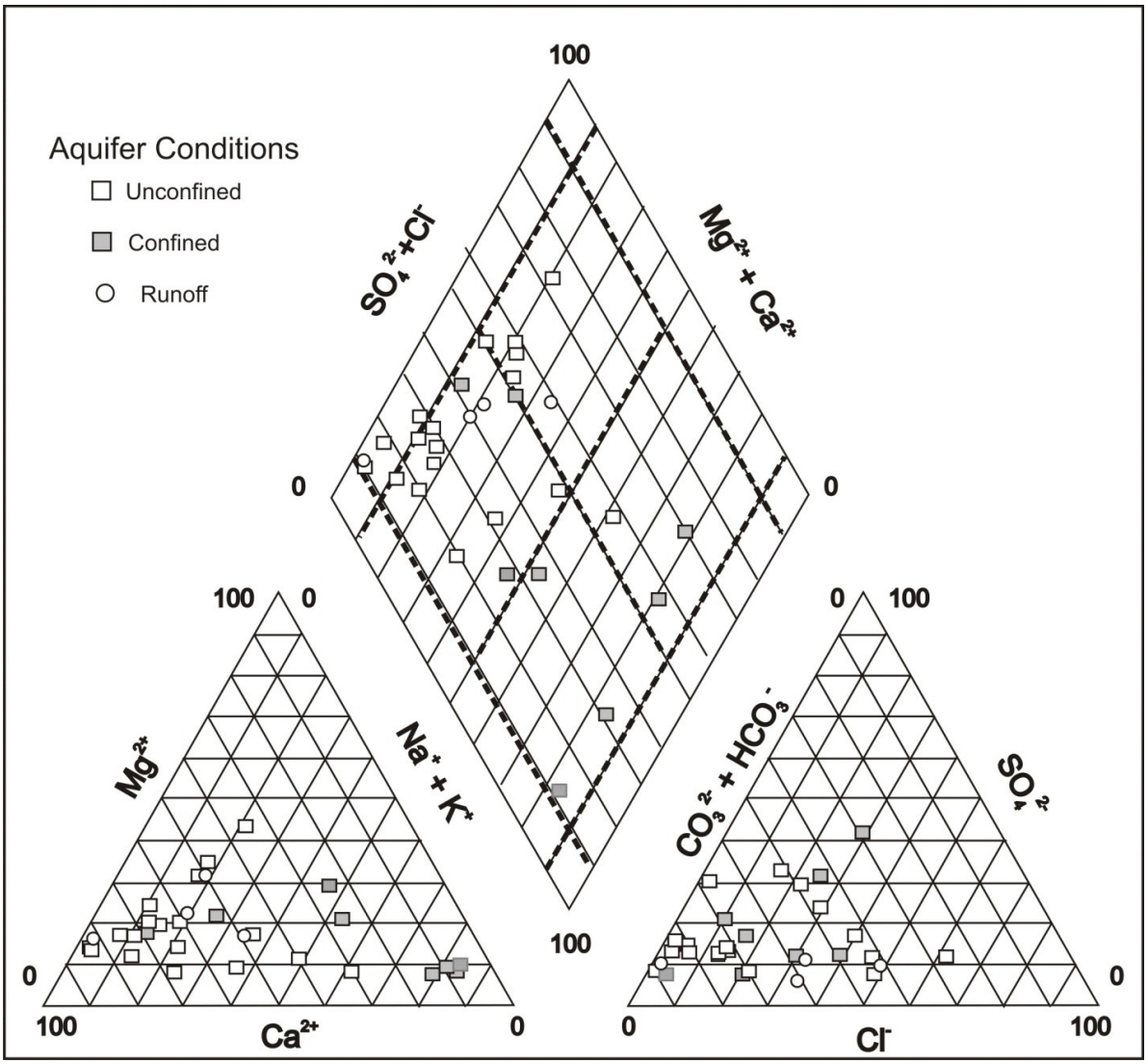


Figure 3.8: Piper diagram representing the results of the chemical analysis for the wells and the runoff samples as well as the aquifer conditions at the site.

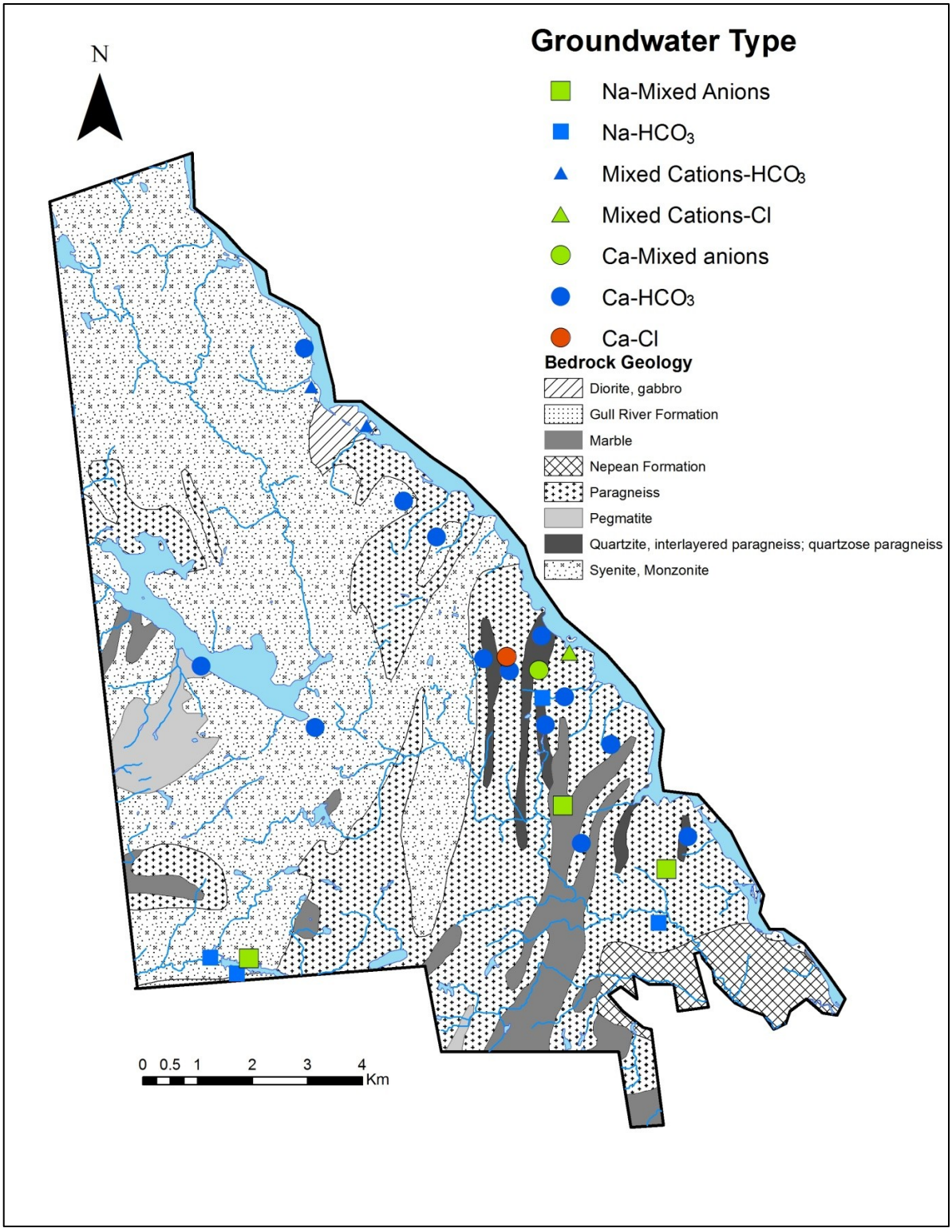


Figure 3.9: Spatial distribution of groundwater groups based on the Piper diagram classification.

Table 3.4: Correlation matrix for the 12 bacteriological and chemical variables measured. Values in bold indicate significant correlations (p-value <0.05).

	F^-	Cl^-	NO_3-N	SO_4^{2-}	Ca^{2+}	K^+	Mg^+	Na^+	HCO_3^-	pH	TC	FC
F^-	1.00											
Cl^-	**-0.40**	1.00										
NO_3-N	**-0.66**	0.26	1.00									
SO_4^{2-}	0.14	**0.53**	-0.05	1.00								
Ca^{2+}	**-0.55**	**0.46**	**0.62**	0.16	1.00							
K^+	0.08	**0.48**	-0.20	0.30	-0.18	1.00						
Mg^+	-0.39	**0.56**	0.29	0.14	**0.53**	**0.52**	1.00					
Na^+	0.35	**0.43**	-0.30	**0.69**	-0.28	**0.65**	0.16	1.00				
HCO_3^-	0.22	0.19	0.17	0.34	0.27	0.34	**0.49**	**0.54**	1.00			
pH	**0.64**	-0.13	**-0.53**	0.37	**-0.55**	**0.49**	-0.07	**0.68**	*0.38*	1.00		
TC	-0.10	0.02	-0.02	-0.16	-0.29	0.36	0.23	0.21	0.11	0.12	1.00	
FC	-0.15	0.04	-0.05	-0.29	-0.03	0.19	0.25	-0.11	-0.11	-0.28	**0.50**	1.00

Table 3.4 presents the correlation matrix of the 12 bacteriological and chemical components, distinguishing relevant hydrochemical relationships (indicated by values in bold). The dataset is non-normally distributed, therefore, Spearman correlations are used to identify the significant relationships between ionic species. There is a positive correlation between Na^+, K^+ and Cl^-, between Cl^-, Ca^{2+} and Mg^{2+}, and between SO_4^{2-}, Na^+ and Cl^-. Nitrate (as N) positively correlates with Ca^{2+}. Positive correlations also exist between HCO_3^- and Na^+ and HCO_3^- and Mg^{2+}. Lastly, F^- negatively correlates with Ca^{2+}, NO_3-N and Cl^-.

The concentration of major-ions in groundwater results from the interaction between the water and the rocks. Calcium and Mg^{2+} in groundwater are derived from the dissolution of feldspars and carbonates present in the till (Clark and Fritz, 1997) or the underlying bedrock. The dissolution of carbonates is enhanced by the CO_2 produced through the oxidation of organic matter following these series of reactions (Appelo and Postma, 2005):

$$CH_2O + O_2 \rightarrow H_2O + CO_2 \quad (1)$$

$$CaMg(CO_3)_2 + CO_2 + H_2O \rightarrow Mg^{2+} + 2HCO_3^- + CaCO_3 \quad (2)$$

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^- \quad (3)$$

These reactions increase the concentration of Ca^{2+}, Mg^{2+} and HCO_3^- in the groundwater. Possible additional sources of HCO_3^- include the oxidation of organic matter and plant-root respiration (Halim et al., 2010). Increases in these ions are the direct result of natural processes. However, in a study by Robertson et al. (1991), the authors

mentioned that the presence of Ca^{2+} and HCO_3^- may also be attributed to anthropogenic activities such as septic effluents in residential developments.

The relationships between some of the components are illustrated in the bivariate plots of Figure 3.10. Calcium shows no correlation to Mg^{2+} (R^2=0.1) and there is no correlation between Ca^{2+} + Mg^{2+} versus HCO_3^- (Figure 3.10d). This suggests that the concentrations of Ca^{2+}, Mg^{2+} and HCO_3^- may have various origins such as dissolution of carbonate present in the till, weathering of silicate minerals and/or anthropogenic activities. The ionic species concentrations are normalized by Na^+ because molar ratios are independent of evaporation and dilution process compared to absolute concentration (Gaillardet et al., 1999). When Ca^{2+} and Mg^{2+} are normalized by Na^+, the correlation becomes stronger (R^2=0.81) suggesting that most of the Mg^{2+} has been derived from the same source as Ca^{2+}. The Na^+-normalized plot of Ca^{2+} versus HCO_3^- (R^2=0.99) also suggests that these species have similar origins which may be the dissolution of carbonate species. Carbonate species are present in the overburden and dissolution may be enhanced by the oxidation of organic matter at the surface (Halim et al., 2010). An alternative source of Ca^{2+} is from weathering of marble bedrock. The results from the bivariate plots suggesting similar origins for Ca^{2+}, Mg^{2+} and HCO_3^- are supported by the positive correlations between Ca^{2+} and Mg^{2+} and between Mg^{2+} and HCO_3^- (Table 3.4) which also suggest that dissolution of carbonate species is the source of these ions in the groundwater system. Lastly, the dissolution of carbonates appears to occur in a closed system condition with a PCO_2 of 1.5 (Clark and Fritz, 1997) (Fig. 3.11). Some samples also fall close to the calcite saturation line suggesting dissolution of calcite in saturated condition (Clark and Fritz, 1997), which may occur in the underlying bedrock. However, more data on carbon isotopes or dissolve organic carbon for instance, would be needed to properly describe the weathering process encounter along the recharge pathways.

The weathering of silicates contributes to the concentration of Na^+, K^+ and F^- in the groundwater and the process is usually slower compared to carbonate weathering processes (Clark and Fritz, 1997). A plot of (Ca^{2+} + Mg^{2+}) against (HCO_3^- +$SO4^{2-}$) is used to assess the origins of weathering in the system (Fig. 3.12). The data points falling along, or close to the 1:1 line indicate possible silicate and carbonate dissolution (Yidana and Yidana, 2010). Samples falling above this line are influenced by silicate weathering and ion-exchange processes, whereas the samples below this line are influenced by carbonate weathering. The negative correlation between F^- and Ca^{2+}, NO_3-N and Cl^-, suggests that F^-

originates from water-rock interactions in a groundwater system with longer residence time, whereas the other ions would be allochthonous to the system or from a system with short residence and time possibly impacted by anthropogenic activities, as indicated by the occurrence of Cl^-.

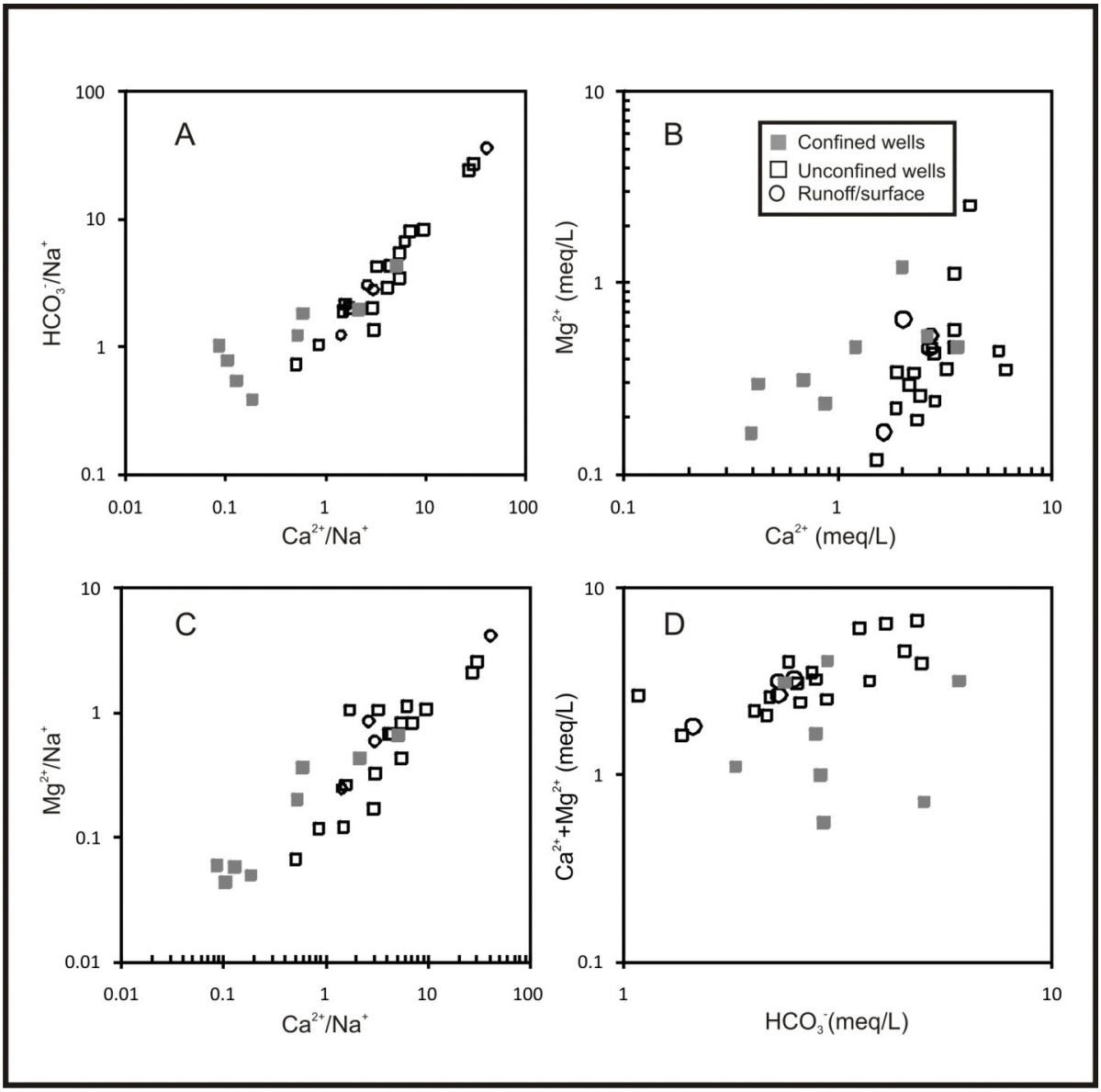


Figure 3.10: Bivariate plots of cations: a) HCO_3^- versus Ca^{2+} normalised by Na^+; b) Mg^{2+} versus Ca^{2+}; c) Mg^{2+} versus Ca^{2+} normalised by Na^+; and d) Ca^{2+} + Mg^{2+} versus HCO_3^-. Open circles represent surface water and runoff samples.

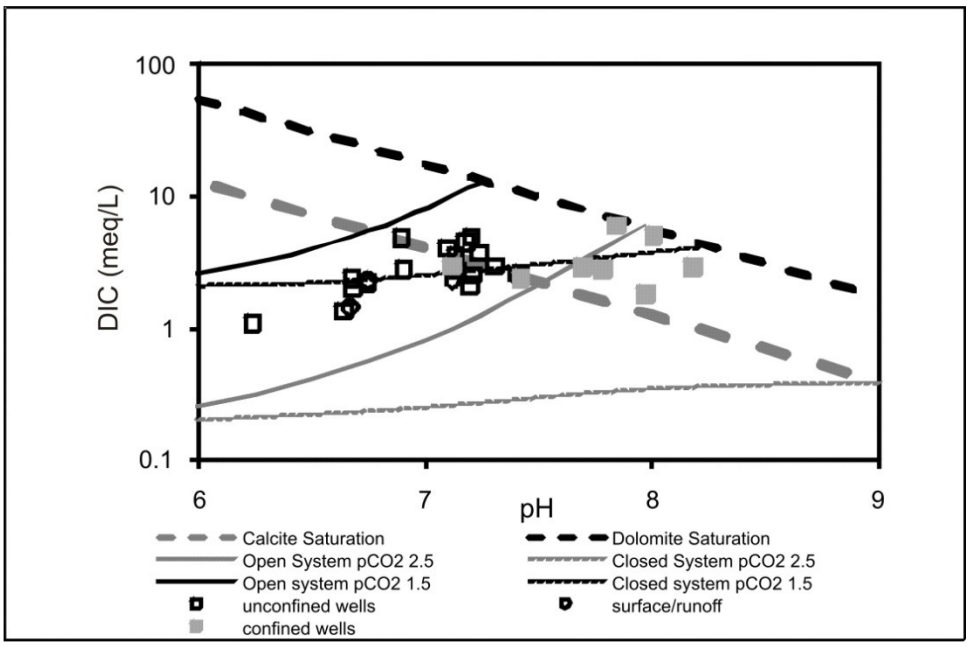


Figure 3.11: Evolution of pH and DIC of surface (triangles) and groundwater (squares) samples in the Municipality of Chelsea.

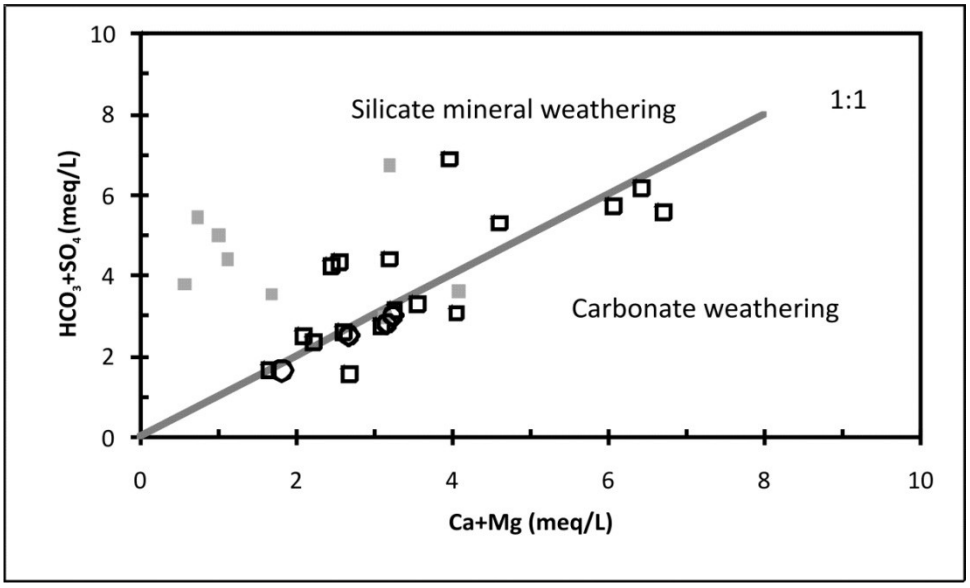


Figure 3.12: Bivariate plot of of HCO_3+SO_4 versus Ca + Mg showing the origins of weathering in the Municipality of Chelsea.

The samples showing a Na-HCO_3 groundwater facies exhibit a higher concentration of Na^{2+} with respect to Ca^{2+} and Mg^{2+}, indicating Ca-Na ion-exchange. The role of the ion-exchange process is assessed in Figure 3.13. The plot of [(Ca^{2+} + Mg^{2+})-(HCO_3+SO_4^{2-})] against (Na^++K^+-Cl^-) shows that the slope of the data points is close to -1. Since there is an increase of (Na+K) related to a decrease in (Ca^{2+}+ Mg^{2+}) or increase in (HCO_3+SO_4^{2-}), it is possible that Ca^{2+}, Mg^{2+} and Na^+ participate in the cation exchange process (Jalali, 2007). The wells showing the Na-HCO_3 facies are located under confined aquifer condition where the confining layer is composed of the Champlain Sea clays. The presence of these marine clays enables the natural water softening process, whereby Na^+ present on the surface of the mineral replaces Ca^{2+} in the groundwater (Appelo and Postma, 2005). Cloutier et al. (2006, 2010) also observed this process in an area proximal to the study area, on the North shore of the St. Lawrence River (northwest of Montréal, Québec).

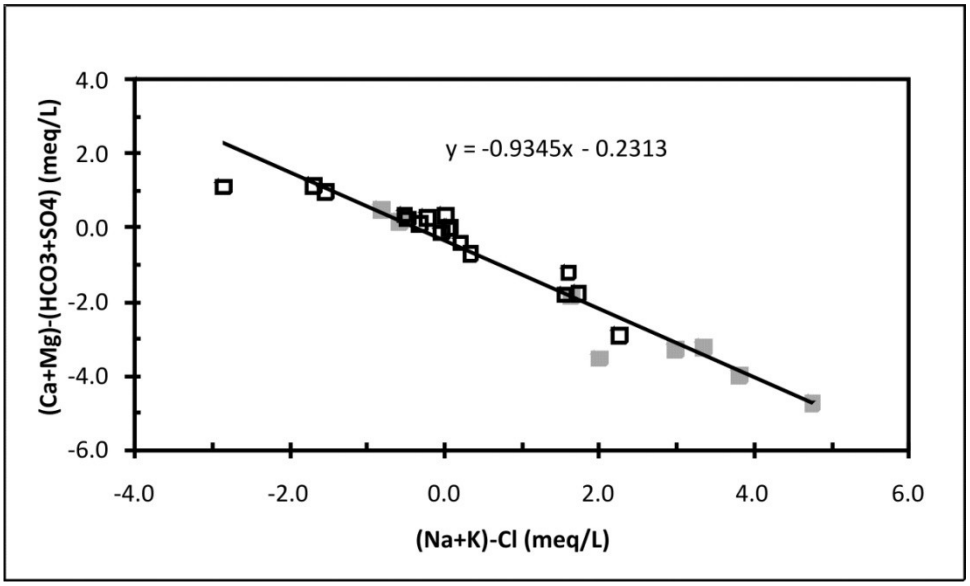


Figure 3.13: Bivariate plot showing the possiblity of of the occurrence of the Na-Ca cation exchange process.

Natural sources of SO_4^{2-} include the oxidation of sulphide minerals such as pyrite following this equation (Wang et al., 2001):

$$4FeS_2 + 15O_2 + 14H_2O \rightarrow 4Fe(OH)_3 + 8SO_4^{2-} + 16H^+ \quad (4)$$

Anthropogenic sources of SO_4^{2-} include sewage effluents and application of fertilizer containing $(NH_4)_2SO_4$. Sulphate is also a redox-sensitive species where at depth it is reduced to H_2S (Clark and Fritz, 1997).

Along with application of fertilizers and road salts, septic effluents may contribute to Cl^- into the groundwater system (Robertson et al., 1991). Natural sources of Cl^- include dissolution of halite or mixing with crustal fluids (Clark and Fritz, 1997), but these are not considered applicable in the study area. Precipitation in the Ottawa area has been shown to not provide a significant input of SO_4^{2-} and Cl^- into the groundwater system (Natchem, 2010). Therefore, the concentration of Cl^- in the groundwater may be impacted by septic effluents as the positive relationship between Na^+, K^+ and Cl^- suggests. Sodium and K^+ may result from the weathering of feldspars, but Cl^- is usually not a component of feldspars. The positive correlation between SO_4^{2-}, Na^+ and Cl^- may also indicate mixing with water from anthropogenic sources. Lastly, the relationships between Cl^-, Ca^{2+} and Mg^{2+}, and between HCO_3^- and Na^+ may imply that Cl^- and Na^+ originate from the surface, if Ca^{2+}, Mg^{2+} and HCO_3^- result from dissolution through the Quaternary sediments in the overburden.

Nitrate is considered one of the most common contaminants in agricultural watersheds, which results from the application of manure and fertilizers. Nitrates are also found in sewage effluents (Clark and Fritz, 1997). Natural sources of NO_3^- include oxidation of organic nitrogen (N) to NO_3^- released during the degradation of organic matter following equation 5 (Clark and Fritz, 1997). First, during the decay of biomass, N is transformed to ammonium (NH_4^+) and then NH_4^+ oxidizes to nitrate through the process of nitrification.

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O \qquad (5)$$

Concentration of NO_3-N is not problematic in the study area of Chelsea. All wells tested are within the regulation limit of 10 mg/L of NO_3-N over the duration of the year. Most well values are below the detection limit which indicates that nitrate reduction is an important process reducing the concentration of NO_3-N produced from the oxidation of organic matter. Some wells show higher concentrations of NO_3-N, but all values are below 5 mg/L. Since there is no correlation between SO_4^{2-} and NO_3-N and between NO_3-N and Cl^- (Fig. 3.14) the source of NO_3-N is likely the result of natural processes such as degradation of organic matter. Septic fields may provide ideal conditions for denitrification process to take place and are not impacting the domestic wells. The positive correlation between Ca^{2+} and NO_3-N suggests that NO_3-N may originate from the infiltration of surface water and a

potential source of NO_3-N is the degradation of organic matter through the nitrification process.

The lack of a strong correlation between well depth and the various ionic concentrations makes it difficult to fully characterize the difference between shallow and deep groundwater systems in the area using only this characteristic (Fig. 3.15). This is because all the wells are open boreholes and the samples represent a mix from different water sources in the water column, where more than two end-members may contribute to the concentration of solute in the groundwater. In most cases, there are only weak positive correlations between the well depth and the ionic concentration of Cl^-, SO_4^{2-}, NO_3-N, Ca^{2+}, Na^+ and K^+ (Fig. 3.15). The exception is the weak negative correlation between the concentration of Mg^{2+} and the well depth where a few shallower wells exhibit higher concentration.

The chemical variables are helpful in understanding some of the processes controlling the groundwater geochemistry and the evolution of the groundwater system at a local scale. Even if the hydrogeological conditions are confined at a well, the water chemistry may behave as in semi-confined or unconfined hydrogeological conditions. Generally, the concentration of Ca^{2+} decreases from unconfined to confined conditions (Fig. 3.16). This decrease, coupled with an increase in Na^+ concentration, suggests that the cation exchange process (Ca-Na) is responsible for the evolution of Ca-HCO_3 to Na-HCO_3 groundwater types (Cloutier et al., 2006; Cloutier et al., 2010). The median for NO_3-N is slightly higher under unconfined conditions suggesting that NO_3-N may result from the oxidation of organic matter (Fig. 3.16) during the infiltration process and reducing conditions that exist along the flow path.

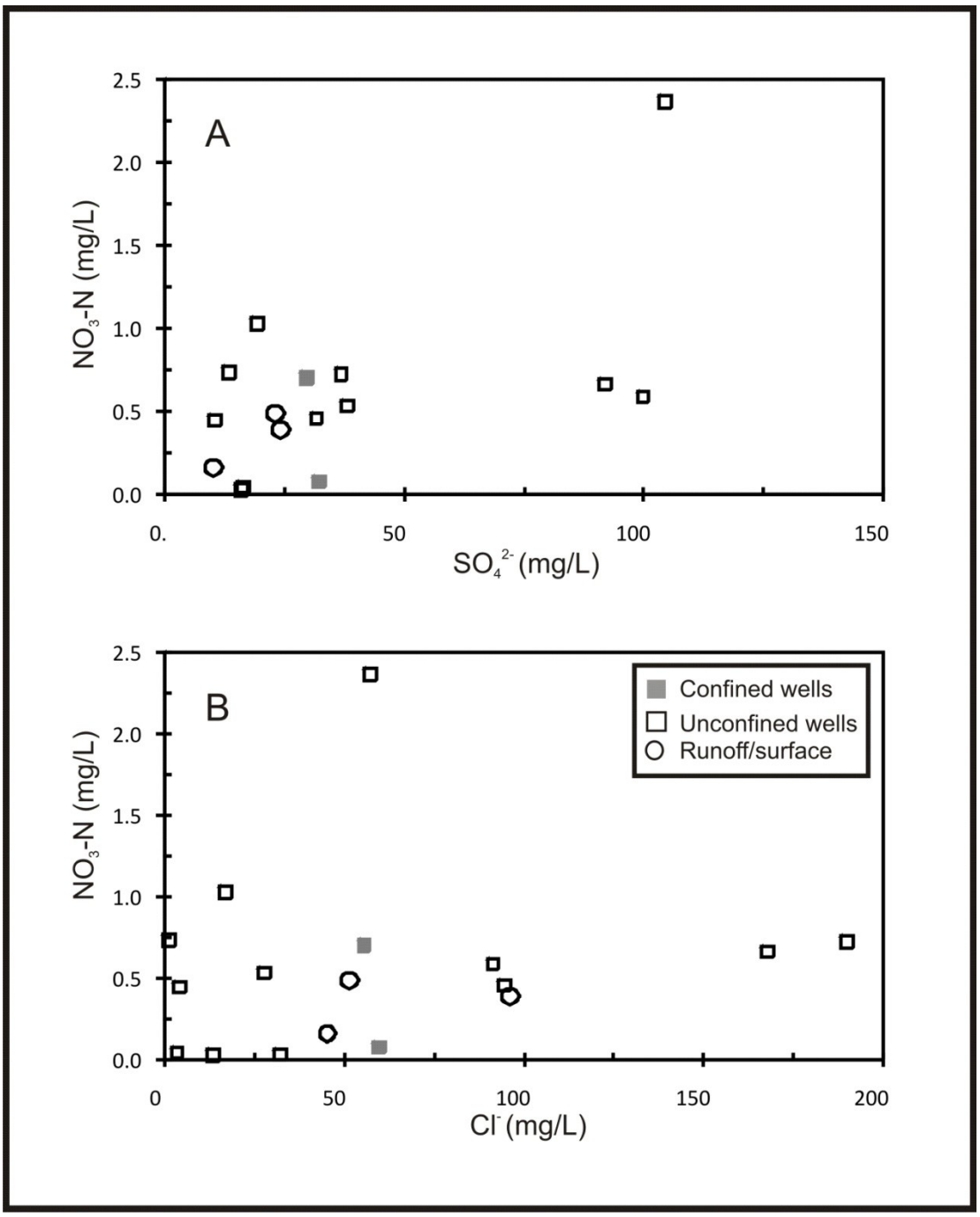


Figure 3.14: Bivariate plots: a) NO_3-N versus $SO4^{2-}$, and b) NO_3-N versus Cl^-.

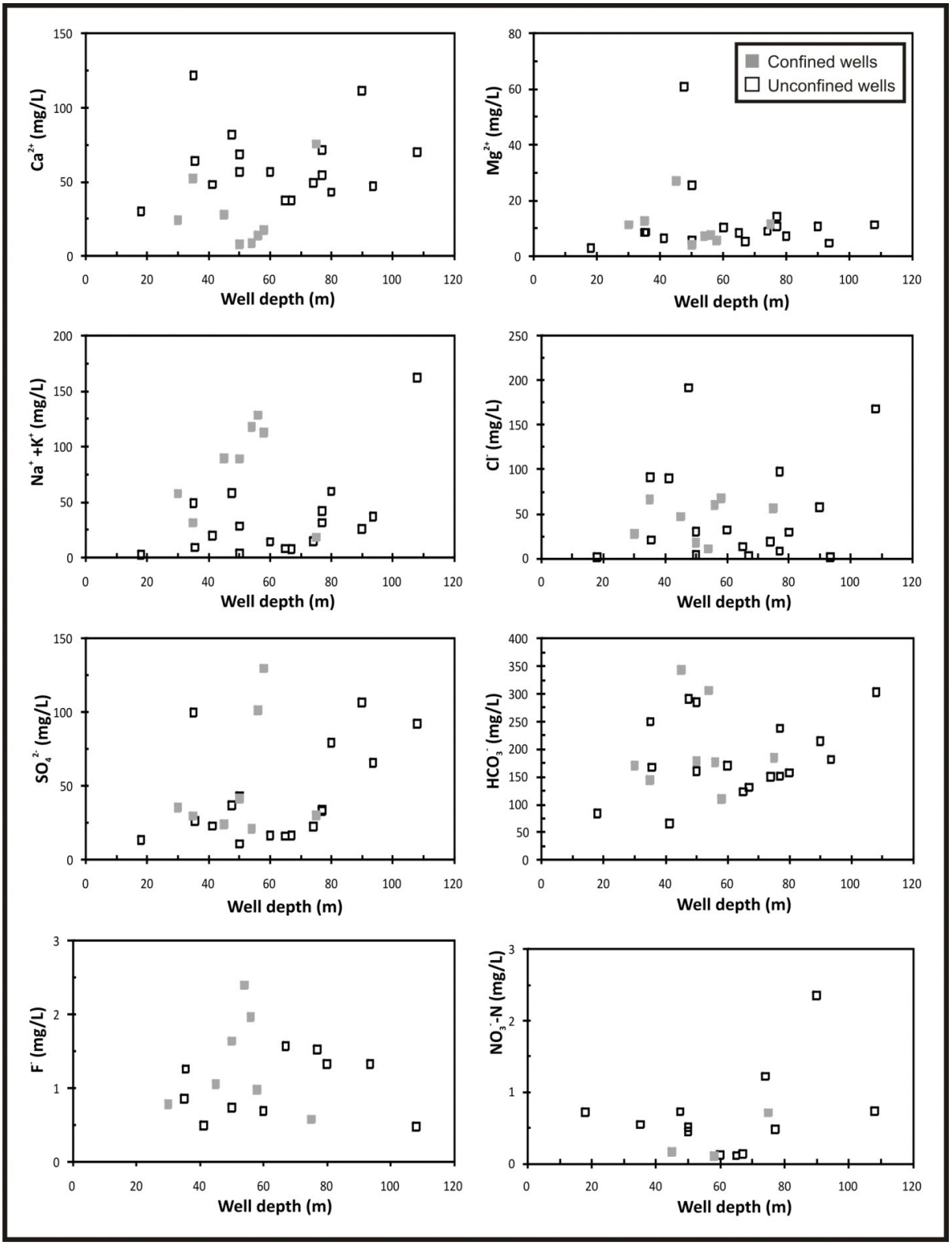


Figure 3.15: Bivariate plots illustrating the relationship between individual ionic species and the well depths of open boreholes from the bedrock to the bottom.

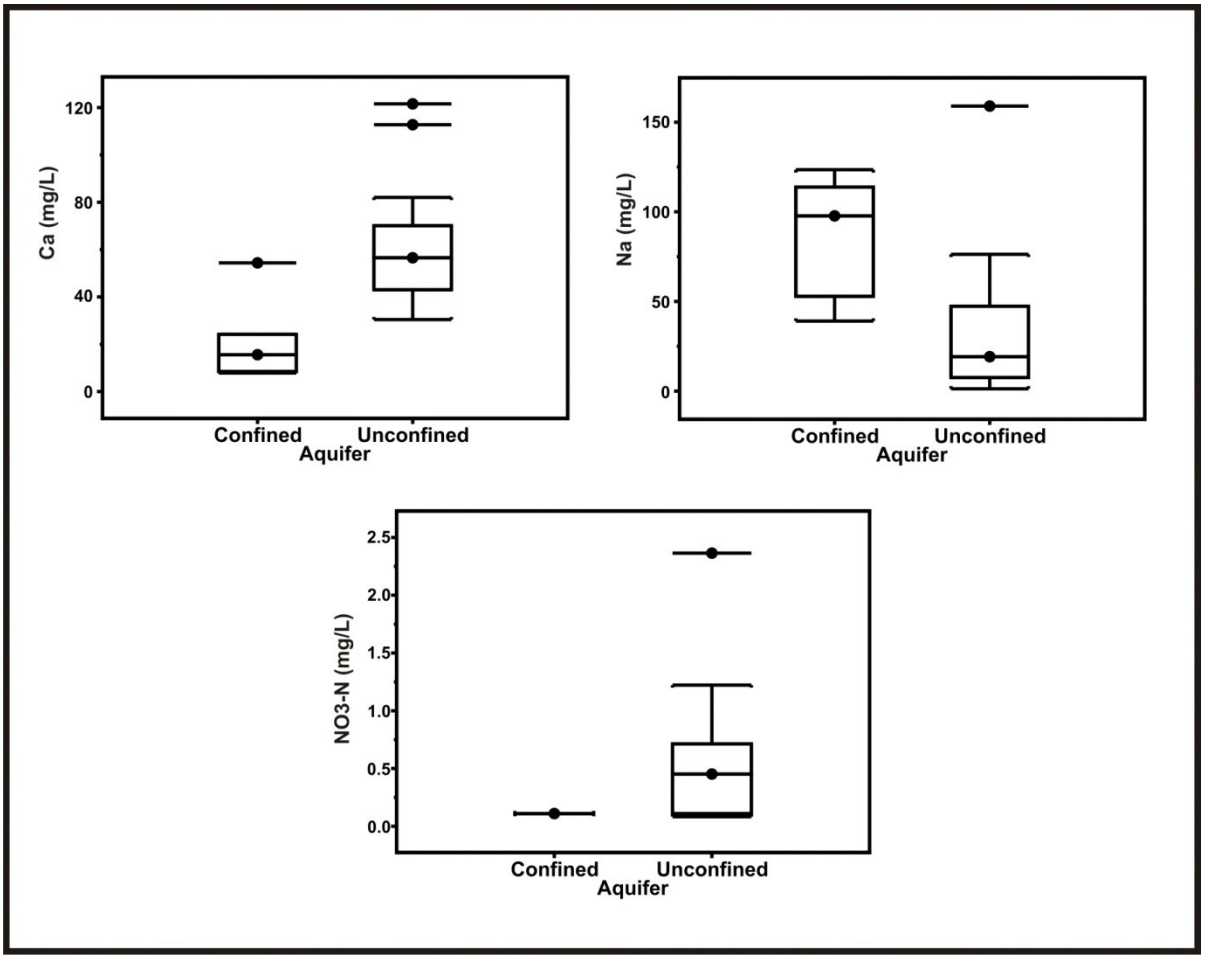


Figure 3.16: Box plots of Ca^{2+}, Na^{+} and NO_3-N versus aquifer conditions.

3.5. Discussion

The results demonstrate spatial variability in the distribution of both coliform bacteria and chemical components of groundwater over the Municipality of Chelsea. The lack of a significant point source of contaminants such as agricultural activities reduces the risk of contamination, but provides an analytical challenge because direct relationships between an obvious source and contamination are not easily observable. To protect the water quality of domestic wells, it is important to understand which process contributes the most to the water composition and to what extent it is affected by anthropogenic inputs. This section first discusses the local factors that affect microbial water quality and then assesses the origins of the major-ions in an attempt to determine if extra-regional, regional or local factors are the strongest modifier of groundwater composition. Multivariate statistical

analyses were employed in an attempt to further distinguish the significance of the hydrogeological processes and evaluate the overall groundwater quality.

3.5.1. Coliform bacteria

Total coliforms (TC) and faecal coliforms (FC) are important groundwater quality indicators and in Chelsea. The bacterial groundwater quality is found to be spatially variable over the study area. Many wells (23/27) exhibited the presence of TC (>0 CFU/100mL) at least once during the sampling period and the relative frequency of samples that tested positive is greater than 46% for 11 wells. Surprisingly, the TC concentration in 19 wells exceeds the Quebec drinking water objective (≥10 CFU/100mL) at least once during the sampling year. The relative frequency of wells contaminated with FC is less compared to TC; FC being detected (FC count >0 CFU/100mL) at least once in 10 wells. The bacterial contamination observed in Chelsea displays patterns that are difficult to explain and may be the result of numerous influences.

Many studies have examined the influence of various factors on the incidence of coliform bacteria in water wells. The thickness of the surficial deposits and the presence of clayey material in the overburden are thought to have a significant impact on the incidence of TC and FC since they influence the soil potential for filtration (Conboy and Goss 2000). Valenzuela et al. (2009) found that the site characteristics, its surroundings, as well as rainfall are the main factors that affect the presence of coliforms in shallow water supply in Chile. Gonzales (2008) showed that coliforms are more likely to be detected in drilled wells having a depth less than 60.9 m.

In this study, overall, the results of the spatial bacterial analysis did not identify significant factors that individually contributed to the incidence of coliform bacteria over the entire study area. The variable “drainage towards the well”, is the only variable that shows a marginally significant effect on the incidence of TC contamination. The observed lack of regionally distinctive variables in the study may result from a number of causes, including:

1) Limited sample dataset of 27 wells. This study only considered drilled wells, which are less vulnerable to contamination compared to shallow dug wells. A larger population, with more variation in well construction similar to the

study of Goss et al. (1998) and Conboy and Goss (2000) may have readily identified more prevalent physical factors in the study area.

2) Characteristics of the dataset. This study demonstrates that many variables work in combination to influence the occurrence of coliform bacteria in private water wells and it is difficult to quantify the relative proportions of this combination. Individual well characteristics, surficial deposits and bedrock geology are all contributors to bacterial contamination in the study area. Future studies may find more value in focusing on fewer variables with a potentially wider range of outcomes rather than selecting many variables with a narrow range of values.

3) Lack of obvious point source of coliform bacteria. Within the Municipality, agricultural activities are relatively minor and forest lands are important. As a result, the source of coliforms is not primarily associated with the presence livestock or manure spreading, but is interpreted to be associated to local sources near the wells. This study also showed that residences in proximity to each other may experience a different microbial water quality than their neighbours. In these settings, the presence of TC is associated with the infiltration of surface water in preferential pathways, the proximity to water bodies and/or the presence of insects inside the well, and indicates a breach in the system. A defect in the septic system or the presence of wildlife is generally indicated by the occurrence of FC.

The analysis focused on site characteristics, and did not examine other variables which may have provided a more significant contribution to the incidence of coliform bacteria. For example, the results from Zimmerman et al. (2001) and Swistock and Sharpe (2005) suggest that direct contamination from the wellhead area appeared to be less important than the contamination occurring from the large scale aquifer system. The presence of natural preferential pathways proximal to the well, such as fractures, allow bacteria to travel faster and deeper (Conboy and Smith, 2005; Levison and Novakowsky, 2009) and it is well accepted that coliform bacteria travel from several tens of metres (Conboy and Goss, 2000) up to 4 km (Malard et al., 1994) in the absence of natural

attenuation mechanisms. A second important variable not considered in the study is the effect of seasonal variations on bacterial contamination events (Chapter 4).

3.5.2. Water chemistry

Examination of the spatial distribution of the chemical variables is used to trace groundwater pathways (Jiang et al., 2009) and provide insight on the location of the dominant processes. The challenge is to identify if the source of a specific ion is from a natural or anthropogenic origin. Piper diagrams (Piper, 1944) are also employed to identify hydrogeochemical facies (Fig. 3.8), in an attempt to group similar wells and assist in the identification of links between the presence of bacteria and processes contributing to the observed groundwater chemical characteristics.

A number of interpretations on the controlling factors are made from the major-ion geochemistry:

1) Influence of bedrock geology:
    - Ca^{2+} concentration appears to be higher in wells drilled in metamorphic bedrock compared to igneous bedrock due to the dissolution of marble (Fig 3.6).
    - Dissolution of carbonate is interpreted as the most important input of HCO_3^- and its concentration increases along the flow path.
    - Under unconfined conditions, the distribution of Na^+ is spatially variable and is attributed to weathering of silicate minerals in the local bedrock.
    - Under confined conditions, distribution of Na^+ is mainly affected by the presence of marine clays which facilitates the Ca-Na ion exchange process.
    - Wells exhibiting higher values for F^- are found in both igneous and metamorphic bedrocks. There is no clear trend in the spatial distribution of F^-, which may result from of bedrock geology heterogeneity or recharge pathways.

2) Hydrogeological conditions:
    - The median for Ca^{2+} and Mg^{2+} is higher in unconfined compared to confined conditions (Fig. 3.16) due to the dissolution of carbonate species during recharge.
    - The concentrations of NO_3-N are higher under unconfined compared to confined conditions, which indicates that NO_3^- is not reduced and/or that anthropogenic activities introduced nitrate to the system. However, based on the fact that nitrate concentrations higher than 3 mg/L (NO_3-N) are observed only in one well (W13) during the sampling period, it is likely that the presence of nitrates is associated to natural nitrification processes rather than anthropogenic sources (Rudolph et al., 1998).

3) Anthropogenic inputs:
    - Na^+ may be influenced by anthropogenic activities such as local septic effluents.
    - The concentrations of Cl^- and SO_4^{2-} increase from recharge to discharge areas, which possibly indicates inputs from anthropogenic activities such as a septic effluent along the flow path. Of particular interest is that Cl^- concentration is higher where wells are clustered together, suggesting the influence of septic effluents or small-scale application road salts.

4) Hydrogeochemical facies:
    - The groundwater is characterized mainly by the Ca-HCO_3 facies which are located in areas of inferred recharge, under mostly unconfined conditions, with the samples interpreted to represent the first step in the evolution of groundwater. Surprisingly, this facies shows the lowest relative frequency values for TC and FC (Table 3.5) with the presence of coliform bacteria resulting from surface water infiltration through preferential pathways near the well head.
    - The presence of other hydrogeochemical facies such as Na-HCO_3, Ca-Cl and various mixed facies indicates the presence of other processes that influence groundwater chemistry.
    - Wells characterized by the Na-HCO_3 facies are located mainly in the lowlands where processes such as Na-Ca ion-exchange may occur and

affect the evolution of groundwater. Even if the time of travel from the recharge area is longer, TC are detected in all four wells with this facies (Table 3.5). This suggests that these wells are vulnerable to natural processes such as surface water infiltration resulting from rapid recharge pathways or the proximity to a water body; but they also may be impacted by anthropogenic activities such as road and/or water softener salts.

- Wells characterized by the Ca-Cl and mixed facies show the highest level of incidence for both TC and FC (Table 3.5) and are likely influenced by nearby anthropogenic activities. In a municipality such as Chelsea, all residences have a septic tank and the domestic effluents may contribute to the water chemistry. This group of wells may exhibit the most mixing between the groundwater system, surface water and domestic effluents.

Table 3.5: Average relative frequency of detection (TC and FC) based on groundwater hydrogeochemical facies.

	Ca-HCO_3 (n=13)		Na-HCO_3 (n=4)		Ca-Cl (n=1)		Mixed species (n=7)	
	TC	FC	TC	FC	TC	FC	TC	FC
Mean RF (%)	26.5	2.2	49.2	4.0	54.5	9.1	58.2	10.0

3.5.3. Evaluation of groundwater quality

In order to further evaluate the quality of groundwater in the study area and the influence of regional versus local factors, the geochemical data was subjected to two multivariate statistical analyses: hierarchical cluster analysis (HCA) and principal component analysis (PCA).

The results of the cluster analysis are illustrated in the dendrogram of Figure 3.17. The phenon line is arbitrarily drawn at a linkage distance of 6 based on a visual observation of the dendrogram. This permits the separation of the dendrogram into five distinct clusters. Table 3.6 presents the descriptive statistics for the 5 clusters obtained and the spatial

distribution of the clusters is illustrated in Figure 3.18. The results of the cluster analysis are also used to describe the evolution of groundwater over the study area.

The first cluster (W4, W14, W17, W22 and W27) shows the lowest concentrations of Cl^-, K^+, Mg^{2+}, Na^+ and the lowest relative frequency of detection for TC and FC. All of these wells are located where a thin layer of overburden covers the bedrock and in a preferential recharge area. The degree of water mineralisation in shallow groundwater system is usually lower than in deeper groundwater system unless the shallower system is impacted by anthropogenic activities (Ayraud et al., 2006). The low concentration of ions in this cluster implies a short residence time of the water in the bedrock, and indicates that the main source of water is from the shallow groundwater system. This also indicates that the presence of TC or FC is not necessarily a result of infiltration in a preferential recharge area and reinforces the importance of the source in the incidence of coliform bacteria

The second cluster (W5, W11, W16, W24 and W26) has the lowest values for F^-, SO_4^{2-}, HCO_3^- and pH, the second highest concentrations of Ca^{2+} and Cl^-, and the second highest relative frequency of incidence of TC and FC. The lower pH suggests less dissolution of carbonate species and release of HCO_3^- through the unsaturated zone. All the wells are located in an inferred recharge area where the overburden is thin. Preferential pathways combined with non-point sources of coliform bacteria in proximity of the wellhead increase the incidence of coliform bacteria in the wells.

The third cluster (W1, W6, W7, W13, W15, W18 and W20) shows the most water mineralization with a low relative frequency of incidence of TC. This cluster has the highest concentrations of Cl^-, NO_3-N, Ca^{2+}, Mg^{2+} and second highest for HCO_3^- . With the exception of W1, the wells forming this cluster are geographically close to each other, located down-gradient from other residences, and are under unconfined or semi-confined conditions accompanied by thin overburden. Deeper aquifers tend to have higher concentration of dissolves species because of longer residence time in the aquifer compared to shallower groundwater systems where the concentrations are usually lower. However, the concentration of dissolved species increases if the shallower groundwater system is impacted by anthropogenic activities. This implies that some of these wells draw water from either a deeper aquifer or are affected by anthropogenic activities.

The fourth cluster (W9, W10, W12, W19, W23 and W25) is characterized by the highest average for F^-, SO_4^{2-}, Na^+ and pH and by the lowest values of Ca^{2+} and NO_3-N. FC

are not detected during the sampling period for this cluster. Five out of six wells are located in the southern section of the Municipality in a confined aquifer (Fig. 3.17). The clay layer is interpreted to protect the wells against contaminants from the surface and the relative frequency of incidence is expected to be low. The presence of marine clay also influences the chemistry of the water because cation-exchange processes may occur. The incidence of TC may result from the proximity of some wells to water bodies or cracks in the clay layer. This increases the vulnerability to contamination by coliform bacteria if a hydraulic connection exists between the well and the surface water body.

Lastly, the fifth cluster (W2 and W3) is characterized by the highest average values for K^+, HCO_3^- and both TC and FC. From a bacteriological assessment, it is the cluster with the poorest water quality. These wells are located in proximity to the Gatineau River and have water levels near the elevation of the river. This indicates that W2 and W3 are possibly GUDI wells (groundwater under direct influence of surface water).

In the context of hydrodynamic evolution, clusters 1 and 2 are interpreted to represent recharge in the Precambrian Hills, whereas the third cluster is characterized by a signature of a deep groundwater system and/or the most influence by anthropogenic activities. As the water flows into the ground towards discharge areas and confined conditions, it evolves towards Na^+ rich water which is represented by clusters 4 and 5.

To summarize the water quality, wells in cluster 1 show the best quality both chemistry and microbial quality, whereas wells in cluster 2 also show low concentration of ions, but a high relative frequency of incidence of TC and FC. The cluster 2 wells appear to be affected by rapid recharge pathways. Cluster 3 shows relatively good microbial water quality, however, the concentrations of dissolved species are relatively high, which indicates longer residence time or mixing with septic effluents. Cluster 4 represents a groundwater system that has evolved from Ca-HCO_3 facies towards a more mineralized composition. Lastly, cluster 5 shows the poorest microbial water quality, which may result from the influence of surface water.

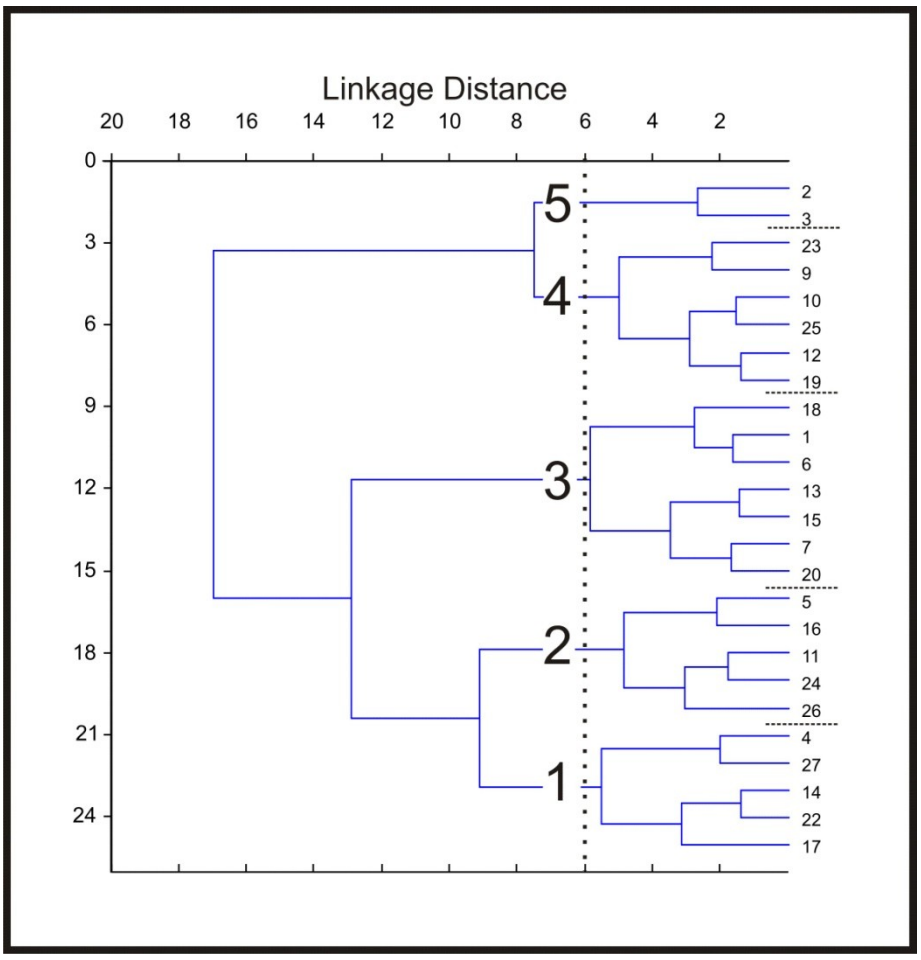


Figure 3.17: Cluster analysis with statistical grouping. The phenon line is arbitrarily drawn at a linkage distance of 6 based on a visual observation of the dendrogram to permit the separation of the dendrogram in five distinctive cluster groups.

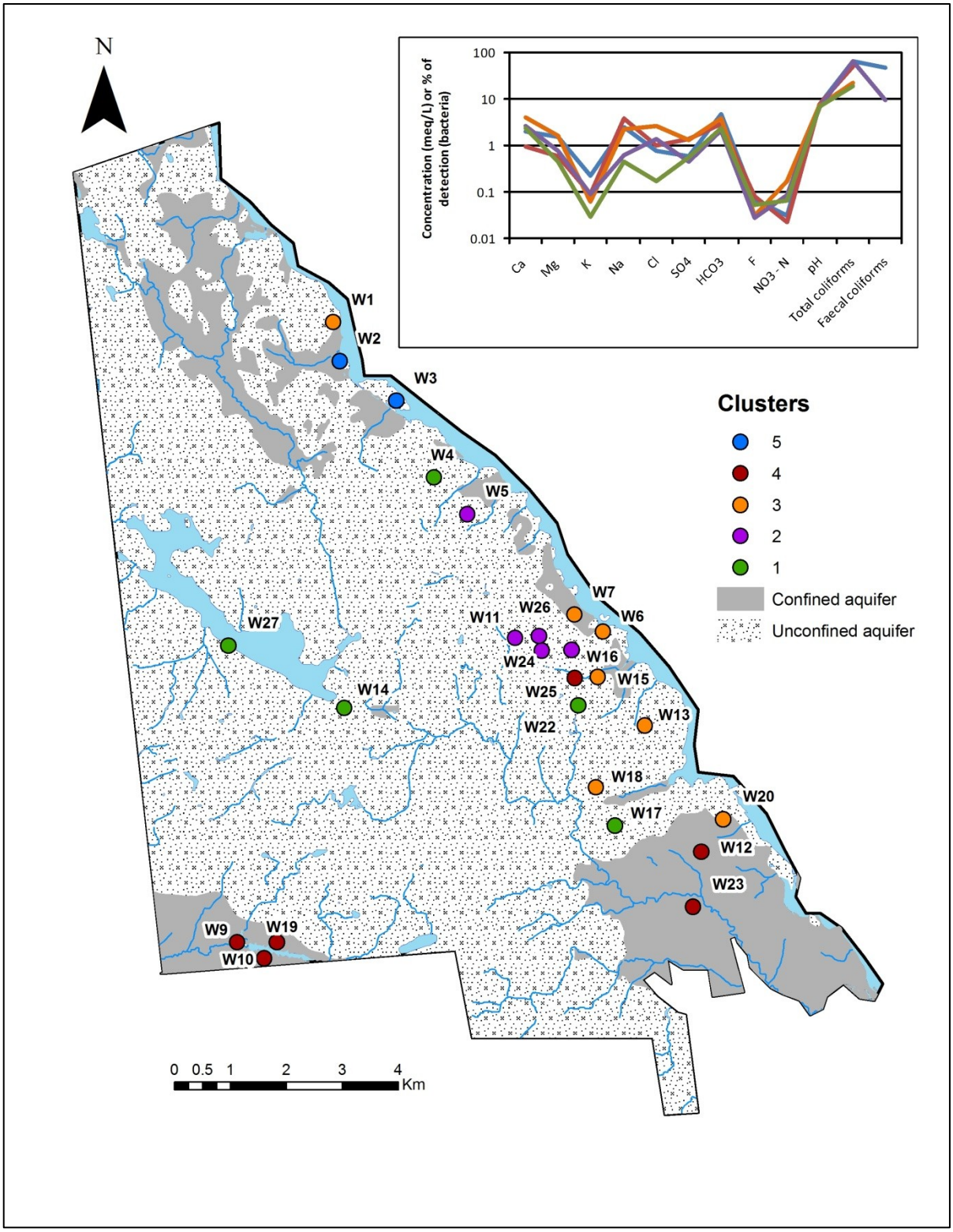


Figure 3.18: Spatial distribution of the cluster groups over the study area.

Table 3.6: Descriptive statistics of the cluster groups. Values in bold represent the highest value for the variables while underlined values represent the lowest value for the variables.

Clusters (phenon Line=6)	Descriptive statistics	F (mg/L)	Cl (mg/L)	NO_3-N (mg/L)	SO_4 (mg/L)	Ca (mg/L)	K (mg/L)	Mg (mg/L)	Na (mg/L)	HCO_3 (mg/L)	pH	Total Coliforms (% of positive)	Faecal Coliforms (% of positive)
Cluster 5 (N=2)	average	1.3	27.6	0.1	28.4	41.2	**8.7**	18.9	57.2	**290.5**	7.6	**65.0**	**48.3**
	stdev	0.3	27.5	0.0	6.2	18.7	7.9	11.6	25.6	74.3	0.6	49.5	25.9
	Min	1.1	8.1	0.1	24.1	28.0	3.2	10.7	39.1	238.0	7.2	30.0	30.0
	Max	1.5	47.0	0.2	32.8	54.4	14.3	27.1	75.3	343.1	8.0	100.0	66.7
	C.V (%)	25.6	99.6	28.9	21.7	45.3	90.1	61.4	44.8	25.6	7.5	76.1	53.6
Cluster 4 (N=6)	average	**1.5**	35.4	0.1	**68.0**	19.1	3.5	7.1	**90.7**	183.1	**7.8**	48.9	0.0
	stdev	0.6	23.2	0.0	42.5	13.2	1.2	2.4	29.9	65.4	0.3	14.5	
	Min	0.8	10.7	0.1	21.0	7.9	2.1	4.0	53.4	110.7	7.4	35.7	
	Max	2.4	67.9	0.1	129.7	43.0	5.1	11.3	123.5	306.4	8.2	66.7	
	C.V (%)	40.4	65.5	4.8	62.5	68.9	33.5	34.1	32.9	35.7	3.4	29.7	
Cluster 3 (N=7)	average	0.6	**94.4**	**0.8**	62.4	**83.0**	2.5	**20.1**	50.7	238.9	7.2	22.3	0.0
	stdev	0.1	61.3	0.7	35.2	24.7	0.7	18.9	49.7	60.0	0.2	30.7	
	Min	0.5	30.3	0.1	29.6	52.1	1.5	8.5	16.0	144.4	6.9	0.0	
	Max	0.9	191.5	2.4	106.4	121.6	3.5	61.0	158.9	303.1	7.4	77.8	
	C.V (%)	25.5	65.0	87.6	56.3	29.8	29.1	93.7	98.1	25.1	2.1	137.4	
Cluster 2 (N=5)	average	0.5	50.3	0.4	22.1	52.7	3.6	9.6	14.1	132.3	6.7	**64.1**	9.7
	stdev	0.1	40.1	0.5	7.3	12.5	4.1	3.0	5.4	40.9	0.3	23.5	6.2
	Min	0.5	13.3	0.1	15.9	37.6	1.1	6.3	7.0	65.8	6.2	30.0	0.0
	Max	0.7	97.4	1.2	33.7	71.6	10.9	14.2	20.5	171.0	6.9	87.5	16.7
	C.V (%)	16.8	79.9	117.4	32.8	23.8	113.8	30.7	38.3	30.9	3.8	36.7	63.9
Cluster 1 (N=5)	average	1.0	6.0	0.3	26.3	47.0	1.2	5.4	10.7	145.0	7.1	18.9	0.0
	stdev	0.5	8.2	0.3	22.7	13.8	0.4	2.1	14.5	38.9	0.3	23.9	
	Min	0.5	1.1	0.1	10.5	30.1	0.5	2.9	1.3	83.7	6.7	0.0	
	Max	1.6	20.5	0.7	65.6	64.1	1.6	8.6	36.2	181.8	7.3	55.6	
	C.V (%)	49.1	135.9	89.3	86.3	29.4	33.0	38.1	136.1	26.8	3.6	126.1	

As previously mentioned, a second multivariate technique, principal component analysis (PCA) was performed to identify which variables provided the greatest variation in the chemical and microbial composition of the water. The analysis finds hypothetical variables that account for the variance (Hommer et al., 2001), in order to identify patterns in large datasets (Moore et. al., 2009). The purpose of applying this statistical technique is to aid in the identification of the major processes affecting the composition of the water. The PCA was conducted using a dataset of 12 bacteriological and chemical variables. A component (eigenvector of the dataset covariance matrix) is considered significant if its eigenvalue is greater than one (Kaiser criterion) (Jolliffe, 2002). The loadings represent the correlation coefficients between the variables and the components, and is considered significant if the value is greater than 0.3 (Moore et. al., 2009). A positive loading demonstrates a direct relationship between the component and the variable. The influence of the variable on the component is evaluated based on the absolute value whereas the greatest influence is exerted by the strongest value. Results of the PCA analyses are presented in Table 3.7 with Figure 3.19 displaying the position of the variable in the plane defined by the position of the first two components and Figure 3.20 illustrating the spatial distribution of the component scores to provide insight on the processes interpreted to be responsible for each individual component in the region. The eigenvalues for the first four components are 3.59, 3.09 and 1.90 and 1.01, which explains 80% of the variance.

The first component (PC1) accounts for 29.9% of the variance and is composed primarily of positive loadings of Na^+, K^+, pH, HCO_3^-, SO_4^{2-} (Fig 3.19). It is interpreted to represent the water-rock interaction processes along the flow path, which may provide an indication of the residence time. As water infiltrates, dissolution of carbonate in the unsaturated zone occurs because of the presence of CO_2. As the carbonic acid dissolves carbonate minerals in the soil, the pH increases and the concentration of HCO_3^- increases to saturation. As the hydrogeological condition evolves from unconfined to confined, it is possible that cation exchange occurs and Ca^{2+} (from dissolution) is replaced by Na^+ from the marine clays that leached in the aquifer. This may have also contributed to the presence of SO_4^{2-} in this component because SO_4^{2-} may also have marine origins (Clark and Fritz, 1997). It is also possible that the redox conditions are not ideal to promote sulphate reduction. The presence of K^+ in this component indicates the weathering of silicate minerals. The wells showing high positive scores for component 1 are located mainly in the southern area of the Municipality and are under confined conditions. This

supports the hypotheses of the autochthonous origins of this component regarding the occurrence of Na-Ca ion exchange in this area of the Municipality. The wells showing negative scores for this component are located mostly in recharge areas. Two wells with higher scores for this component are located in proximity to a neighbour; therefore, it is probable that these wells are affected by nearby septic effluents. PC1 represents the water residence time in the aquifer interpreted from water-rock interaction processes (regional factor), but may also represent input from anthropogenic activities (local factor), depending on the site location.

The second component (PC2) is interpreted as representing the hardness of water. It accounts for 25.8% of the variance and is characterized by positive loadings of Mg^{2+}, Ca^{2+}, NO_3-N and Cl^-, and a negative loading of F^- (Fig 3.19). A positive correlation exists between Mg^{2+} and HCO_3^- (Table 3.4) and it has been shown that Ca^{2+} and Mg^{2+} are likely originating from the same source (Fig. 3.10b). Nitrate also shows a positive loading in this component and has been interpreted to originate from nitrification process. The origins of Ca^{2+}, HCO_3^- and NO_3-N suggest that infiltration through the overburden and the decomposition of organic matter contribute to these ions in the groundwater. The positive loading of Cl^- in this component also suggests its origin from the surface. Chloride input from the surface may result from septic effluents or small-scale application of road salt and fertilizers. The scores for this component increase towards the Gatineau River; and the influence of this component is minimal in higher elevations of the Gatineau Hills. In the study area, as water travels along a flow path from the recharge towards discharge areas, the concentration of dissolved species increases resulting from weathering processes in the overburden and in the overlying bedrock and from mixing with various sources of water such as septic effluent. The second component is interpreted to represent the processes contributing to the hardness of water (regional factor) and mixing with septic effluents (local factor).

The third component (PC3) explains 15.9% of the variance and has a high positive loading of SO_4^{2-}, with negative loadings of K^+, TC and FC. No correlation exists between these components, but the presence of coliforms is an indicator of rapid recharge, possibly through preferential pathways to the well. High SO_4^{2-} concentrations indicate mixing with groundwater that did not undergo sulphate reduction processes with a long residence time. The wells showing high negative scores are vulnerable to rapid infiltration of surface water as indicated by the presence of TC. The presence of FC indicates contamination by septic

effluent or by infiltrating water containing faecal material from wildlife in proximity to the well. The third component shows more variability when residences are closer together and under unconfined conditions. The strongest modifier of groundwater composition is interpreted to be site-specific with minor significance of extra-regional factor.

The fourth component (PC4) accounts for 8.5% of the variance and is composed of positive loadings of SO_4^{2-} and Cl^-, and a negative loading of HCO_3^-. Septic effluents are a known source of Cl^- and SO_4^{2-} and also have been shown to contribute to the concentration of HCO_3^- in groundwater (Robertson et al., 1991). Although this component shows a negative loading of HCO_3^-, this last component is interpreted to represent mixing with domestic effluents. Spatially, only one well (W26) shows a high score in the fourth component. This well is located in a inferred preferential recharge. Rapid recharge may explain why a lower concentration of HCO_3^- is observed. This well is in proximity to other houses and FC are also detected once during the sampling period, both of which are linked to contamination from septic effluents. However, other wells (W2, W5, W11 and W16) exhibit similar characteristics to W26, but show negative scores for this component. The potential influence of septic effluents is also observed in components 1 and 2 which may provide more influence in these wells than in W26. PC4 represents a site-specific factor to groundwater quality.

Table 3.7: Principal components analysis (PCA) factor loadings. Values in bold indicate significant loadings.

	PCA Loadings			
Variable	PC 1	PC 2	PC 3	PC 4
F^-	0.29	**-0.40**	0.01	-0.19
Cl^-	0.25	**0.39**	0.08	**0.42**
NO_3-N	-0.15	**0.38**	0.24	-0.20
SO_4^{2-}	**0.30**	0.08	**0.40**	**0.41**
Ca^{2+}	-0.22	**0.42**	0.22	-0.08
K^+	**0.35**	0.20	**-0.31**	0.05
Mg^{2+}	0.20	**0.44**	-0.10	-0.28
Na^+	**0.49**	0.04	0.08	0.21
HCO_3^-	**0.34**	0.19	0.12	**-0.63**
pH	**0.41**	-0.25	0.09	-0.20
TC	0.09	0.10	**-0.52**	0.03
FC	0.01	0.16	**-0.57**	0.09
Eigen Values	3.59	3.09	1.90	1.01
Explained variance (%)	29.93	25.76	15.85	8.45
Cum. variance (%)	29.93	55.69	71.53	79.98

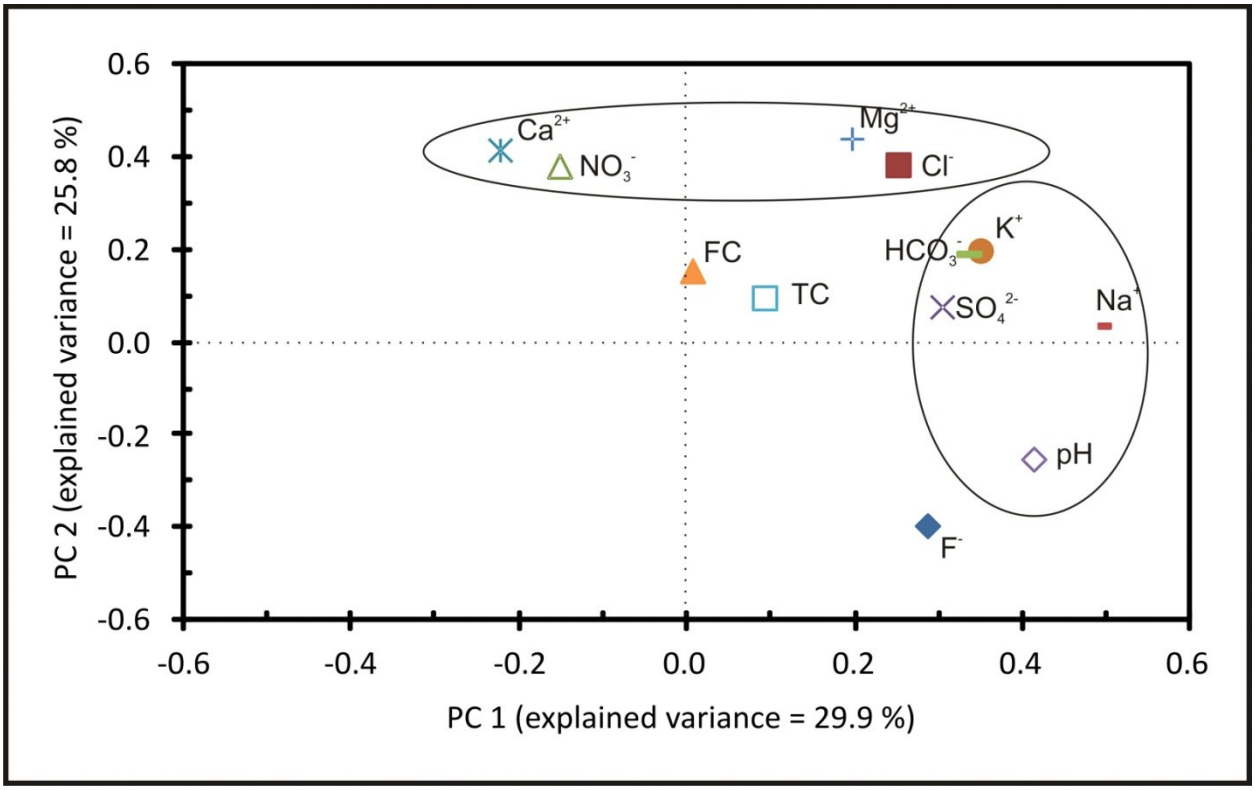


Figure 3.19: Plot of loadings for component 1 and 2.

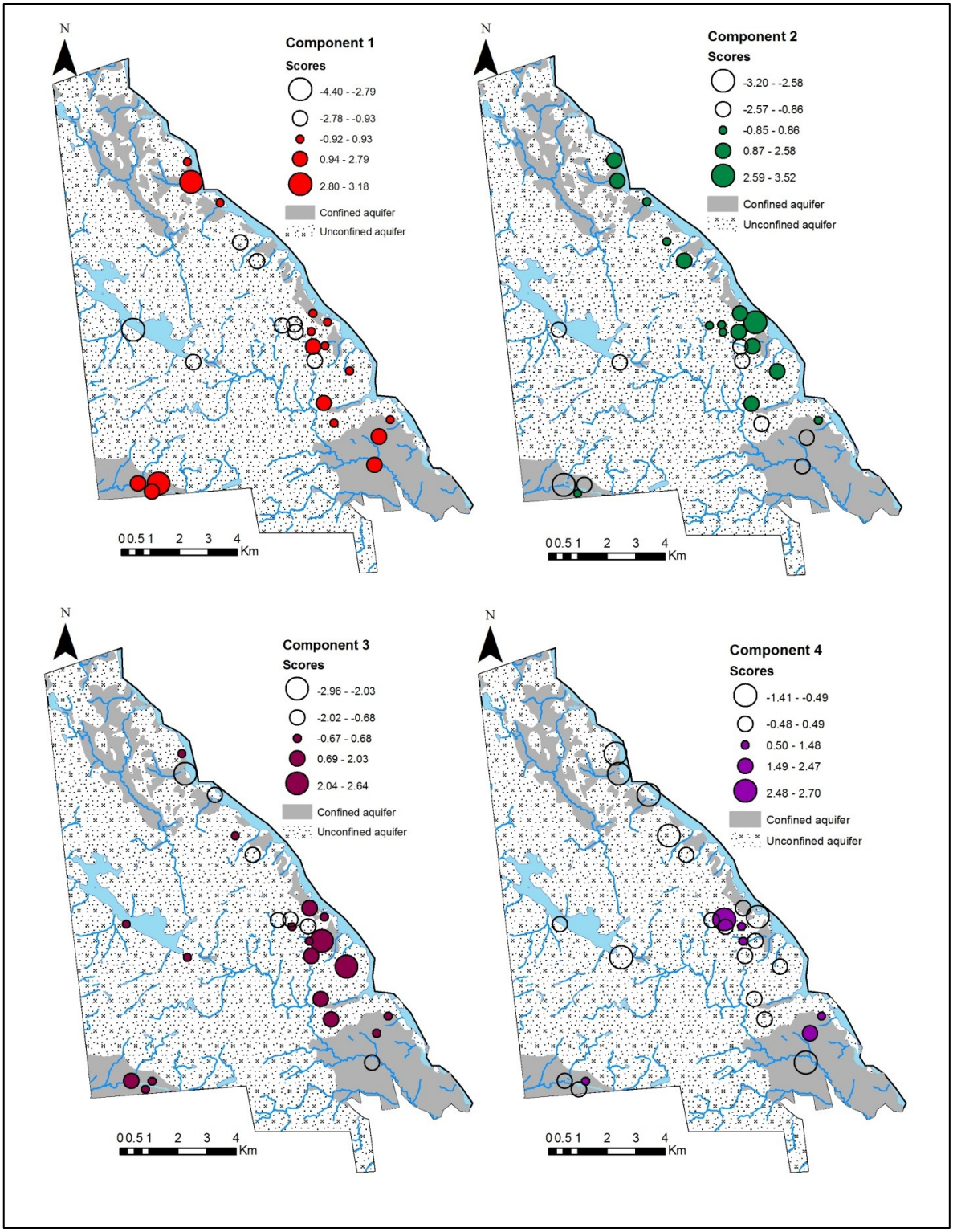


Figure 3.20: Spatial distribution of PCA scores over the study area.

Examination of the HCA and PCA analyses in conjunction shows that wells in the first cluster are negatively affected by PC1, PC2 and PC4 with no clear trend with PC3 (Fig. 3.21). The lack of trend with PC3 is because certain wells show a low concentration of bacteria at some point during the sampling period. These wells are located in areas of inferred recharge with a short residence time of water, which is illustrated by both statistical techniques. The second cluster is positively affected by PC2 and PC4, and negatively affected by PC1 and PC3 (Fig. 3.21). The positive relationship with PC2 and PC4 could indicate a longer residence time of water or input from anthropogenic activities. Preferential recharge pathways may also exist near the well head as indicated by the negative relationship with PC3 and this would explain why this cluster shows a high relative frequency of incidence of coliform bacteria. The third cluster shows a positive relationship with PC2 and PC3, and did not exhibit any trend with the other components (Fig. 3.21). This signifies that these wells are strongly affected by dissolution processes along the flow path, mixing with deeper aquifers and/or anthropogenic activities. Lastly, clusters four and five show similar trends regarding their relationships with the principal components (Fig. 3.21). There is a strong positive influence of the PC1, which is related to water-rock interaction processes and mixing with septic effluents. Some of these wells are also impacted by rapid recharge as demonstrated by the negative influence of PC3.

The integration of the HCA and PCA helps to further characterize the processes involved in the hydrodynamic evolution of the groundwater. For example, wells in cluster 1 and 2 are located in inferred recharge areas (similar location), but wells in cluster 2 are more affected by anthropogenic activities and rapid recharge compared to wells in cluster 1. The multivariate analysis led to the differentiation between the principal factors which contribute to groundwater quality in the Municipality of Chelsea and also qualifies their relative importance. Regional processes such as water-rock interaction and cation exchange appear to have the strongest influence on groundwater quality, whereas local or site-specific processes such as rapid recharge near a well or mixing with septic effluent water appear to be of minor significance in the study area. The multivariate analysis demonstrates that even over a relatively small area, the relative importance of a contributing factor to the groundwater quality may be variable, with a specific combination unique to each individual well.

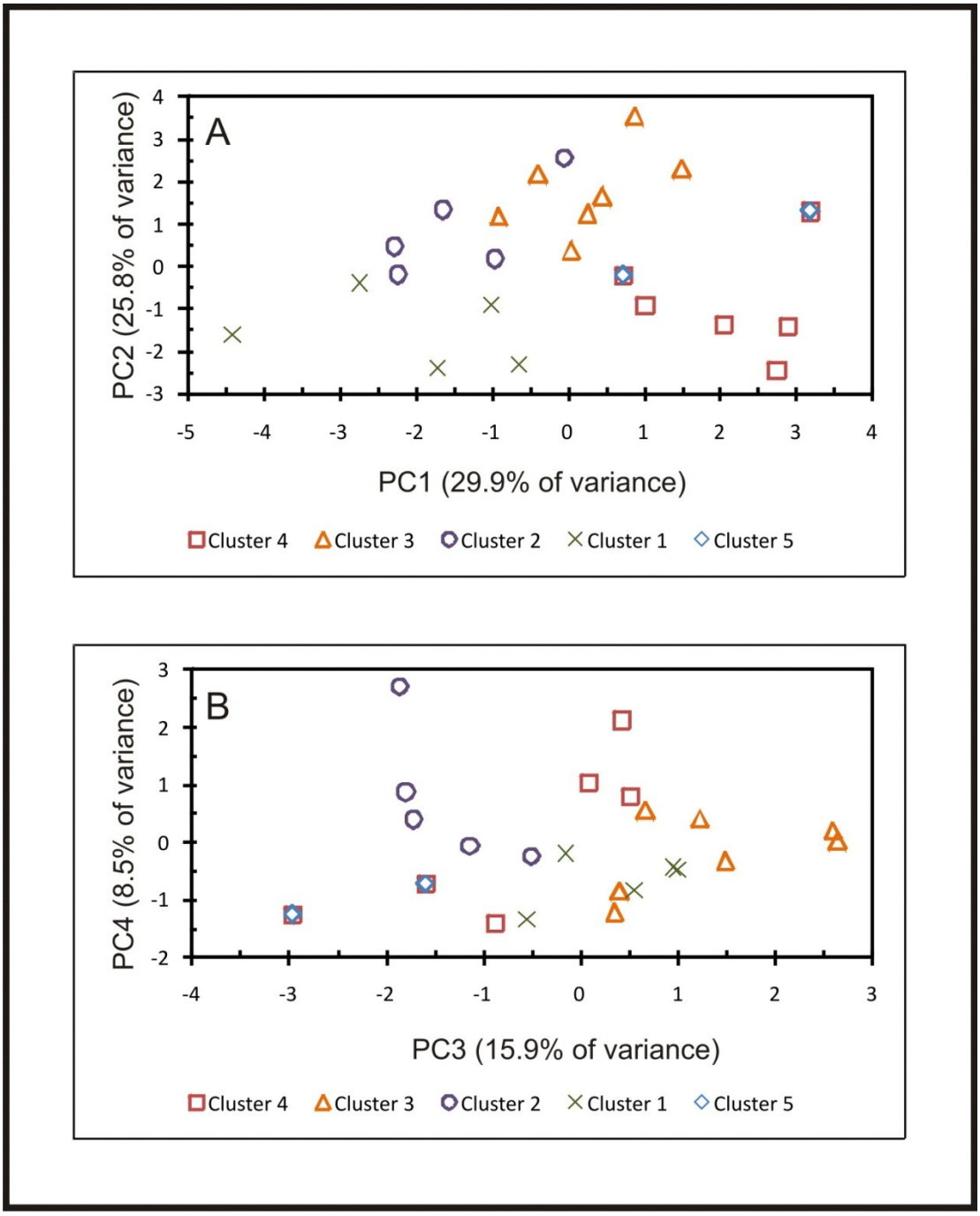


Figure 3.21: Bivariate plots of the five clusters obtained from the HCA: A) The first and second component of the PCA; and B) The third and fourth component of the PCA.

3.6. Conclusions

In this study, the spatial distributions of microbial and geochemical variables which affect groundwater quality in a fractured bedrock aquifer are assessed. The results suggest that sources of bacterial contamination exist near the water wells despite the relatively low level of agricultural activities in Municipality of Chelsea, Québec. This study also showed that residences located in proximity to one another may experience a different microbial water quality than their neighbours. The variable “drainage towards the well” in conjunction with presence of preferential pathways near the wellhead, are shown to increase the vulnerability of wells to surface water infiltration.

Hydrogeochemical facies of the Chelsea area were classified with a Piper diagram. Groundwater type vary broadly from Ca-HCO_3, Na-HCO_3 or mixed cations-HCO_3 type to Ca (or mixed cations)-Cl or Ca-mixed anions, with Ca-HCO_3 as the predominant water type. The spatial distribution of hydrogeochemical facies suggests that the groundwater composition is affected by water-rock interactions processes, the confining aquifer conditions and anthropogenic activities. As water infiltrates in preferential recharge areas (higher elevations), it dissolves carbonates present in the thin layer of till overlying the bedrock. The groundwater evolves from a Ca-HCO_3 towards a Na-HCO_3 facies as it flows from unconfined to confined aquifers and appears to also be influenced by the Na-Ca cation-exchange process. Generally, concentrations of HCO_3^-, Cl^- and SO_4^{2-} increase from recharge areas to discharge areas near the Gatineau River. Increases in these concentrations are attributed mainly to water-rock interaction processes such as weathering, but also to anthropogenic activities such as septic effluents. The influence of anthropogenic activities may also explain why the mixed groundwater facies are observed in areas where residences are clustered.

Multivariate techniques of PCA and HCA were performed to evaluate the groundwater quality, to provide an overview of the hydrodynamic evolution of the groundwater and to elucidate patterns in the dataset. The HCA groups the wells based on their overall water quality and provides an overview of the hydrogeochemical evolution of the groundwater in the study area. The integration of microbial data into the multivariate analysis helps to identify local factors that affect water quality. For example, wells with low ionic concentrations in the water samples exhibit short residence times, and combined with poor microbial water quality (i.e. bacterial contamination) may indicate the presence of rapid recharge and preferential pathways near the well. The PCA identifies four components

which provide the greatest variation on groundwater composition. The PCA led to the differentiation of influencing factors on water quality with regional factors (weathering and ion exchange processes) interpreted to be the principal contributor. However, the PCA also demonstrates that septic effluents also contribute the mineralization of the groundwater, and identifies wells affected by preferential recharge pathways, which are both considered local factors in the study area. Together, HCA and PCA provide a better picture of the processes which affect the groundwater quality in the Municipality of Chelsea, Québec. The HCA provides the sequence of groundwater evolution based on the overall water quality, whereas the PCA helps characterize the importance of the processes at each step of the hydrochemical evolution. Even over a small area, the analysis demonstrates that the importance of a contributing factor to groundwater quality is variable, with a specific combination unique to each individual well.

The processes affecting water quality in a fracture bedrock aquifer are difficult to predict because of heterogeneity in the fracture network, which is further expounded in Chelsea, Québec, by the lack of an obvious point source of bacteria contamination. In this setting, the presence of preferential pathways and the proximity of potential sources are considered important contributors to the presence of coliform bacteria in domestic water wells. Multiple analyses were performed to identify which factors affect the quality of groundwater. The unique attributes of the wells, the complexity of bedrock geology, the presence of septic systems and the multiple origins for most ions make the identification of the main characteristics that influence the presence of coliform bacteria and ion concentrations a challenge. No single statistical analytical technique is able to provide a complete picture of the processes taking place over the study area – the combination of many techniques formulated a more complete picture. It also may be more beneficial to examine each well individually and to consider the seasonal variability in the analysis. In spite of these challenges, this analysis is useful as a baseline to assess the impact of anthropogenic activities for future studies, to evaluate human pressure on the aquifer and to assist the Municipality in protecting the groundwater, especially in more populated areas of the study area.

Chapter 4: Bacterial and chemical assessment of seasonal variability of groundwater quality within a gneissic bedrock aquifer, Chelsea, Québec, Canada

4.1. Introduction

Groundwater is an important source of water for Canada as 30% of its inhabitants rely on the resource for household usage (Environment Canada, 2010a). It is estimated that three to four million Canadians depend on private drinking water supplies (Corkal et al., 2004; Charrois, 2010), with one third of the rural population using private wells for domestic water use (StatCan, 2009). In some rural areas, such as the Municipality of Chelsea, Québec (Canada), all the residences depend on groundwater as their source of water. In Canada, there is no regulation to monitor private water supplies compared to public water supplies. The responsibility of monitoring private water supplies for microbial and chemical water quality resides with the user. Even though some Canadian provinces recommend yearly monitoring of private supplies, a survey by Statistics Canada (2007) reported that only 35% of households using private water supplies had their water tested within the previous 12 months. Some studies in Ontario reported that between 61 to 65% of well owners did not get their water tested during the past 12 months (Jones et al., 2006; Kreutwizer et al., 2011). The lack of regulation makes local private water supplies more vulnerable to microbial contamination compared to public water supplies. Rural residents are often unaware that groundwater quality changes over time even though the scientific community has documented that a variety of spatial and climatic factors affect groundwater quality of private water wells (Goss et al., 1998; Richardson et al., 2009).

Studies have found that the groundwater quality of private water wells is affected by local settings, the well construction and proximity to anthropogenic activities (Conboy and Goss, 2000; Goss et al., 1998, Rudolph et al., 1998) and reflects a combination of extra-regional, regional and site specific factors with the cumulative effect observed at the well (Korkka-Niemi, 2005). Extra-regional factors relate to the bedrock and surficial geology whereas regional factors relate to the type of aquifer and residence time. However, some of these factors are also considered local characteristics because the rock type, geological features and topography may control local recharge and thus, affect the transport of pathogens and contaminants from the surface, or near the surface, towards a drinking water

well. Surficial material and thickness of these deposits offer natural protection of the water resource through attenuation processes. Consequently, this reduces the concentration of pathogens and contaminants reaching water wells (Conboy and Goss, 2000). The well construction (local factor) may also contribute to the presence of coliforms in water with the proportion of wells contaminated by coliform bacteria decreasing with increasing well depth (Goss and al., 1998; Conboy and Goss, 2000; Gonzales et al., 2008). The type of well also has an influence on the percentage of contaminated wells (Goss et al., 1998) with drilled wells being usually less vulnerable to contamination than dug and bored wells (Conboy and Goss, 2000) because they draw water from deeper aquifers. Older wells are also more vulnerable to contamination because the casing material may have degraded over time.

Seasonal variability in coliform bacteria concentration is another issue to consider, which has been related to climatic factors such as precipitation, temperature (e.g. Richardson et al., 2009; Conboy and Goss, 2000) and recharge (Levison and Novakowsky, 2009). Many studies demonstrate the effect of seasonality on the failure to meet the drinking water objective (DWO) for private water supplies. Reid et al. (2003) studied private water supplies in Scotland and observed a positive relationship between the amount of rainfall and water quality failure. Richardson et al. (2009) observed a similar trend when analysing microbial concentrations of private water supplies in England. The timing of sampling and the amount of rainfall were significant factors in the detection of E. *Coli* along with “situational factors” related to the source of water and the type of water supply. Oliphant et al. (2002) demonstrated temporal variability in bacterial concentration in shallow dug wells in an alluvial aquifer (Alberta, Canada). The temporal variability in the degree of contamination was interpreted to result from seasonal variations in the groundwater system. Valenzuela et al. (2009) studied 42 shallow groundwater wells in Chile for indicator microorganisms (total and faecal coliforms and faecal streptococci) over a one year period. The results showed that bacteria indicators were consistently detected but their concentrations varied depending on the season. Peaks in coliform concentration were observed during winter (June) and were mainly the result of higher demand combined with minimal water yield. Levison and Novakowsky (2009) studied bacteria transport in a gneissic bedrock aquifer with thin overburden. Their findings showed strong seasonal variability in coliform concentration, with daily variations in faecal coliforms. Recharge processes (dilution and transport) were found to be important factors controlling contaminants in areas of thin overburden. These studies consistently indicate the

importance of monitoring private water supplies for seasonal variations in microbial content because of the potential impact on human health.

Seasonal variations in coliform bacteria concentration may result from temporal change in the source (e.g timing of manure spreading) or from a change in the recharge pathway, such as rapid infiltration of runoff water, which is also one of the principal reasons cited for the bacterial contamination. The susceptibility of a well to rapid infiltration of runoff water depends on the presence of preferential pathways near the well, or in the recharge area. Development of a preferential pathway increases the potential for rapid recharge and decreases the attenuation potential of the soil, which makes the aquifer more vulnerable to surficial contaminants (Cey et al., 2006; Levison and Novakowsky, 2009). Crystalline bedrock and karst aquifers are vulnerable to contamination for similar reasons: the primary porosity is often minimal and flow largely depends on secondary porosity created by fractures and weathering. Fractures act as macropores and offer little filtration and sorption allowing surficial contaminants to travel faster and deeper (Conboy and Smith, 2005). Thin soil cover may also lead to poor filtration and rapid infiltration of surface water, causing widespread contaminant migration (Cey et al., 2006; Levison and Novakowsky, 2009). A large proportion of the groundwater in Chelsea is drawn from unconfined crystalline bedrock aquifers with variable thickness of overburden. In areas of thin overburden, the water is more susceptible to contamination because fractures may become active during a rainfall event and potentially act as preferential pathways (Cey et al., 2005). Rapid recharge to a well through different preferential paths has the potential to influence the well-water as it may dilute the concentration of solutes in the well (Toran and White, 2005). Preferential pathways are present in the overburden and the aquifer, but also are the product of poor well construction. The well itself may act as a preferential pathway to surficial water and contaminants if its annular space, created during the drilling of the well, is not properly sealed with impermeable material such as concrete or bentonite.

Prior to evaluating the impact of a faulty seal on water chemistry, wells with a faulty seal must be identified as such. Chapter 2 described the development and application of a simple method to detect faulty seals in private water wells. Alternate scenarios described the infiltration of runoff water and assessed the relative contribution of the well construction (presence of a preferential path in the annular space) compared to local characteristics of the site. The wells tested were classified into categories based on data from results of the infiltration and tracer tests, and a number of wells with faulty seals were identified.

Chapter 3 evaluated the overall groundwater quality in Chelsea (QC), examining the spatial distribution in the detection of coliform bacteria (total and faecal) and groundwater chemistry. Major processes affecting the microbial and chemical quality of the groundwater were identified. Microbial water quality was shown to be influenced primarily by infiltration of runoff water (i.e. recharge) and septic effluents. Infiltration through the unsaturated zone, cation exchange processes and anthropogenic activities contributed to concentration of ionic species in groundwater systems. Local characteristics were evaluated to identify controlling variables on the presence of coliform bacteria in water wells. Statistical analysis did not identify any specific trends, which was interpreted to mean that bacterial contamination was spatially controlled by an unquantifiable combination of factors. Seasonal controls were not considered in chapter 3.

Understanding pathways and factors affecting contamination of domestic wells and how these variables are affected by seasonal variation is important in source water protection. This paper presents the results of a study carried-out from spring 2008 to spring 2009 in a crystalline bedrock aquifer located in Chelsea, Québec, a municipality located 15 km north of Ottawa, Ontario (Canada). The purpose of this research is to better understand monthly variability of bacterial and hydrogeochemical water quality in Chelsea, QC. The study investigates seasonal variations in bacterial (total and faecal coliforms) contamination and major-ion chemistry in private drinking water wells. These data are used to assess the potential for natural (i.e. fractures) or anthropogenic (i.e. well construction) preferential recharge pathways and how wells with a faulty seal impact bacterial and chemical water quality. Multivariate statistical analyses are also employed in an attempt to further discriminate between extra-regional, regional, local and anthropogenic controls on the groundwater quality in the study area of Chelsea, Québec.

4.2. Study area

4.2.1. Chelsea, QC

The Municipality of Chelsea (QC) is located 15 km north of Ottawa, ON (Canada). The surface area of the Municipality is approximately 110 km^2 in a roughly triangular shape (Fig. 4.1). The study site is composed of a mix of flat areas and small hills with local areas of more abrupt topography. The eastern boundary is the Gatineau River, which flows from

northwest to southeast. The average daily temperature ranges from -11.5°C in January to 20.7°C in July. The average annual precipitation for the Chelsea area is 987.1 mm per year including 214.8 mm water equivalent in the form of snow (Environment Canada, 2010). Recharge primarily occurs after the spring snowmelt and in late fall, when evapotranspiration is minimal (Golder Associates, 1990). During the summer, recharge is minimal because the water available for infiltration is limited by evapotranspiration, but it may occur after a long rainy period. Minimal infiltration occurs during the winter months due to the frozen soil cover.

Figure 4.1 shows topography and locations of the sampling sites. Surface elevation ranges from 100 m (along the Gatineau River) to 340 m (Precambrian hills). Most of the Municipality is situated on the Canadian Shield, which consists predominantly of Precambrian crystalline igneous and metamorphic rocks (GSC, 2008). The igneous rocks are mainly composed of syenite and monzonite whereas the metamorphic rocks consist of paragneiss, marble and quartzite (Fig. 4.2). Bedrock frequently crops out in the study area. In the southern limits of the municipality, overlying the Precambrian bedrock are limestone and sandstone units of the Ordovician (Ottawa and Nepean formations). Main faults are oriented NW-SE with other structural lineaments (fold and faults) trending east-west (Golder Associates 1990). Most of the surficial deposits resulted from the last period of glacial melting, 12 000 years ago (Golder Associates, 1990). In most areas, Precambrian bedrock is overlain by a thin veneer of till and/or glacio-fluvial deposits consisting of sand and pebbles, or thicker deposits of offshore marine silt and clay. These fine-grained marine units deposited from the Champlain Sea and are located along the Gatineau River and near the northern and southern boundaries of the Municipality (GSC, 2008). The thickness of the surficial deposits varies from <1 m (till on bedrock) to 50 m (Champlain Sea deposits).

In fractured bedrock, the groundwater flow is mainly dictated by the topography and the orientation of the fractures and joints (Conboy and Goss, 2000). The regional groundwater flows northwest to southeast, roughly paralleling the Gatineau River. Confining conditions (confined and unconfined aquifers) are inferred from the surficial deposits map (Fig. 4.2). Clay and silt deposits provide an impermeable protective layer to the aquifer below. Areas classified as offshore-marine deposits and landslide areas are designated as confined. Even though some areas along the Gatineau River are classified as confined, the aquifer is thought to behave as semi-confined or unconfined because of the proximity to recharge areas. The areas covered by other deposits (glacio-fluvial sediments,

organic deposits, till, Precambrian bedrock and near-shore marine deposits) are not thought to be protected by an impermeable layer and the aquifer is therefore considered unconfined. The aquifer conditions are considered confined when the area is covered by the thick layer of silt and clay and unconfined when the surficial sediments are composed of till and glacio-fluvial deposits.

4.2.2. Site characteristics

The 27 sampling sites located in Chelsea (Québec, Canada) are representative of the various local settings found on the Municipality and are presented in Table 4.1. The wells vary in age from 1 to 40 years. The depth varies from 18 to 108 m and the static water level from <1 to 34 m below ground surface. Most sites are located in the Gatineau Hills where the thickness of the overburden is <2 m. The composition of the surficial material varies depending on the location of the well. The soil for the sites located near the Gatineau River and in the south-west area of the municipality is composed mainly of clay. The soils in higher elevations are composed mainly of fine-grained material such as silt and fine-grained sand. The wells are also classified according to the confining condition at the site, which is largely determined by the presence or absence of a clayey layer at the site. Nine wells are under confined conditions whereas the other 18 are unconfined. Finally, the wells are classified according to their location relative to the Gatineau Hills or the Gatineau River: highland, meaning they have no uphill neighbour; midland, indicating the presence of one or more neighbours uphill from the well; and lowland, meaning the well is located in a flat area near the Gatineau River or the St-Laurence lowlands.

4.2.3. Classification of wells based on water type

Chapter 3 classified the wells according to their water type and described the spatial variability in the distribution of the chemical species over the study area. The groundwater facies Ca-Mg-HCO_3 is the dominant water type over the study area, with 50% of the wells classified in this water type. Wells are located mainly in preferential recharge area with thin overburden. To further characterize this group, it is sub-divided based on the Ca/Mg molar ratio. Subtypes are: Ca (Ca/Mg>6) and Ca-Mg (Ca/Mg<6) (Scanlon, 1989). Eight wells are classified in the Ca-Mg water subtype (W1, W5, W7, W11, W14, W20, W22 and W24) and

five wells are classified into the Ca-water subtype (W4, W13, W15, W17 and W27). The second dominant groundwater facies is a mixed type composed of either anions, cations, or both (W2, W3, W6, W12, W16, W18 and W19). No trends are identified in the spatial distribution of wells in this water type. Four wells show a Na-HCO_3 water type (W9, W10, W23 and W25). Most wells classified into this category are located in the southern section of the study area, under confined hydrogeological conditions. The exception is W25 which is located in a topographic low under unconfined conditions and thin overburden. A lone well is categorized as a Ca-Cl water type (W26). To simplify the analysis this well is grouped with the mixed-water type. The wells are grouped by water type to describe the seasonal variability in coliform bacteria concentration and water chemistry.

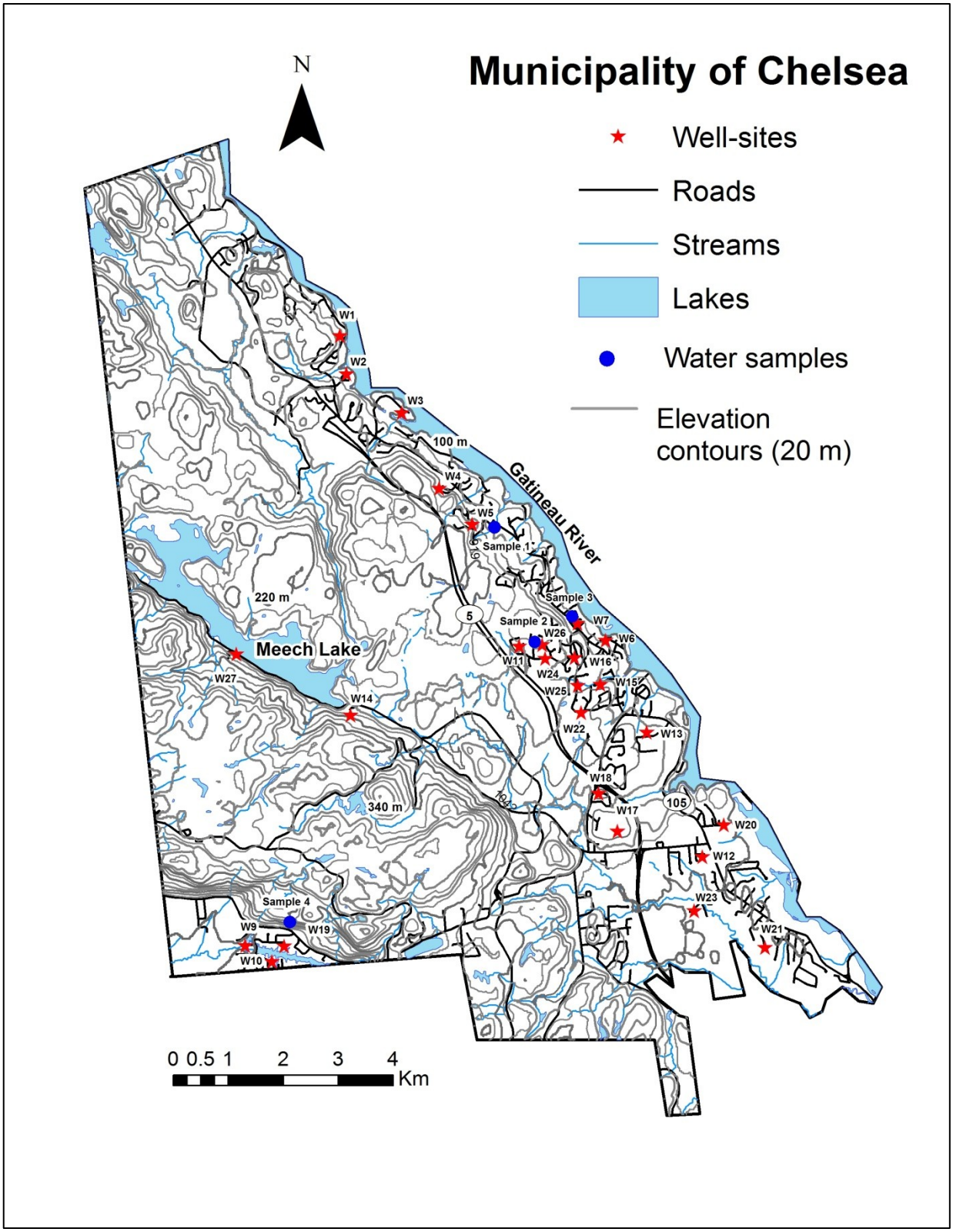


Figure 4.1: Municipality of Chelsea showing major geographic features, study sites and sampling locations. Contour spacing is 20 m.

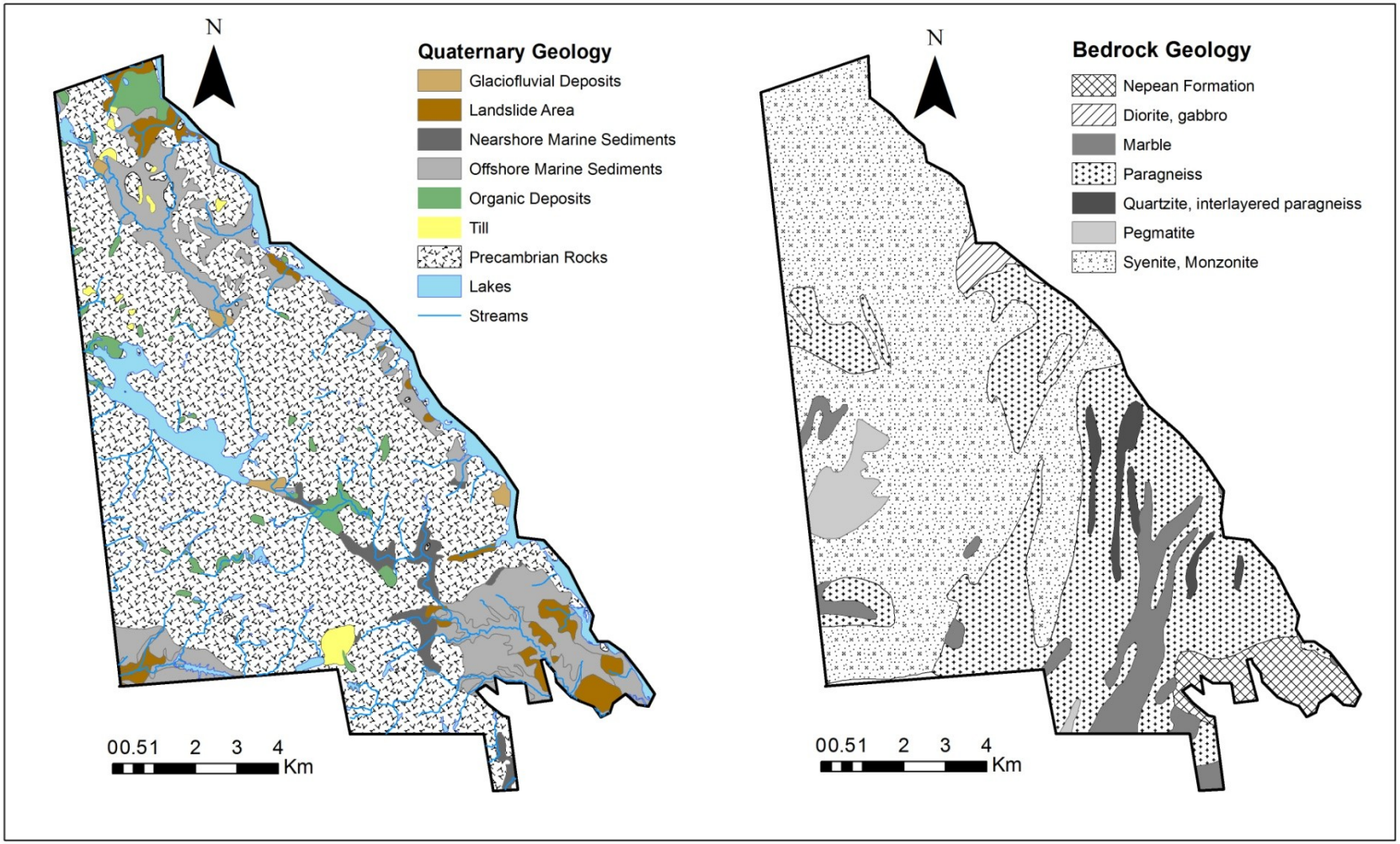


Figure 4.2: A) Surficial deposits map of the Municipality of Chelsea. Precambrian rock indicates the presence of thin Quaternary deposits. B) Bedrock geology map of the Municipality of Chelsea. (Geological Survey of Canada, 2008)

Table 4.1: Physical characteristics and frequency of bacterial incidence (TC or FC >0 CFU/100mL) in well-water from the sampled wells.

Well #	Well age (yrs)	Well depth (m)	Water level (m)	Soil thickness (m)	Surficial geology	Hydrogeological conditions	Bedrock geology	Relative location	Total coliforms	Faecal coliforms
W1	40	50	27	<2	sandy silt	unconfined	syenite, monzonite	midland	9/14	1/14
W2	2	45	25	>5	clay	confined	Syenite, Monzonite	lowland	8/11	4/11
W3	30	77	3.3	<1	till	unconfined	syenite, monzonite	lowland	4/14	3/14
W4	22	50	11	<1	till	unconfined	syenite, monzonite	midland	8/14	0/14
W5	15	74	24	<1	till	unconfined	paragneiss	highland	8/14	1/14
W6	12	47.5	7	<1	clayey fine sand	unconfined	paragneiss	lowland	6/14	0/14
W7	15	75	10	>5	clay	confined	quartzite/paragneiss	midland	1/13	0/13
W8	30	37	7.2	<5	till	unconfined		midland	4/6	0/6
W9	20	50	7.7	>5	clay	confined	syenite, monzonite	lowland	6/13	0/13
W10	20	30	6	>5	clay	confined	syenite, monzonite	lowland	7/12	1/12
W11	20	65	5	<1	till	unconfined	paragneiss	midland	10/14	1/14
W12	20	58	24.5	>5	clay	confined	paragneiss	lowland	5/14	0/14
W13	4	90	5.4	<2	silty fine sand	Unconfined	paragneiss	midland	0/14	0/14
W14	20	67	16	<1	sandy silt	unconfined	syenite, monzonite	highland	1/13	0/13
W15	6	35.1	2.5	<1	fine grain sand	unconfined	paragneiss	midland	0/14	0/14
W16	15	77	16	<1	silty fine sand	unconfined	quartzite/paragneiss	highland	11/12	4/12
W17	2	93.5	17.8	<1	silty fine sand	unconfined	paragneiss	highland	4/14	0/14
W18	1	108	10.7	<2	fine sand	unconfined	Marble	highland	6/12	0/12
W19	20	56	3	>5	clay	confined	syenite, monzonite	lowland	4/14	0/14
W20	10	35	29	>5	clay	confined	quartzite/paragneiss	lowland	0/13	0/13
W21	15	84	10.6	>5	clay	confined	sandstone	lowland	3/14	0/14
W22	15	35.5	3	<1	sandy silt	unconfined	quartzite/paragneiss	midland	0/14	0/14
W23	20	54	34	<5	sandy silt	confined	paragneiss	highland	7/13	0/13
W24	6	60	0.5	<2	clayey sand	unconfined	paragneiss	midland	3/14	0/14
W25	18	80	0.5	<2	till	unconfined	quartzite/paragneiss	midland	5/13	1/13
W26	15	41.22	2.6	<2	fine sand	unconfined	paragneiss	midland	6/11	1/11
W27	1	18	6	>5	medium/coarse sand	unconfined	pegmatite	lowland	4/14	1/14

Note:

Well age:	in 2008
Water level:	m below ground surface
Location:	relative emplacement of the well to the Gatineau Hills
Value given as fraction:	positive samples/total number of samples
Hydrogeological condition:	at the well

4.3. Methods

4.3.1. Sampling and analytical procedures

A total of 27 sites were selected for the study. All wells are classified as drilled wells, but local characteristics of the site are variable. The sites were selected based on their relative elevation and the confining conditions at the site. The history of contamination of the well was also considered in the selection process, but to a lesser extent. The selection provides a representative dataset of the various combinations of well depth, soil thickness and geographic location within the Municipality. From the suite of 27 wells, 9 are located in clayey surficial (confined conditions) deposits, whereas the other 18 are in areas with minimal thickness (<1 to 2 m) of surficial deposits.

Wells were sampled every month, from April 2008 to May 2009, and analysed for total coliforms, faecal coliforms and ion chemistry. Both water samples (bacteria and chemical analysis) were collected at the same location inside the house. The well owners (volunteers) were responsible for collecting the water samples on a specific date. At each site, the samples were consistently collected by the same volunteer. This reduced the uncertainty introduced during water sampling and ensured that it remained the same throughout the sampling period. The volunteers were given directions to remove any aerator from the tap, to let the water run for five minutes before sample collection and to reduce the flow while collecting the water samples. Instructions were also given to take extra care to avoid touching any component of the bottle opening and to keep the samples cold (with icepacks) until collection. It is assumed that water samples were collected properly and that the error introduced from collecting the water samples is minimal. The samples were collected in sterile 250 mL bottles containing sodium thiosulphate furnished by a certified laboratory in Ottawa, Ontario. The samples were then picked up, stored in a cooler with ice packs and dropped off at the laboratory where they were analysed within 24 hours. The private laboratory used the methods 9222B (total coliforms) and 9222D (faecal coliforms) for coliforms enumeration from the protocol: Standard Methods for the Examination of Water and Wasterwater, 21st edition, 2005.

The samples analysed for ion chemistry were collected in 250 mL plastic bottles with a screw cap. The samples were collected immediately after the sample for the bacterial analysis. The volunteers were instructed to leave minimal headspace and to reduce the

flow rate while collecting the sample in order to avoid disturbance of the water. The samples were refrigerated until transported to the lab. Samples were filtered and acidified in the laboratory shortly after arrival at the lab. Chemical analysis was completed at the geochemistry laboratory at the University of Ottawa. Cations ($Ca^{2+,}$ K^+, Mg^{2+} and Na^+) were analyzed using inductively coupled plasma atomic emission spectroscopy (ICP-AES), whereas anions (F^-, Cl^-, $SO_4^{2-,}$ NO_3^-) were analyzed using ion chromatography. Bicarbonate concentration (HCO_3^-) was determined using a portable Hatch titration system in the laboratory shortly after the collection of the water samples. Analytical error on the chemical analysis is within 10%. Samples with errors above this value were eliminated from data analysis in this study. Duplicates on the chemical analysis are within 5%.

4.3.2. Statistical Data Analysis

A total of 27 wells were sampled monthly for 14 months (April 2008 to May 2009) and a total of 256 samples were used to describe the geochemistry of the groundwater in the Municipality of Chelsea. Descriptive statistics, correlations, statistical tests (Wilcoxon rank test), principal component analysis (PCA) and hierarchical cluster analysis (HCA) were performed on the monthly ionic concentration for individual wells-sites using PAST software (Hommer et al., 2001) and S-Plus software (version 8.0).

In Chapter 3, multivariate statistical analyses (HCA and PCA) were used to identify the natural and anthropogenic components affecting the groundwater quality at a local scale. In this chapter, the same analyses were performed to determine if the components affecting water quality differ when the relative frequency of contaminated wells is the highest.

PCA is a multivariate statistical analysis used to reduce the complexity in large datasets and provide insight on the structure of the dataset (Cloutier et al., 2008; Güler et al., 2002; Moore et al., 2009). PCA was carried out on 12 variables (Ca^{2+}, $Mg^{2+,}$ Na^+, K^+, F^-, Cl^-, NO_3-N, SO_4^{2-}, HCO_3^-, total and faecal coliforms) to identify which of these variables provides the greatest variation on the well-water. The analysis is applied to the average value for each variable and the censored data were replaced by the detection limits. Log transforms and normalization are commonly used in multivariate analysis (Cloutier et al., 2008; Güler et al., 2002; Moore et al., 2009) and were applied to the chemical dataset of this study prior to analysis because distributions of the chemical variables are non-normal

(Chapter 3). The normalized data were obtained by subtracting the distribution mean from the measured values for individual samples and by dividing by the standard deviation of the distribution (Cloutier et al., 2008; Güler et al., 2002; Moore et al., 2009).

HCA is used to classify samples into geochemical facies based on their similarity (Cloutier et al., 2008; Güler et al., 2002; Mencio and Mas-Pla, 2008). The log- transformed and normalized data sets were used for the cluster analysis. The cluster analysis consists of using a linkage rule which links nearby points by the use of a similarity matrix. Different linkage rules such as complete linkage, average linkage and Ward's methods are commonly used in HCA (Güler et al., 2002; Mencio and Mas-Pla, 2008). Ward's method differs from the other clustering method because it uses analysis of variance to evaluate the distances between clusters (Güler et al. 2002). Ward's linkage rule combined with the Euclidean distance as the measure of similarity has been shown to form more homogeneous and distinctive clusters (Güler et al., 2002; Mencio and Mas-Pla 2008; Cloutier et al. 2008) where each member is more similar than any member from another cluster. For these reasons, Ward's method using the Euclidean distance was selected for the cluster analysis.

4.4. Results and Interpretations

4.4.1. Seasonal variability in coliform bacteria

As outlined earlier, seasonal variability in the level of bacterial concentration is a major issue to consider, and considerable effort was placed on examining seasonal trends. The results of the 27 wells were combined in the analysis to show the overall seasonal variability in coliform bacteria concentration in the study area. However, only 25 of these were retained for analysis and then classified according to their water type to detect seasonal trends as a function of water chemistry. Statistical analyses were also used to identify the physical site characteristics that affect the monthly concentration of coliform bacteria. Of the other two wells, one (W21) was rejected because samples were not collected prior to the treatment system (water softener) and the other (W8) because the database was incomplete.

4.4.1.1. Seasonal variability in Chelsea, QC

The presence of coliform bacteria in sampled wells shows seasonal trends in the relative frequencies of samples (expressed as a percentage) that tested positive for coliform bacteria (Figure 3). The values range from 10 to 67% and are relatively higher from July to December 2008 compared to other months. This trend is also observed for FC, but to a lesser extent since the relative frequency of positive samples ranges from 0 to 15%. Lastly, the relative frequency of wells exceeding the provincial drinking water objective (DWO) of 10 CFU/100mL is greater from July to October with the value ranging from 25 to 40%. Detailed descriptions of the monthly results for indicator micro-organisms total coliforms (TC) and faecal coliforms (FC) are summarized in Appendix D.

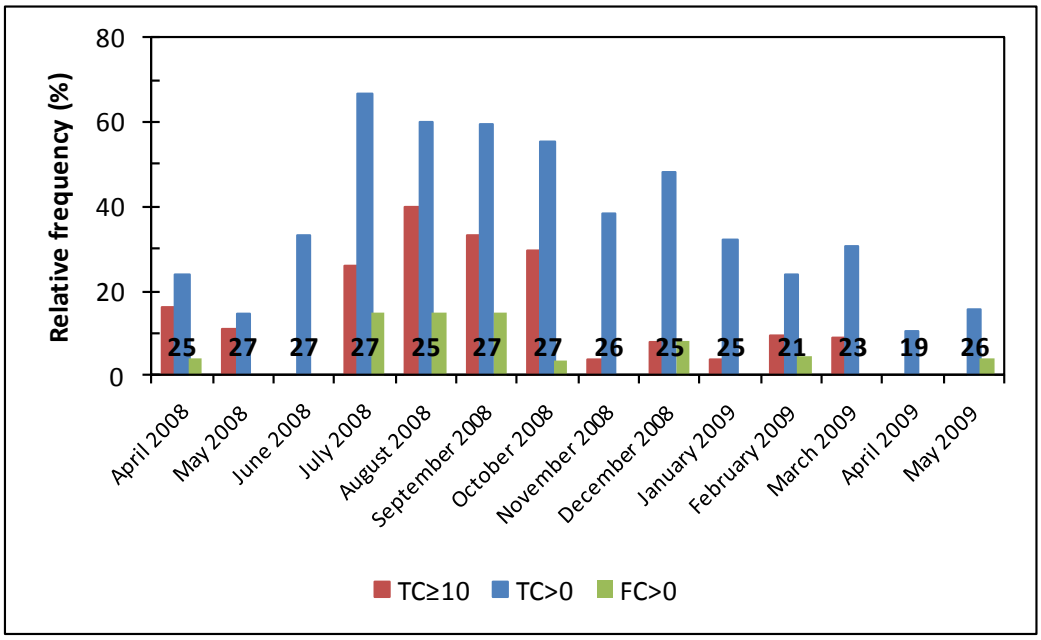


Figure 4.3: Percentage of samples testing positive for TC and FC. Number of samples collected monthly (n) is labelled on the columns.

The sampling period was designed to evaluate the effect of snowmelt in the study area over two spring seasons. In 2008, snowmelt occurred at the beginning of April whereas it occurred in March in 2009. TC are detected in 23% of the wells sampled after the 2008 snowmelt with 15% of the wells exceeding the DWO for TC and one well for FC (Fig. 4.3). During the spring 2009 (March samples), TC are detected in more than 30% of

the wells with 10% exceeding the DWO whereas FC are not detected during that same period.

The effect of snowmelt on bacteria contamination did not appear to be reproducible year-to-year. Some wells are affected by snowmelt in 2008 but did not show the same response in 2009. For example, well W19 shows a high concentration of TC in April 2008 (1600 CFU/100 mL), but a lower concentration in March 2009 (25 CFU/100 mL). This well was re-sampled one week after the April 2008 sample and the TC concentration decreased to 6 CFU/100 mL. This suggests that coliform bacteria concentration may be variable on a daily basis (Levison and Novakowsky, 2009) and the timing of sampling influences the results.

Snowmelt alone did not have the expected effect on the relative frequency of occurrence or contamination of coliform bacteria. Relative frequencies of occurrence and contamination are not significantly different during these periods compared to months not affected by snowmelt. A possible explanation for this lack of trend is that recharge water from snowmelt may contain a smaller concentration of coliform bacteria, either from of dilution or the absence of an active source of coliform bacteria at that time of the year. Only a few wells are affected by coliform bacteria at this time of the year, which suggests that the influence of summer and fall recharge may control the occurrence of coliform bacteria.

Summer and autumnal recharge have an effect on the percentage of samples that tested positive for TC and FC. Higher relative frequency of “TC positive” samples (TC>0 CFU/100 mL) are observed from July to December 2008. During this period, the relative frequency ranges from 40 to 70%. The percentage of wells exceeding the DWO is higher from July to October 2008 and the percentage of wells contaminated by FC is higher from July to September 2008. To evaluate the effect of summer/fall recharge relative to spring snowmelt, statistical analysis (one-way ANOVA) was performed comparing the monthly relative frequency of “TC positive” samples. With a 95% confidence level, no significant differences between monthly relative frequencies are detected (p-value > 0.05). Even though the relative importance of summer/fall recharge appears to be greater than spring snowmelt, it is not statistically significant.

The timing of recharge appears to affect the concentration of coliform bacteria in the study area. Spearman correlation coefficients were calculated to assess the influence of the timing and amount of precipitation on the monthly relative frequency of positive

samples. Spearman's correlation was used instead of linear correlation to calculate coefficients of correlation because the data distribution is non-normal (Davis, 2002). The amount of precipitation was given by the sum of precipitation compiled for up to 30 days before a sampling event. The coefficients of correlation (Spearman's rho) obtained are shown in Table 4.2 and significant correlations (p-value <0.05) are in bold. There is a significant positive correlation between the amount of precipitation 1 day before sampling and the relative frequency of TC positive samples. However, the relative frequency of wells which exceed the DWO for TC does not appear to be related to the amount of precipitation. The relative frequency of positive FC samples is positively correlated to the amount of precipitation for up to one week before the sampling event. The positive correlations illustrate the direct relationship between the precipitation and the presence of TC and FC in private wells in the study area.

Table 4.2: Coefficients of correlation obtained using Spearman's rho. Significant correlations are displayed in bold.

	Amount of precipitation before sampling								
Variables	30 days	15 days	7 days	6 days	5 days	4 days	3 days	2 days	1 day
RF of TC > 0	0.29	0.08	0.28	0.20	0.09	0.17	0.30	0.39	**0.54**
RF of TC ≥ 10	0.05	0.14	0.50	0.48	0.39	0.38	0.47	0.35	0.49
RF of FC > 0	0.16	0.33	**0.66**	**0.60**	**0.53**	0.45	0.39	0.33	**0.73**

Results from the correlation analysis show that some wells are affected by rapid recharge from a rainfall event. Many storm events occur during the year, however during the course of this study samples were collected only after one storm event (September 2008). Wells W6, W12 and W18 show high TC concentration in September which is interpreted as the result of the rainfall event. For some wells such as W9, W10, W11 and W23, characterizing the response is difficult because these are consistently contaminated prior to the rainfall event whereas for other wells the link is more evident. Lastly, coliform bacteria are not detected during the sampling period in some wells (e.g., W13, W14, W15 and W22) and it remains unclear if it is because the well is not susceptible to rapid recharge, or there is no active source of coliform bacteria in the well capture zone.

The correlation results demonstrate the lag time between a storm event and the response in the well. The observed response in some wells is as fast as 1 day. Conducive

conditions such as intensity of the storm or the initial soil moisture may have been in place to activate a preferential recharge pathway (Cey et al., 2006) near the well and a source of coliform bacteria is present. These data demonstrate that in the study area, local settings, presence of a source, seasonal effects and proximity to rapid recharge pathways impact the vulnerability of a well to bacterial contamination.

4.4.1.2. Seasonal variability as a function of water type

The water type of a well is usually an indication of processes encountered along the flow path and the content of major-ions may also reflect variations in residence time from the recharge areas to the well (Scanlon, 1990). Data on TC and FC are used to evaluate if a particular water type is more susceptible to seasonal variations in bacterial concentration. Monthly sums of TC and FC as a function of water types (e.g. Ca-Mg-HCO_3, Na-HCO_3 and mixed) are compared to monthly cumulated precipitation to determine if there is a link between the amount of precipitation and coliform bacteria detection, and to evaluate the vulnerability of a specific water type to rapid recharge. Seasonal variations of coliform bacteria count and relative frequency of TC and FC occurrence specific to each water type is illustrated in Figures 4.4 to 4.6 with a complete description provided in Appendix D.

Seasonal patterns in coliform bacteria concentration are observed in all three water types (Figs. 4.4 to 4.6). The mixed-water type appears to be more affected by the spring 2008 recharge compared to the Na-HCO_3 or Ca-Mg-HCO_3 water types. However, in March 2009, all water types are affected by the spring recharge with the relative frequency of positive samples subsequently decreasing. The Ca-Mg-HCO_3 and Na-HCO_3 water types are strongly affected by summer and fall recharge compared to the mixed-water type. The mixed-water type is affected by later summer/fall recharge, but shows a higher consistent relative frequency of positive samples throughout the year which shows that well in this water type are more vulnerable to contamination.

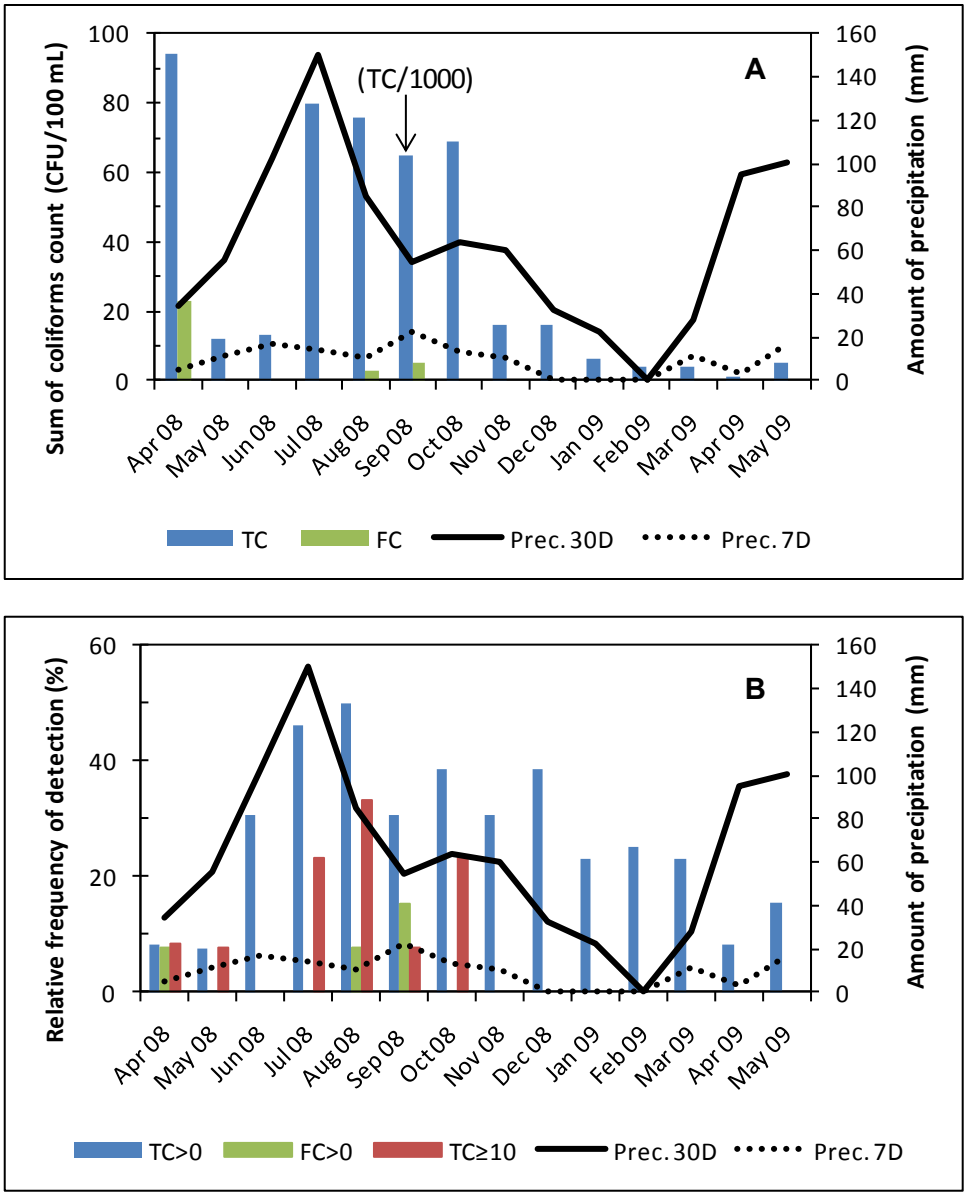


Figure 4.4: Ca-HCO_3 water type: A) Monthly sum of coliform bacteria and 30-day and 7-day cumulative precipitation prior to sampling and B) Monthly relative frequency of samples which tested positive for coliform bacteria and 30-day and 7-day cumulative precipitation prior to sampling.

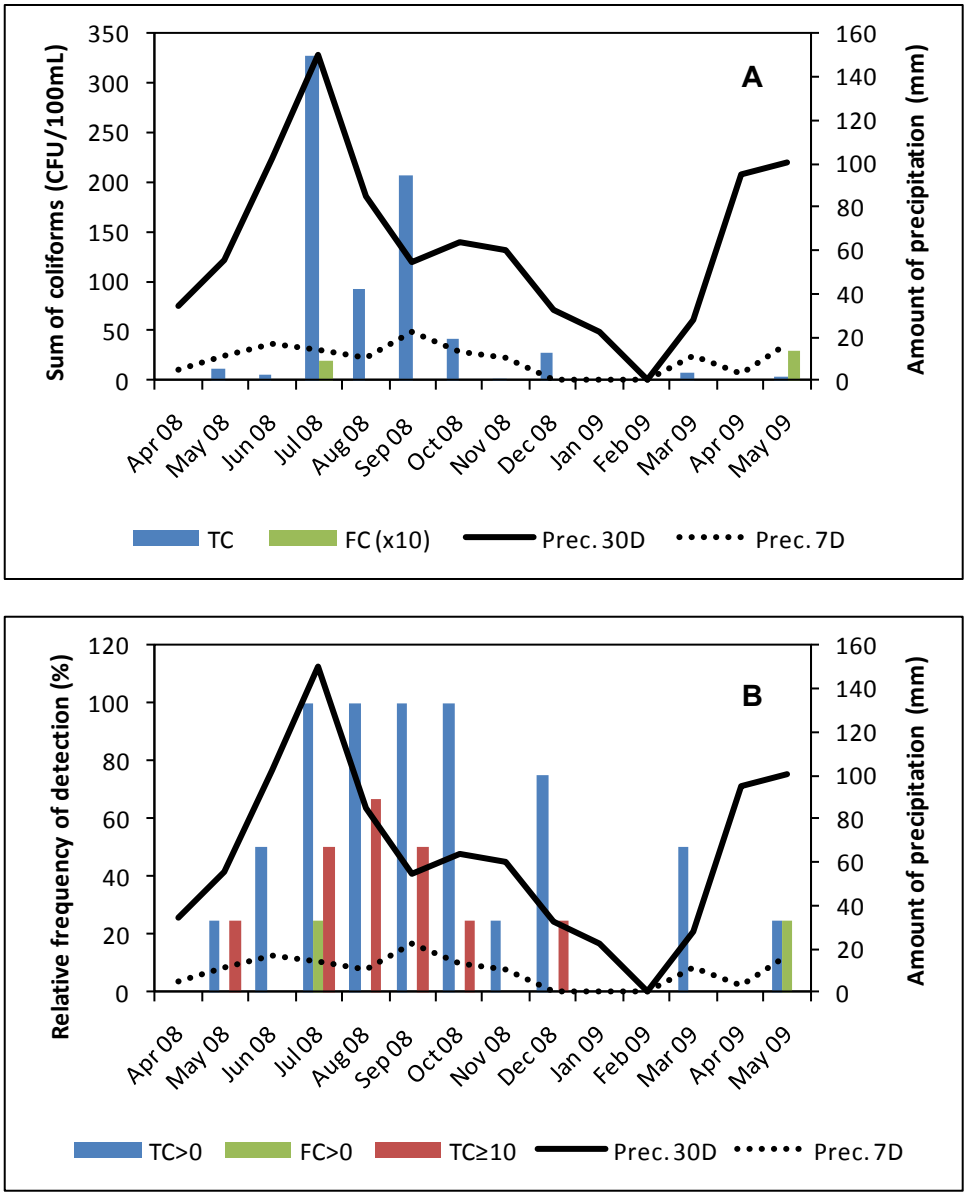


Figure 4.5: Na-HCO_3 water type A) Monthly sum for total and faecal coliforms and 30-day and 7-day cumulative precipitation prior to sampling and B) Monthly relative frequency of detection and 30-day and 7-day cumulative precipitation prior to sampling.

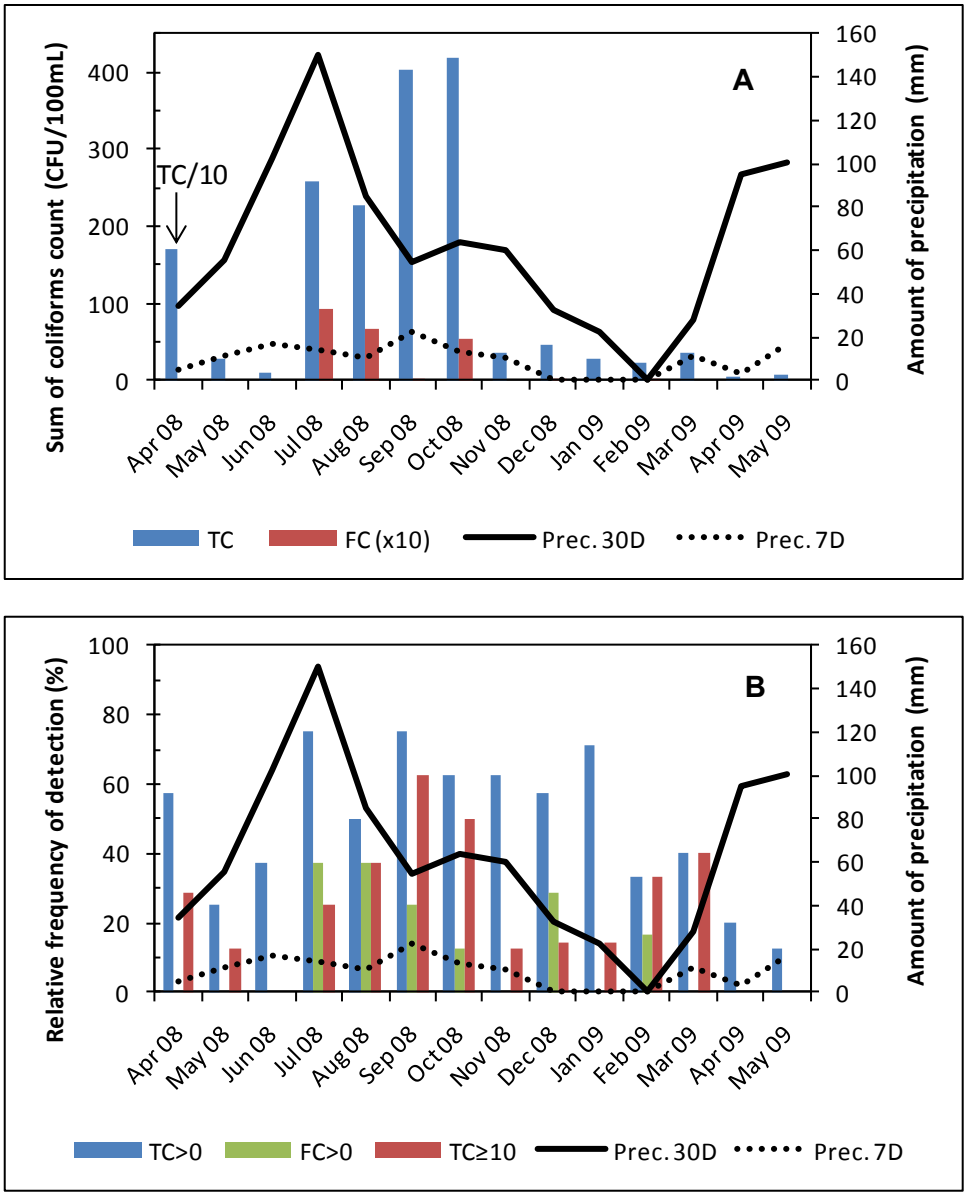


Figure 4.6: Mixed water type: A) Monthly sum for total and faecal coliforms and 30-day and 7-day cumulative precipitation prior to sampling and B) Monthly relative frequency of detection and 30-day and 7-day cumulative precipitation prior to sampling.

Well contamination is also linked to rapid recharge from precipitation (Taylor et al., 2004). July 2008 has the highest cumulative precipitation and also shows highest TC count for the Ca-Mg-HCO_3 and mixed-water types. In the Na-HCO_3 water type, the high concentration of coliform bacteria in July results from the high TC count observed in W25. W25 appears to be strongly affected by the amount of precipitation in July. This suggests a lag time between a storm event and the arrival of coliform bacteria in a well. Certain wells

reacted to a storm event that occurred a few days prior to the sampling date in September. The occurrence of intense rainfall is linked to the contamination of wells W1, W6, W12 and W18. Although, wells W10 and W23 are already contaminated in August, the TC count does increase in September (Appendix D).

Certain water types appear to be more vulnerable to coliform bacterial contamination based on observations of their seasonal response. For example, TC are frequently detected in wells in the Na-HCO_3 water type and all wells in the mixed-water type show at least one contamination event. The Ca-Mg-HCO_3 water type appears less vulnerable because it is the only water type where coliform bacteria are not detected in some wells, and is characterized by lower overall mean concentration.

4.4.1.3. Seasonal variability and physical site characteristics

Chapter 3 identified the local site characteristics that contributed to the presence of coliform bacteria. The analysis was performed using the yearly value for the relative frequency of contamination (or sample testing positive for coliform bacteria) with results indicating that “drainage towards the well” was the only factor to noticeably increase the vulnerability of a well to the presence of coliform bacteria. Seasonality was not assessed, but was thought to have contributed to the overall lack of distinctive trends in identifying contributing factors to contamination. Seasonality in coliform bacteria concentration has been demonstrated in the previous section.

The relationships between the bacterial indicators and the characteristics of the sites are assessed using non-parametric tests (Wilcoxon Rank sum test, Kruskal-Wallis rank sum test) in S-Plus statistical software version 8.0. The Wilcoxon Rank sum test (Wilcoxon, 1945) is equivalent to the Mann-Whitney U (S-Plus user manual, 2008) and it evaluates the median concentration found in well groups with specific sites characteristics (Davis, 2002). When more than 2 groups are compared (e.g. relative emplacement), the Kruskal-Wallis rank sum test is performed. This latter test is similar to the one-way ANOVA and uses a similar procedure to the Mann-Whitney non-parametric test (Davis, 2002). Analysed factors and categories are shown in Table 2 of Chapter 3. The category “well age” is modified to include only two groups instead of three: less or greater than 10 years old.

Significant and weak relationships between factors and coliform bacteria concentration are shown in Table 4.3. P-values less than 0.05 are considered significant whereas p-values between 0.05 and 0.1 are considered marginally significant (weak relationship). Although statistically significant, in some cases, there is no logical reason for a variable to contribute to the coliform bacteria concentration. For example, the presence of an insect proof cap as an important factor contributing to the presence of coliforms in January is questionable since the temperatures are below the freezing point and limit the potential for insects to die-off in the well. This trend may have resulted from none of the wells having an insect proof cap being contaminated in January 2009.

After erroneous relationships are screened-out, it is apparent that certain physical site characteristics coupled with seasonal changes are causing bacterial contamination in the wells. The variable “well age” is found to be marginally significant in July and August 2008. It is interpreted that older wells (>10 years old) tend to be contaminated more often than younger wells (<10 years old) and are more vulnerable to contamination from summer recharge. These results are similar to the findings from Conboy and Goss (1998) who showed that well age affects contamination in water wells. The variable “water level” is significant in September 2008 and marginally significant in October 2008. Wells with a water level below the casing shoe (>6 m) are more vulnerable to contamination when compared to wells with a water level above the casing shoe (<6 m). This may provide insights on the dilution potential of surface water before reaching a well. If the water level in the well is higher, infiltration water is likely getting diluted before entering the well, compared to a lower water level where the water enters the well at any depth. The presence of grout in the annular space is marginally significant in October 2008 and the estimated soil depth is a significant factor to contamination in November 2008. These factors are related to infiltration of runoff water during warmer months and represent the contribution of recharge through preferential pathways. The results from this statistical analysis show the importance of considering seasonality in the assessment of contributing factors to contamination, but that the interpretation requires that logic be applied as well.

Table 4.3: Statistically significant factors affecting the concentration of bacteria indicator using the Wilcoxon Rank sum test. Significant values are indicated in bold and marginally significant are indicated by italics.

Factor	Month sampled	Indicator	P-value	Logical?
Insect proof cap	April 2008	TC	*0.070*	N
		FC	*0.057*	N
	May 2008	TC	**0.008**	Y
	February 2009	FC	**0.021**	N
Bugs in well	May 2008	TC	**0.005**	Y
Area sunk around the well	April 2008	TC	**0.002**	Y
		FC	**0.029**	Y
Estimated soil depth	April 2008	TC	*0.070*	Y
	November 2008	TC	**0.047**	Y
	February 2009	TC	*0.090*	?
Water Level	September 2008	TC	*0.062*	Y
		FC	*0.064*	Y
	October 2008	TC	**0.052**	Y
	January 2009	TC	**0.004**	?
Well age	July 2008	TC	*0.078*	Y
	August 2008	TC	*0.086*	Y
	February 2009	TC	*0.090*	?
Presence of grout	October 2008	FC	*0.075*	Y

4.4.2. Seasonal variability in chemistry results

Seasonal variations in ionic concentration are first analysed by examining the ionic strength and the major-ions concentration of the 25 wells. Shallow groundwater systems usually developed in the upper weathered section of crystalline bedrock and are subject to seasonal variability in water chemistry resulting from annual recharge (Ayraud et al., 2006, 2008). The degree of water mineralisation in shallow groundwater system is usually lower than in deeper groundwater system unless impacted by anthropogenic activities (Ayraud et al., 2006). The water ionic strength is an indication of the degree of mineralization and is used to evaluate the degree of seasonal variation in the water chemistry. Seasonal variations in water chemistry is interpreted to indicate a change in the flow field related to different recharge patterns or attributed to a seasonal difference in the magnitude of a source.

As an approximation of the degree of seasonal variation in chemical concentration, the coefficient of variation (CV) is calculated for the ionic strength and the major-ions (Scanlon, 1989). The CV is also used to distinguish between variability from the laboratory analysis and seasonal factors. Duplicate analysis shows a CV of less than 5%. Based on this value, an arbitrary cut-off value of 10% is established for the CV. Seasonal variability is therefore observed when a well has a CV greater than 10% for ionic strength and ionic species concentration.

In order to better identify and compare trends in the ionic strength and major-ions variations, the sampling year is divided in five periods: 1) April to May 2008; 2) June to August 2008; 3) September to December 2008; 4) January to February 2009; and 5) March to April 2009. Periods 1 and 5 are defined to evaluate the effect of recharge from snowmelt on ionic strength values. Periods 2 and 4 represent summer and winter baseflow, respectively, and period 3 represents fall recharge.

4.4.2.1. Seasonal variations in water chemistry in Chelsea, QC

Most wells (W6, W7, W11, W12, W13, W15, W18, W19, W25 and W27) exhibit a lower ionic strength value during the spring (periods 1 and 5) which corresponds to recharge from snowmelt (Fig. 4.7). The lag time from snowmelt to recharge in the well water is variable. For example, at some wells (W7, W11 and W19) the effect of snowmelt is observed within weeks, whereas at others (W15, W13, W27, W6 and W12) the lag time is one to two months.

Increases in the ionic strength values are generally observed from period 1 to period 2 (W1, W5, W6, W11, W12, W13, W15 W16 W19 and W26), but some wells also exhibit decreases (W2, W18, W23 and W24). A decrease in ionic strength during summer may indicate that the principal aquifer system from which the well draws the water is shallow and is subject to recharge. Wells characterized by higher ionic strength values during summer time are interpreted to a have minimal recharge and water drawn from a deeper groundwater system.

The behaviour of ionic strength appears to be variable during period 3 where increases (W1, W5, W11, W12, W13 and W27), decreases (W2 and W18) or a combination of both (W5, W11 and W15) are observed in the wells. When increases in ionic strength

values occur, the ratio of shallow groundwater to deeper groundwater system may decrease; whereas decreases indicate that the well is subject to fall recharge. Lastly, period 4 is relatively short with no major trends detected.

Some wells display little variation in ionic strength values, but strong seasonal patterns are observed in other wells. The ionic strength CV is a measure of the overall variability in the water chemistry and the values for wells in the study area ranges from approximately 2 to 26% (Fig. 4.8). Ten wells are characterized by CV >10%: W2, W6, W7, W11, W13, W15, W16, W18, W26 and W27. The remaining 15 wells have a CV <10%. Seasonal variations in water ionic strength are interpreted to reflect different recharge patterns over the study area. A detailed analysis of changes in specific ion concentration such as NO_3-N, Ca^{2+} and Cl^- may provide insights on the nature of recharge and the source of ions.

4.4.2.2. Seasonal variations based on water type

The wells are classified according to their water types to compare the seasonal variations in specific ions. Results for the Ca-Mg-HCO_3 water type, the Na-HCO_3 water type and the mixed- and Ca-Cl water types are displayed in figures 4.9, 4.10 and 4.11, respectively. A CV<1 signifies that the concentration of a specific ion are below the limit of detection.

The ionic strength CV for wells classified in Ca-HCO_3 water type ranges 2 to 21% (Fig. 4.8) and does not appear to be influenced by the sub-water type (Fig. 4.9). The degree of variation varies depending on the species and when detected, NO_3-N shows the highest degree of variation for most wells, followed by Cl^-, F^- and Na^+. Calcium and Mg^{2+} show the least amount of seasonal variation in this water type. Certain wells exhibit greater seasonal variation than others. For example, CV for W20 are always below 10% while other wells have CV ranging between 20-30% for most ion species. This illustrate that most wells in this water type draw water from a dynamic groundwater system likely affected by rapid recharge.

The ionic strength CV for wells classified in Na-HCO_3 water type ranges 4 to 11% (Fig. 4.8). Anions generally show more seasonal variations compared to cations for wells classified in this water type. Sulphates and Cl^- show the most variability in the CV whereas

Mg^{2+}, Na^{+} and K^{+} show a lower degree of variation. Well W10 has the lowest CV for all dissolved species whereas W23 the highest CV for most dissolved species. Coefficients of variation for W9 are relatively higher for Ca^{2+} and Cl^{-} compared to other ions. Well W25 shows relatively low CV for all ions except for Ca^{2+}, which shows a slightly higher percentage of variation. Overall, most wells from this water type show little seasonal variation in water chemistry which is interpreted to indicate that the groundwater system from which the water is drawn is fairly non-dynamic throughout the sampling period.

The ionic strength CV for wells classified in mixed- and Ca-Cl water types ranges 3 to 16% (Fig. 4.8). Cations generally show greater seasonal variations compared to anions for wells in this group. From the wells in this group, W18 shows the highest CV for most dissolved species (excepted for SO_4^{2-}) and W19 shows the lowest CV. Coefficients of variation for W2 are relatively higher for NO_3-N, SO_4^{2-} and Ca^{2+} compared to the other ions, whereas W16 has a higher CV for K^{+} and has a relatively high CV for Cl^{-} concentration. Both wells W6 and W12 exhibit a CV range from 15 to 20%. Well W3 is an exception and displays less variation in cation concentration compared to anion concentration.

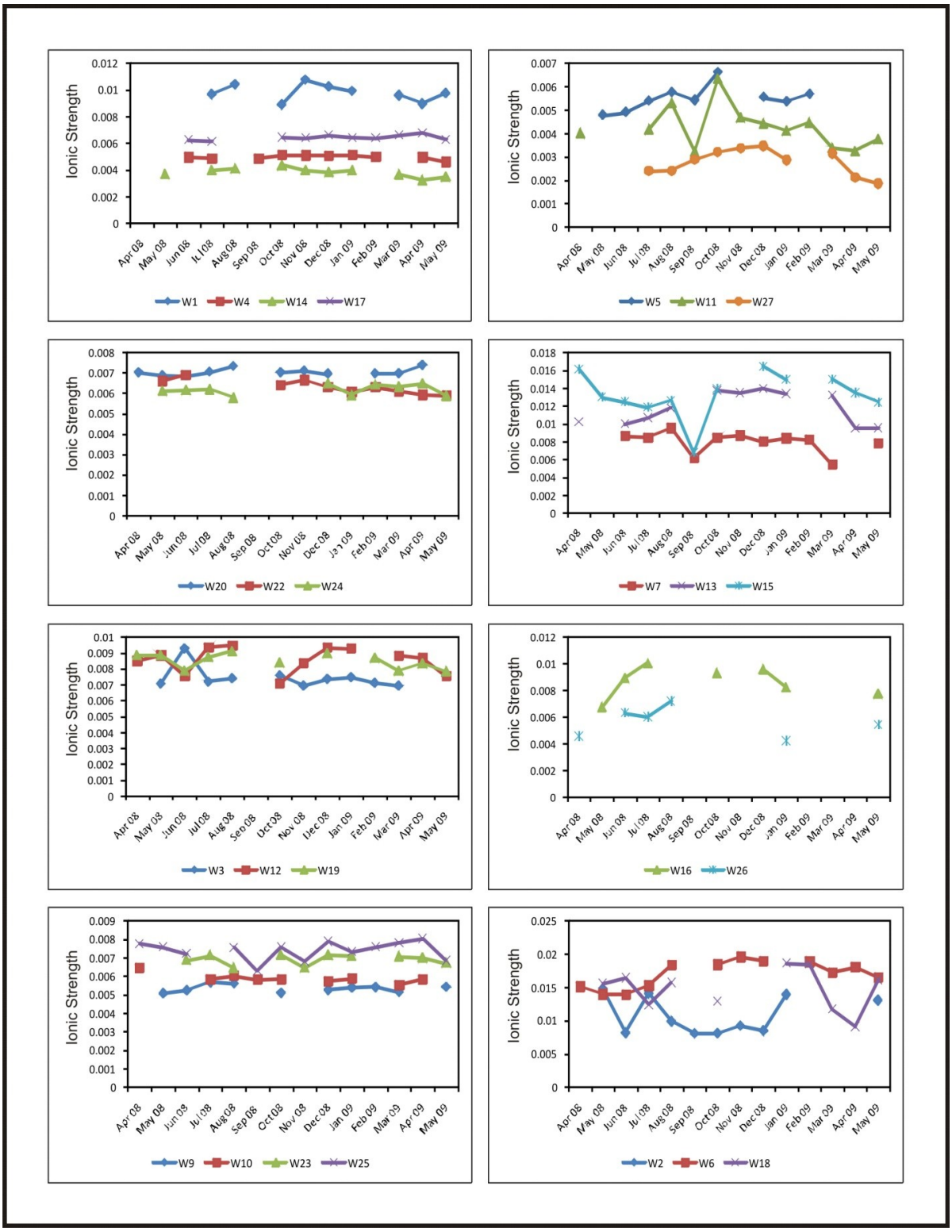


Figure 4.7: Seasonal variations in ionic strength of wells over the study area. Wells are displayed in plots based on similar trends and range of values. Ionic strength scale (y-axis) is variable in each plot to allow visual observation of relative values and trends.

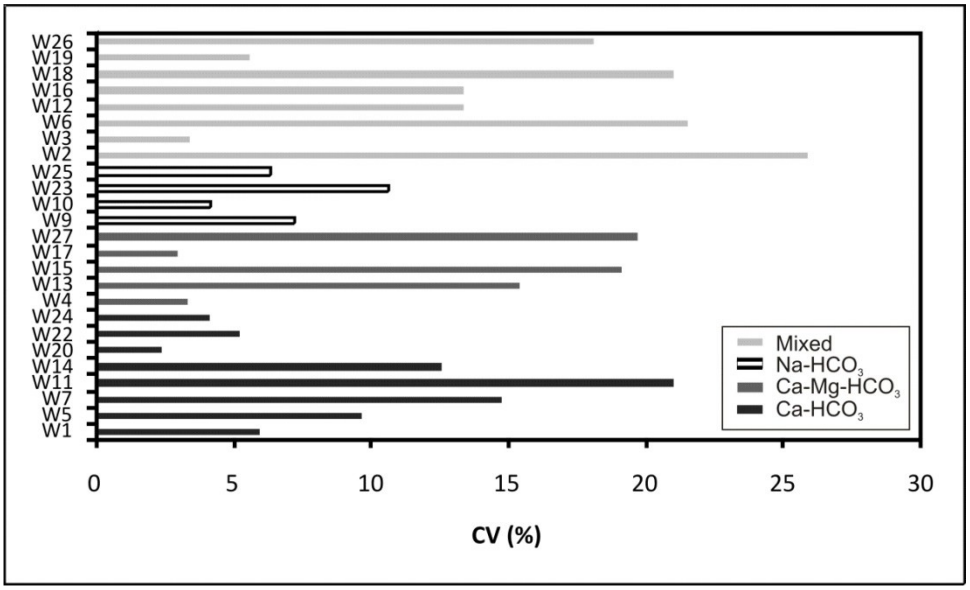


Figure 4.8: Coefficient of variation of the ionic strength of all wells. The wells are classified depending of the water type.

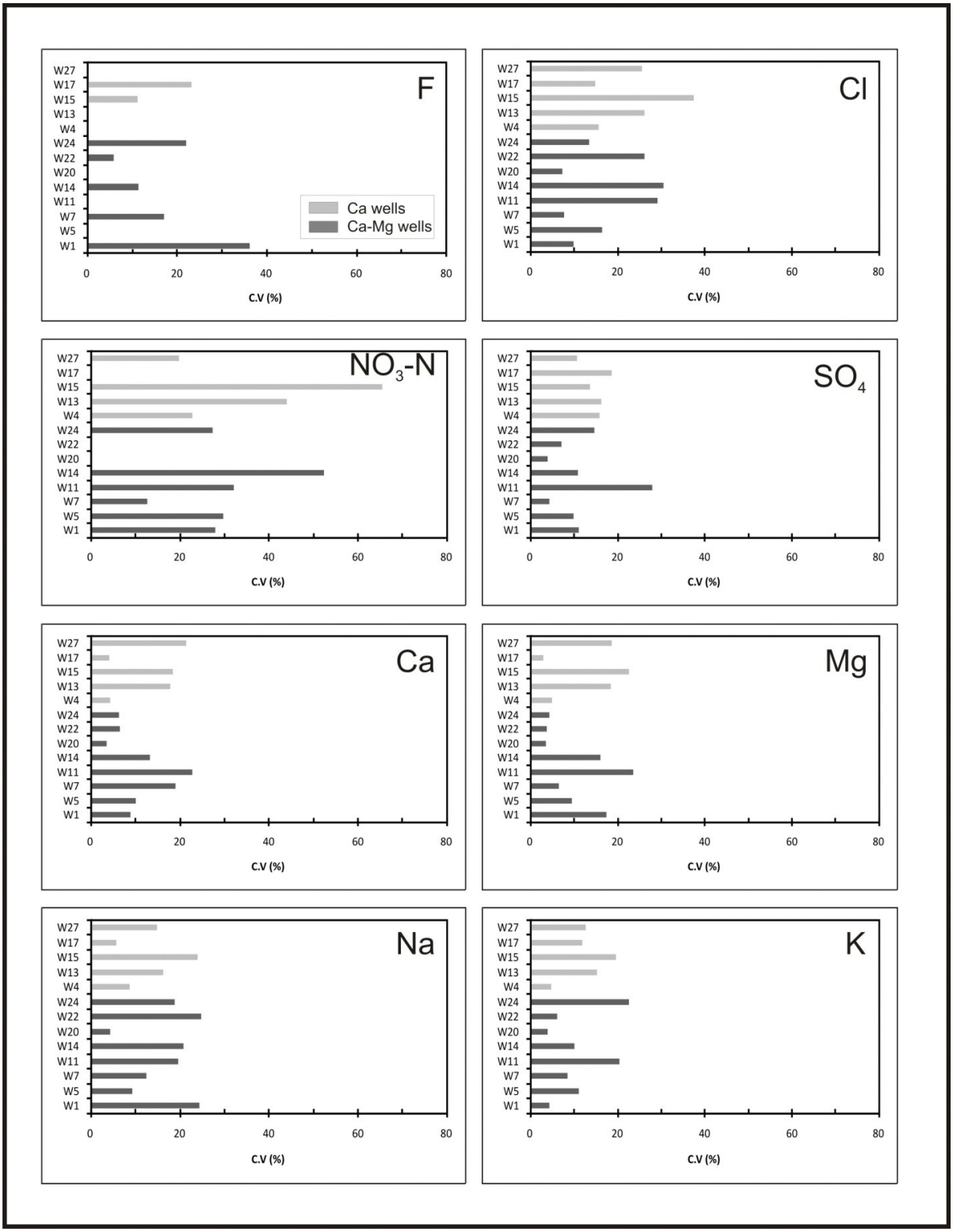


Figure 4.9: Coefficient of variability (CV) for wells in the Ca-HCO_3 water type and Ca-Mg-HCO_3 subtype.

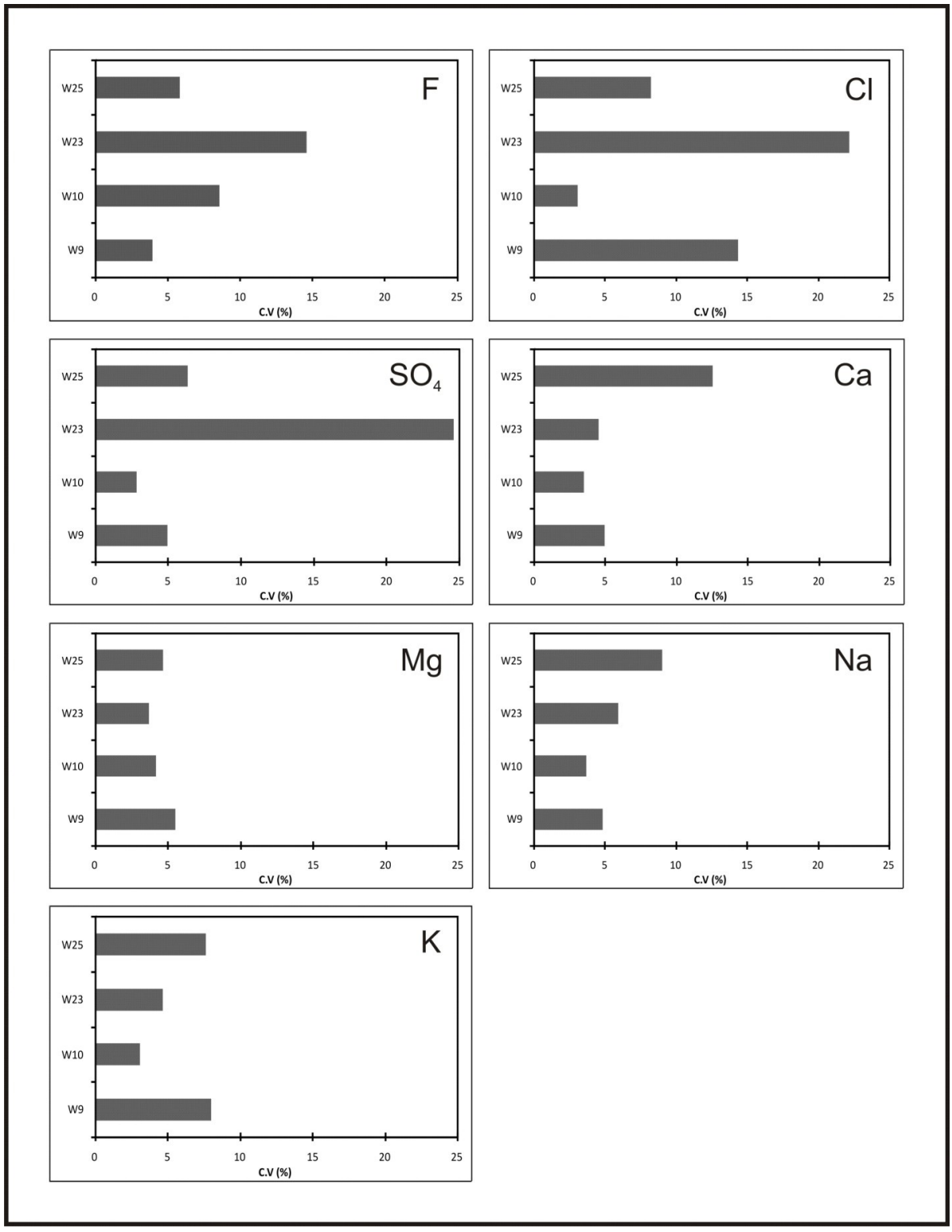


Figure 4.10: Coefficient of variation for wells classified as Na-HCO_3 water type. There is no CV for NO_3-N since this ion is not detected in the water samples from this group.

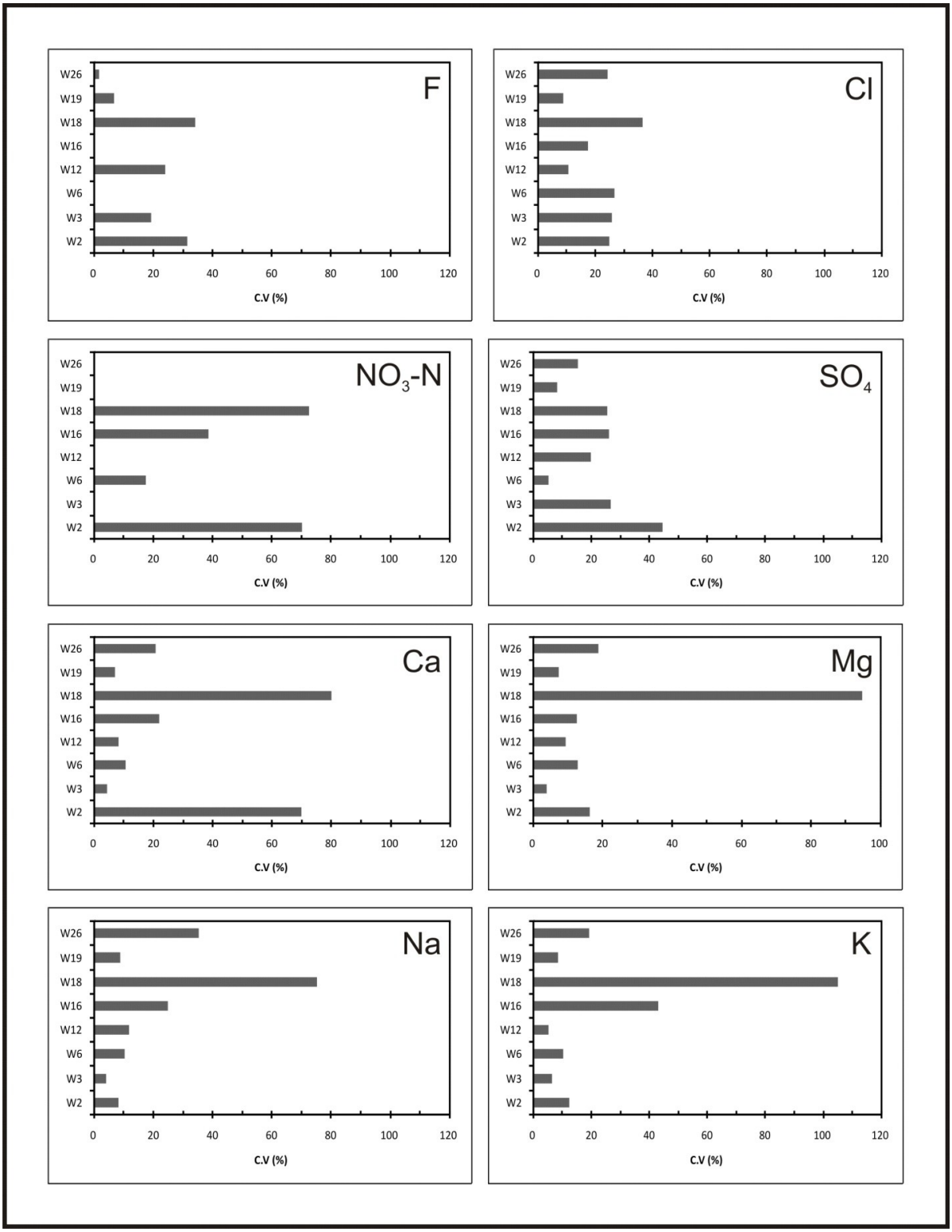


Figure 4.11: Coefficient of variation for well classified in the mixed- and Ca-Cl (W26) water type.

When detected, NO_3-N concentration is relatively low and is interpreted as the result of natural sources. Nitrate concentration is generally lower during summer months and gradually increases during fall recharge (Appendix D). Increases correspond to the end of the growing season where intakes of NO_3^- by plants decrease (Toran and White, 2005). Nitrate in the soil matrix that did not denitrify to nitrogen is carried in the shallow groundwater system with infiltrating water. The transition from period 3 to period 4 (winter baseflow) is generally characterized by a decrease in the concentration, when infiltration is interpreted to be minimal. Some wells (W4, W5, W6, W13, W15 and W27) also exhibit decreases in concentration during periods 1 and 5 that are interpreted as dilution resulting from mixing with snowmelt water. Wells where NO_3-N is consistently or sporadically detected are more prone to variations in the concentration of other anions and cations, such as Ca^{2+} and Cl^-.

Variations in the ionic concentration (e.g. Cl^- and Ca^{2+}) may reflect changes in the groundwater system or mixing with other ionic sources such as domestic effluents. In the study area, seasonal variations in Cl^- concentrations are either interpreted as change in the contribution from the shallow or deep groundwater system or mixing with Cl^- rich sources. For example, W4, W13 and W15 show lower concentrations of Cl^- and Ca^{2+} during the summer months, implying that the contribution of shallow groundwater is more important during period 2 (Appendix D). Concentrations of Ca^{2+} and Cl^- generally increase during late fall (period 3) and in some cases (W13, W15 and W27) the increases in Cl^- are correlated to increases in NO_3-N concentration. This implies that Cl^- has a surficial origin because lower concentration of NO_3-N is expected in a deeper groundwater system (Toran and White, 2005). If an increase in Cl^- concentration (W9, W12 and W14) is linked to a decrease in NO_3-N concentration (or NO_3-N is not detected), variations in Cl^- concentration provide evidence of change in the water-bearing zone of the well. Certain wells (W5, W11 and W22) exhibit higher Cl^- concentration during period 2 but appear to decrease during periods 3 and 4.

4.4.3. Relationships between coliform bacteria and water chemistry

4.4.3.1. Coliform bacteria and variation in ionic strength

A number of wells show a good relationship between CV and coliform bacteria which is interpreted to be the result of surface/runoff water infiltration. Wells W6, W11, W16, W18 and W26 exhibit the highest CV for ionic strength and a high frequency of coliform occurrence. Similarly, wells W20 and W22 show little seasonal variation in the CV, and coliform bacteria are not detected during the sampling period. Other wells display no obvious relationship between coliform bacteria and variation in ionic strength. For example, coliform bacteria are not detected at wells W13 and W15, but the ionic strength shows seasonal variation; and conversely, wells W9, W10, W23 and W25 show little water chemistry variation, but coliform bacteria are frequently detected. Although some wells are characterized by a good relationship between coliform bacteria contamination and chemical changes, TC and FC are not always detected in wells with greater CV. This suggests that seasonal variations causing change in the groundwater system result in corresponding changes in both water chemistry and the presence of coliform bacteria; however, if changes are only observed in either water chemistry or coliform bacteria, other local factors such as anthropogenic activities or the presence of preferential pathways may play a more significant role than do seasonal variations.

4.4.3.2. Coliform bacteria and variation in ionic concentration

This section describes the relationships between coliform bacteria and ionic concentration of NO_3-N, Cl^-, Ca^{2+}, HCO_3^- and to a lesser extent, relationships with Na^+, Mg^{2+}, SO_4^{2-} and the molar ratios. Supporting data on monthly concentrations of major ions (Cl^-, NO_3-N, Ca^{2+} and HCO_3^-), and total coliforms (TC) and faecal coliforms (FC) for individual wells are shown in Appendix D, along with by figures of monthly concentrations of F^-, SO_4^{2-}, Mg^{2+}, K^+ and Na^+ and linear correlation coefficients to determine relationship between major-ions and coliform bacteria.

The relationship between NO_3-N and coliform bacteria is variable depending on the well. A decrease of NO_3-N from snowmelt (period 1 and 5) to baseflow (period 2) implies that recharge from snowmelt affect the concentration of NO_3-N by dilution (Levison and

Novakowsky 2009). This is observed at W6, W13 and W15, but these wells are not contaminated by coliform bacteria at that time. During baseflow (period 2) it appears that a lower concentration of NO_3-N in July 2008 results in higher TC and FC counts in W16. Certain wells exhibit increases of NO_3-N concentration from summer baseflow (2) to fall recharge (3), which suggests that the concentration is affected by change in recharge patterns in combination with the end of the growing season (Toran and White, 2005). This seasonal pattern is observed at wells W4, W13 and W15, but these wells do not exhibit an evident relationship with coliform bacteria. At well W1, NO_3-N concentration appears inversely correlated to TC counts. A positive relationship between NO_3-N and bacteria is observed at well W5 and W7. Nitrate is sporadically detected at four wells (W2, W11, W14 and W24) and does not appear to be related to seasonal patterns, but may show some association with the detection of TC. For example, at well W2, NO_3-N is only detected from November 2008 to January 2009 and correlates with lower coliform bacteria concentration, whereas at well W11, NO_3-N is only detected in October 2008 and correlates to a high TC concentration. The association of coliform bacteria and NO_3-N may suggest a different pathway or source for coliforms during recharge, with sporadic detection of NO_3-N linked to rapid infiltration nearby the well.

Monthly variations in the concentration of Cl^- is often associated with similar variations of other ions and the presence of coliform bacteria in certain wells in the study area. Decreases in Cl^- concentration, from winter baseflow to snowmelt recharge, result from dilution with snowmelt water. Poor correlation between Cl^- and coliform bacteria are observed during this time frame. Lower concentration of Cl^- during summer baseflow associated with a higher concentration of TC (W4 and W9) indicates that water is drawn from the shallow groundwater system which may be subject to rapid recharge. There are also sporadic variations of Cl^- linked to TC detection during summer baseflow. For example, well W26 shows increases in the concentrations of Ca^{2+}, SO_4^{2-} and Cl^-, and a relatively higher increase in the concentration of Na^+ which correlates to TC and FC contamination. Similar trends are observed between coliform bacteria and ion concentration during fall recharge with sporadic increases or decreases in Cl^- concentration (or other ions) linked to the presence of coliform bacteria. For example, at W1, the October contamination event correlates with decreases in the concentrations of Cl^-, NO_3-N, Ca^{2+} and Mg^{2+} and increases in concentrations of F^-, SO_4^{2-} and Na^+. Coliform bacteria contamination events may also correlate to various combinations in specific ion concentration. For

example, at well W5, the contamination event in August 2008 is associated with a decrease in Cl^- concentration and increases in HCO_3 and NO_3-N, whereas the October 2008 event is linked to increases in the concentrations of Cl^-, Ca^{2+}, HCO_3 and NO_3-N. The monthly analysis of Cl^- concentration, alone or combined with other ionic species, is a good indicator of seasonal change in the flow field, which in return affects the attenuation potential of the system.

There are also links between TC or FC concentration and other major-ions such as Ca^{2+}, HCO_3^- , SO_4^{2-}, Mg^{2+}, Na^+ and in the molar ratios such as Cl^-/SO_4^{2-}. At well W2, the high TC and FC concentrations observed in October 2008 correlate with decreases in Ca^{2+} and HCO_3^-,whereas the July contamination event is related to increases in Ca^{2+} and HCO_3^-. The July contamination event at W4 is linked to an increase in Na^+ and SO_4^{2-} concentrations. Positive correlation between TC, Mg^{2+} and Na^+ is observed at W5. At W16, July 2008 shows a high count of TC and FC which corresponds to a peak in the Cl/SO_4 ratio and higher Ca/Na and Mg/Na ratios. However, a decrease in the molar ratio does not always indicate the presence of coliform bacteria: TC are not detected at W22, but the Cl/SO_4 molar ratio is slightly higher from May to November 2008, and decreases during winter months.

4.4.3.3. Relationship categories

This section showed that seasonality can be observed in both coliform bacteria and water chemistry (ionic strength and concentration), and that there can be significant relationships between the two. The analysis of monthly variations in the concentration of ionic species and molar ratios, combined with variations in coliform bacteria, enabled inferences to be made about variations in the magnitude or direction of the groundwater flow system. It was further observed that individual wells are characterized by different lag times between a recharge event (e.g. rainfall or snowmelt) and the arrival of indicators in the well. This explains why no clear link with precipitation is observed for the entire study area. Based on these observations, the 27 wells were categorized into four classes:

1. Wells where seasonality is observed in both bacteria concentration and water chemistry: W4, W6, W9 and W12.

2. Wells where seasonality is observed in coliform bacteria or water chemistry, but not both: W1, W5, W10, W13, W14, W15, W22, W23 and W27.

3. Wells that show no strong seasonal trends in coliform bacteria and water chemistry; but where there is a relationship (positive or negative) between coliform bacteria and water chemistry: W2, W3, W7, W11, W16, W17, W18, W19, W24, W25 and W26.

4. Wells where seasonality is not observed and there are no obvious relationships between coliform bacteria and water chemistry: W20.

4.4.4. Factors affecting groundwater quality

The water quality in a well reflects a combination of extra-regional, regional and site-specific factors with the cumulative effect observed at the specific location (Korkka-Niemi, 2005). Extra-regional factors relate to the bedrock and surficial geology, regional factors to the type of aquifer and residence time, whereas site-specific factors relate to pollution, surface water infiltration and the well construction (Korkka-Niemi, 2005). In Chapter 3, multivariate statistical analysis techniques (HCA and PCA) were used to identify the natural and anthropogenic components affecting the groundwater quality at a local scale, but seasonal effects on contamination were not considered. Seasonality is shown to be an important contributor to the occurrence of coliform bacteria in water wells with >40% positive TC tests from July to December 2008, compared to <40% positive tests from April to June 2008 and January to May 2009 (Fig. 4.3). Therefore, for analytical purposes the sampling period is divided into 2 periods based on the occurrence of TC: high risk months (July to December 2008) and low risk months (remainder of study period). Only monthly samples that satisfied quality analysis for water chemistry are considered for further analysis. In this section, multivariate analyses are employed on the data from study area to evaluate the underlying causative factors which affect water chemistry, particularly when vulnerability is at its highest from July to December 2008.

4.4.4.1. Correlations

Table 4.4 presents the correlation matrix of the 12 chemical and bacterial components considered for the analysis. Linear correlations were performed on transformed data and the matrix distinguishes significant hydrochemical relations between components (indicated by values in bold). The bottom matrix represents coefficients of correlation when percentages of samples which tested positive are higher (i.e. high risk months), whereas the upper section of the matrix represents coefficients of correlation when percentages of samples which tested positive are lower (i.e. low risk months). A number of similarities are observed in both cases:

- A poor correlation exists between coliform bacteria (TC and FC) and the ionic species. As demonstrated in previous sections, some wells did exhibit good correlation between certain ionic species and coliform bacteria which illustrates the local contamination. The grouping of wells to obtain a more complete picture results in the loss of local resolution and therefore, correlations are not observed.

- There are positive correlations between, Na^+, K^+ and Cl^-, which may result from mixing with effluents or a deeper aquifer system. There is a positive correlation between Cl^- and Mg^{2+} suggesting that a source of Cl^- may also originate from the shallow groundwater system since Ca^{2+} and Mg^{2+} are interpreted as the result of dissolution through the unsaturated zone and along the flow path (Chapter 3). A potential source of Cl^- originating from the surface is septic effluents where the effluent water may mix with infiltrating water. Sulphate, Na^+ and Cl^- also show a strong and positive relationship indicating water from anthropogenic sources or mixing with a deeper aquifer system. These various correlations with Cl^- did not help identify the main source of Cl^- in the Municipality, but rather indicate that the concentration of Cl^- in the groundwater is influenced by dissolution processes along the flow path and possibly by anthropogenic activities.

- Fluoride generally originates from fluoride-bearing minerals present in metamorphic or igneous rocks (Singh et al., 2011). Fluoride negatively correlates with Ca^{2+} and NO_3-N which indicates that Ca^{2+} or NO_3-N do not

originate from dissolution processes in the bedrock, but from dissolution through the overburden during infiltration of runoff water. Nitrate (as N) positively correlates with Ca^{2+} suggesting the NO_3-N may originate from the infiltration of runoff water and the nitrification process.

Table 4.4: Correlation matrix for the 12 variables for months with higher and lower percentage of samples which test positive. Values in bold indicate significant correlations ($p<0.05$). Note: faecal coliforms are not detected during months with low % of positive samples.

		Low risk months										
		F^-	Cl^-	NO_3-N	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	pH	TC>0
High risk months	F^-	1	*-0.38*	**-0.59**	0.18	**-0.46**	0.10	-0.33	0.36	0.25	**0.61**	-0.23
	Cl^-	-0.29	1	*0.39*	**0.57**	**0.48**	**0.47**	**0.62**	**0.46**	0.15	-0.07	0.15
	NO_3-N	**-0.62**	0.18	1	0.14	**0.66**	-0.06	0.33	-0.11	0.16	**-0.42**	0.12
	SO_4^{2-}	0.22	**0.50**	-0.12	1	0.21	0.38	0.27	**0.75**	0.39	**0.47**	-0.03
	Ca^{2+}	**-0.53**	0.28	**0.51**	-0.03	1	-0.06	**0.64**	-0.12	**0.41**	**-0.40**	-0.11
	K^+	0.12	**0.49**	-0.21	0.30	-0.27	1	**0.58**	**0.67**	0.33	**0.48**	0.27
	Mg^{2+}	-0.38	**0.41**	0.22	0.00	**0.56**	**0.40**	1	0.31	**0.52**	-0.05	0.18
	Na^+	**0.49**	**0.43**	*-0.38*	**0.68**	-0.51	**0.66**	-0.08	1	**0.55**	**0.70**	0.18
	HCO_3^-	0.25	0.24	0.19	0.31	0.15	**0.41**	**0.39**	**0.49**	1	0.37	0.00
	pH	**0.72**	-0.19	**-0.55**	0.29	**-0.60**	**0.42**	-0.14	**0.60**	0.24	1	-0.15
	TC >0	-0.02	-0.05	-0.24	-0.17	-0.25	0.23	0.15	0.10	0.00	0.01	1
	FC >0	-0.20	0.05	-0.05	-0.26	0.08	0.19	0.32	-0.11	-0.01	-0.30	**0.50**

Some distinctions are observed when comparing the correlations between months showing the highest percentage of bacterial occurrence (high risk) with the months showing the lowest percentage (low risk):

<u>High risk</u>

- There is a positive correlation between Na^+ and F^- which is not observed during the lower risk months. This suggests that water-rock interaction processes are the source of Na^+ and F^- in the groundwater because F^- is likely related to the local bedrock geology. The water source during summer is from appears to be a deeper groundwater system which to be expected during the summer baseflow period.

- There is a weak negative relationship between Na^+ and NO_3-N which suggests different origins of these ions. Sodium has various origins such as weathering of silicate minerals or effluent water. The negative correlation of NO_3-N with Na^+ indicates that NO_3-N is not the result of mixing with septic effluents, but from natural processes such as nitrification (Clark and Fritz, 1997). This is also supported by the lack of correlation between NO_3-N and Cl^-, which often occurs when both ions originate from septic effluents.

- The weathering of Na- K bearing minerals present in quartzite and granite is the likely the main source of K in the study area. The positive correlation between K^+ and HCO_3^- suggests that K^+ may originate from another source since K^+ is not usually a significant component of carbonate rocks. Septic effluents have been shown to contribute to the concentration of HCO_3^- in groundwater (Robertson et al., 1991). It is therefore possible that septic effluents also contribute to the concentration of K^+ during high risk months.

Low risk

- There is a weak negative correlation between F^- and Cl^- which suggests that Cl^- may not originate from the weathering processes in the bedrock and corroborates the anthropogenic origins of Cl^-.

- There is also a weak positive correlation between Cl^- and NO_3-N indicating that there might be a minor contribution of effluent water to NO_3-N concentration.

- The positive correlation between Cl^- and Ca^{2+} and between HCO_3^- and Ca^{2+} suggests similar groundwater origins such as mixing with septic effluents (water softener).

Although some wells individually show correlations between coliform bacteria and major-ions, the large-scale grouping results in the loss of local resolution, especially when the regional or extra-regional factors are the dominant control on the groundwater geochemistry. Distinctive correlations during the high risk period result from extra-regional

or regional factors such as weathering or natural infiltration of runoff water with minor anthropogenic influence, whereas correlations during low risk periods relate mostly to local anthropogenic sources.

4.4.4.2. Cluster Analysis

The purpose of the cluster analysis is to group the water samples according to their similarity in chemical and bacteriological characteristics, allowing the classification of the wells based on their overall groundwater quality. The results are illustrated in the dendrogram of Figure 4.12. The phenon line is arbitrarily drawn at a linkage distance of 6 based on a visual observation of the dendrogram. This allows the separation of the dendrogram into six clusters for high risk month (RF>40%) and five clusters for lower risk months (RF<40%).

<u>High risk months</u>

Table 4.5 presents descriptive statistics for the 6 clusters defined using months with highest percentage of samples which test positive for coliform bacteria (high risk months). The first cluster (W2 and W3) is characterized by high average concentration of K^+ and HCO_3^-, a high percentage in the occurrence of FC and the second highest percentage in the occurrence of TC. Wells in this cluster are spatially close, located within 100 m of the Gatineau River and the well-water levels are similar to the river elevation. The high percentage of coliform bacteria incidence may indicate mixing with a surface water body, whereas a high concentration of K^+, combined with a relatively high Na^+ concentration at W2, indicates mixing with septic effluent. Both of these sources represent a local contributor to the groundwater quality.

The second cluster (W9, W23, W10, W25, W12, and W19) is defined by high Na^+ concentration and is ranked third for TC detection. This cluster shows the lowest concentration of NO_3-N and Ca^{2+} and with the exception of W25, wells defined by this cluster are under confined (or semi-confined) conditions and located in the southern area of the Municipality. Chapter 3 interpreted the high Na^+ concentration to be the result of the Ca-Na ion exchange process. This process is considered a regional factor which is

influenced by the water residence time. The occurrence of TC is interpreted to reflect a local source, such as the proximity to a water body (W9, W10 and W19) or may be affected by rapid recharge (W12). The high Na^+ concentration of W25 may indicate mixing with septic effluent since a water softener system is used at this residence.

The third cluster (W6, W1, W7, W13, W15 and W18) shows the highest concentrations of Cl^-, NO_3-N, SO_4^{2-}, Ca^{2+} and Mg^{2+}, but interestingly, the third lowest relative frequency of TC occurrence (33%). Faecal coliforms are not detected in this cluster suggesting that if the high ionic concentrations result from mixing with septic effluent, the residence time is long enough to allow the die-off of FC. Factors influencing the water quality in this cluster are classified as extra-regional if the groundwater is drawn from a deeper aquifer or local if the high ionic concentrations result from mixing with septic effluents. W6 and W18 are also affected by rapid recharge near the well, which is interpreted to contribute locally to the high concentration of TC detected during the sampling period.

The fourth cluster (W26, W16, W5, W24 and W11) is characterized by the lowest values for HCO_3^- and pH, but shows a high percentage in the occurrence of TC. The wells forming this cluster have thin overburden, are located in preferential recharge area with most wells (W11, W16, W24 and W26) spatially close. These wells are interpreted to be more prone to rapid recharge events which result in bacterial contamination. Faecal coliforms are also detected in some wells from this cluster which indicates contamination from a septic effluent. Overall, this cluster is strongly affected by local factors.

The fifth (W4 and W27) cluster has the lowest average concentration for F^-, Cl^- and SO_4^{2-} and the second lowest average for the occurrence of TC, whereas the sixth cluster (W17, W20, W14 and W22) show the lowest percentage of samples which test positive for TC and FC is not detected. The low ionic concentration in the water may be indicative of a shorter residence time which means that the impacts of extra-regional or regional factors are minimal. Even though this cluster is mostly affected by local factors, it is interpreted to show best water quality.

Low risk months

Table 4.6 presents descriptive statistics of the five clusters defined using the low risk months which are characterized by the absence of FC. The first cluster (W11, W26, W4 and W5) exhibits the lowest average concentration of F^-, SO_4^{2-} and HCO_3^-. Interestingly, this cluster shows the highest percentage of samples which test positive for TC. Local factors such as rapid recharge from rainfall events and snowmelt, combined with a source of coliform bacteria appear to impact the wells during this period.

The second cluster (W27, W14 and W17) shows the lowest values for Cl^-, Mg^{2+} and TC. The low average concentration for Cl^- and Mg^{2+} may suggest that the wells are located at, or near the initiation point of the recharge pathway, with the low concentration of TC resulting from limited nearby sources. The low ionic concentration in the water indicates a shorter residence time which means that the impacts of extra-regional or regional factors are interpreted to be minimal and as a result, this cluster exhibits the best water quality despite the local influence.

The third cluster (W9, W23, W10, W25, W12 and W19) is characterized by a high average concentration of F^-, SO_4^{2-}, Na^+ and pH with low values of Ca^{2+} and NO_3-N. TC are also detected in this cluster. The high ionic content indicates possible influence from an extra-regional factor such as water-rock interactions or a regional factor such as ion exchange processes. This cluster appears to exhibit longer residence times compared to the previous two clusters. However, the presence of coliform bacteria also indicates local inputs to the water quality.

The fourth cluster (W16, W2, W18, W1 and W6) has high values of Cl^-, NO_3-N, Ca^{2+}, K^+, Mg^{2+} and HCO_3^-, and the second highest percentage of TC. This may indicate that the quality of the water for these wells is influenced by anthropogenic activities and rapid recharge. Local factors are the primary contributor to groundwater quality for this cluster.

Lastly, the fifth cluster (W13, W15, W3, W22, W24, W7 and W20) is defined by the absence of TC, the highest Ca^{2+} concentration and the second highest concentration for most other ionic species. This cluster is characterized by a strong influence of extra-regional or regional factors and exhibits a good water quality with respect to coliform bacteria contamination.

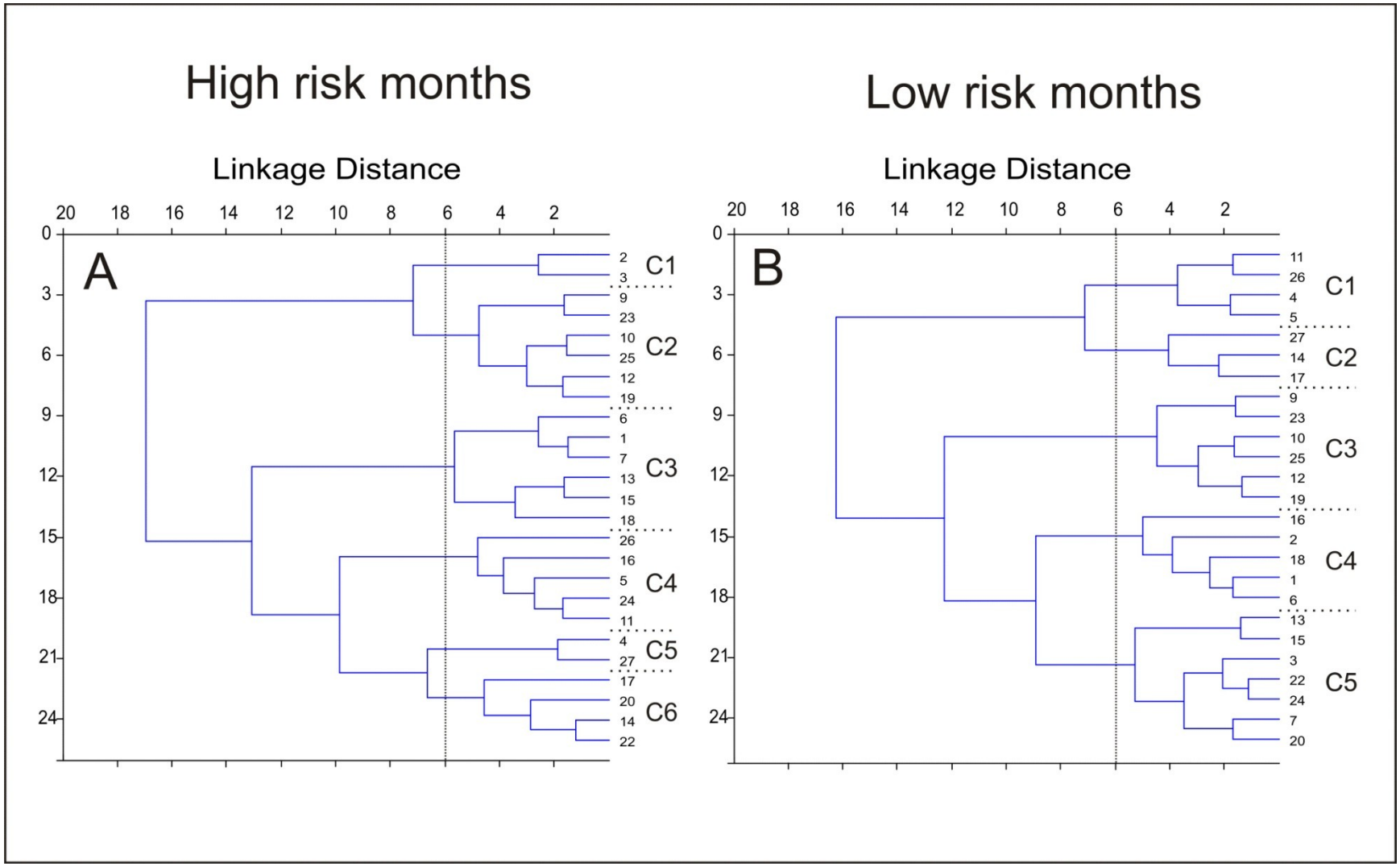


Figure 4.12: Dendrogram from cluster analysis: a) High risk months with >40% of samples which test positive for presence of coliform bacteria; and b) Low risk months with <40% of samples which test positive for presence of coliform bacteria.

Table 4.5: Descriptive statistics for the clusters obtained by the cluster analysis for the high risk months. The highest value for a given chemical or bacterial variable is in bold while the lowest value is underlined.

Clusters (phenon Line=6)	Descriptive statistics	F (mg/L)	Cl (mg/L)	NO_3-N (mg/L)	SO_4 (mg/L)	Ca (mg/L)	K (mg/L)	Mg (mg/L)	Na (mg/L)	HCO_3 (mg/L)	pH	Total Coliforms (% of positive)	Faecal Coliforms (% of positive)
Cluster 1 (N=2)	average	1.3	27.7	0.1	28.2	41.8	**8.7**	19.0	57.1	**293.8**	7.6	80.0	**63.3**
	stdev	0.3	27.3	0.0	5.8	19.6	7.9	11.5	25.8	69.7	0.6	28.3	4.7
	Min	1.1	8.4	0.1	24.1	28.0	3.1	10.9	38.8	244.6	7.2	60.0	60.0
	Max	1.5	47.0	0.2	32.3	55.7	14.3	27.1	75.3	343.1	8.0	100.0	66.7
	C.V (%)	24.2	98.6	28.9	20.7	46.8	90.7	60.4	45.2	23.7	7.5	35.4	7.4
Cluster 2 (N=6)	average	**1.5**	35.1	0.1	67.1	18.3	3.5	7.1	**92.0**	183.9	**7.9**	75.0	0.0
	stdev	0.6	23.9	0.0	43.2	11.9	1.2	2.5	30.5	62.6	0.3	27.9	
	Min	0.8	8.7	0.1	17.0	7.5	2.1	3.9	54.2	107.2	7.4	25.0	
	Max	2.2	69.1	0.1	128.0	39.3	5.1	11.4	129.2	296.0	8.2	100.0	
	C.V (%)	38.5	68.1	4.8	64.3	65.1	34.4	35.6	33.1	34.0	3.7	37.2	
Cluster 3 (N=6)	average	0.6	**95.9**	**1.0**	**68.1**	**82.9**	2.3	**20.8**	64.0	259.2	7.1	33.3	0.0
	stdev	0.1	65.2	0.9	37.8	34.6	0.7	21.6	78.2	53.2	0.1	38.0	
	Min	0.5	30.1	0.5	29.3	26.8	1.4	4.9	16.1	198.2	6.8	0.0	
	Max	0.8	191.8	2.7	117.7	121.7	3.2	61.8	221.3	338.2	7.2	100.0	
	C.V (%)	19.9	67.9	91.1	55.5	41.8	28.2	103.7	122.3	20.5	1.9	114.0	
Cluster 4 (N=5)	average	0.5	53.9	0.4	21.9	58.0	3.2	10.4	15.3	147.5	6.6	**100.0**	24.0
	stdev	0.0	44.8	0.5	6.5	15.5	3.0	3.2	6.6	46.2	0.3	0.0	18.8
	Min	0.5	13.7	0.1	14.7	42.8	1.2	7.2	7.6	77.2	6.0	100.0	0.0
	Max	0.6	104.6	1.3	29.9	84.1	8.6	15.8	25.1	195.3	6.9	100.0	50.0
	C.V (%)	7.0	83.1	123.2	29.8	26.8	94.6	30.7	43.3	31.3	5.2	0.0	78.2
Cluster 5 (N=2)	average	0.5	2.4	0.6	11.8	44.8	1.4	4.5	1.8	125.2	6.9	28.3	0.0
	stdev	0.0	1.7	0.1	2.6	17.8	0.3	2.1	0.7	50.1	0.5	16.5	
	Min	0.5	1.2	0.5	10.0	32.3	1.2	3.1	1.3	89.8	6.6	16.7	
	Max	0.5	3.5	0.7	13.6	57.4	1.6	6.0	2.2	160.6	7.2	40.0	
	C.V (%)	0.0	70.0	25.2	21.7	39.6	19.6	46.1	37.4	40.0	6.6	58.2	
Cluster 6 (N=4)	average	1.1	23.8	0.1	32.7	51.5	1.7	8.0	20.6	159.0	7.3	18.8	0.0
	stdev	0.5	29.9	0.0	18.0	10.9	1.3	3.6	14.2	22.8	0.1	37.5	
	Min	0.5	1.3	0.1	17.0	39.6	0.5	4.8	8.2	137.3	7.2	0.0	
	Max	1.7	66.5	0.2	58.6	65.5	3.5	12.8	37.1	187.4	7.5	75.0	
	C.V (%)	42.3	125.8	19.5	55.0	21.1	76.3	45.3	69.1	14.3	1.8	200.0	

Table 4.6: Descriptive statistics for the clusters obtained by the cluster analysis for the low risk months. The highest value for a given chemical or bacterial variable is in bold while the lowest value is underlined.

Clusters (phenon Line=6)	Descriptive statistics	F (mg/L)	Cl (mg/L)	NO_3-N (mg/L)	SO_4 (mg/L)	Ca (mg/L)	K (mg/L)	Mg (mg/L)	Na (mg/L)	HCO_3 (mg/L)	pH	Total Coliforms (% of positive)	Faecal Coliforms (% of positive)
Cluster 1 (N=4)	average	0.5	29.5	0.4	17.2	44.9	1.5	6.7	8.7	119.4	6.7	**50.0**	
	stdev	0.0	35.5	0.5	4.8	9.6	0.4	1.2	5.7	43.5	0.3	20.4	
	Min	0.5	4.3	0.1	11.0	32.3	1.1	5.6	2.0	60.1	6.3	25.0	
	Max	0.5	82.1	1.1	21.3	55.7	2.1	8.2	14.8	161.0	7.1	75.0	
	C.V (%)	0.3	120.3	109.4	28.1	21.5	27.4	18.5	65.5	36.4	4.7	40.8	
Cluster 2 (N=3)	average	1.1	1.1	0.3	32.9	36.0	0.9	4.0	13.5	125.6	7.0	0.0	
	stdev	0.6	0.2	0.4	32.5	9.8	0.4	1.3	19.1	51.7	0.3		
	Min	0.5	1.0	0.1	12.8	26.9	0.5	2.6	1.2	74.7	6.7		
	Max	1.5	1.4	0.7	70.3	46.5	1.2	4.9	35.5	178.0	7.2		
	C.V (%)	49.3	18.1	114.2	98.8	27.3	37.7	31.4	142.2	41.2	3.7		
Cluster 3 (N=6)	average	**1.5**	35.8	0.1	**69.1**	19.7	3.5	7.2	**89.9**	184.1	**7.8**	25.2	
	stdev	0.7	22.5	0.0	41.8	13.9	1.1	2.4	29.6	70.0	0.3	13.3	
	Min	0.8	13.0	0.1	25.7	8.2	2.1	4.1	52.8	113.7	7.4	12.5	
	Max	2.6	66.8	0.1	131.2	45.1	5.1	11.2	120.2	318.9	8.1	42.9	
	C.V (%)	44.1	62.8	4.8	60.5	70.6	32.7	32.8	32.9	38.0	3.3	52.7	
Cluster 4 (N=5)	average	0.7	**108.8**	**0.6**	49.4	71.1	**6.7**	**28.5**	63.5	**282.5**	7.1	45.3	
	stdev	0.3	70.2	0.3	23.4	13.2	5.5	19.3	44.5	110.0	0.3	21.9	
	Min	0.4	30.6	0.2	35.8	57.9	2.0	13.0	22.2	118.9	6.7	25.0	
	Max	1.2	191.3	0.8	90.7	88.6	13.0	60.2	132.2	428.7	7.6	80.0	
	C.V (%)	47.6	64.5	48.4	47.3	18.5	82.2	67.8	70.1	38.9	4.8	48.4	
Cluster 5 (N=7)	average	0.9	48.6	0.5	48.4	**75.0**	2.3	10.3	24.6	193.2	7.1	0.0	
	stdev	0.4	31.3	0.7	36.7	28.0	0.8	1.4	15.7	44.9	0.2	0.0	
	Min	0.5	7.9	0.1	16.7	52.0	1.3	8.6	6.9	140.0	6.9	0.0	
	Max	1.6	100.5	2.0	105.7	124.7	3.5	12.7	50.4	268.4	7.4	0.0	
	C.V (%)	46.9	64.4	130.2	75.8	37.3	35.1	13.5	63.8	23.3	2.2		

4.4.4.3. Principal Component Analysis

Principal component analysis (PCA) was performed to identify which measured variables provide the greatest variation in the water composition. PCA is done using the 10 chemical variables and micro-organism indicators TC and FC. The PCA decomposes the covariance matrix of the variables into its principal components and their magnitudes, thereby enabling grouping of like variables based on the magnitude of their covariance. In this case, a component is considered significant if the eigenvalue is greater than one and a loading is considered significant if the value is greater than 0.3 (Moore et al., 2009). The high risk months and low risk months did not exhibit the same number of components (Table 4.7) which is interpreted to mean that more components affect the composition of the groundwater during the high risk months or that the high and low risk months are different statistical populations with different characteristics for the variables.

High Risk Months

Table 4.7 presents the results of the PCA for high risk months (RF>40%). The eigenvalues for the first four components are 3.57, 2.88, 1.87 and 1.11, which explains 79% of the variance. These four new variables (principal components) represent linear combinations of the twelve initial variables reducing the complexity of the analysis and the amount of variables to consider. The loss of information by reducing the original amount of variables is 21%. The spatial distribution of the component scores, which are the linear combinations for each variable at each well, is shown in Figure 4.13.

The first component (PC1) accounts for 30% of the variance and is composed of positive loadings for Na^+, F^- and pH, and a negative loading for Ca^{2+}. The positive correlation between Na^+ and F^- (Table 5) suggests that water-rock interactions are the source of the dissolved species since both of these ions may result from weathering of minerals found in igneous or metamorphic rocks (Singh et al., 2011). The negative loading of Ca^{2+} associated with the positive loading of Na^+ may suggest that cation exchange processes are important in Chelsea. Wells with high PC1 scores are located primarily near the southern boundary of the study area with most wells being located in confining conditions where cation exchange processes was shown to be plausible (Chapter 3). The first component is therefore interpreted to represent water-rock interactions from weathering

or cation exchange processes and is considered an extra-regional factor affecting the groundwater quality.

The second component (PC2) accounts for 24% of the variance and is composed of positive loadings for Cl^-, Mg^{2+}, K^+, Ca^{2+} and HCO_3^-. A positive correlation exists between Mg^{2+} and HCO_3^- (Table 6) with Ca^{2+} and Mg^{2+} originating from the same source in this system (Chapter 3). Wells with high C2 scores are located spatially between recharge and discharge areas. This suggests that disperse infiltration through the overburden and dissolution along the flow path are processes represented by PC2. These processes occur in the shallow groundwater system because the dissolution of carbonate minerals is more efficient under open system conditions (Clark and Fritz, 1997). The positive loading of Cl^- also suggests that this variable is originating from the shallow groundwater system with possible mixing with effluent water. The second component is interpreted as an extra-regional factor because it represents the water hardness with minor local influence as indicated by the potential mixing with surficial septic effluents.

The third component (PC3) accounts for 16% of the variance and has a positive loading for SO_4^{2-} combined with negative loadings for TC and FC. TC and FC may indicate rapid surface water infiltration and/or contamination from septic effluents if FC are detected. Wells with high negative scores have a lower concentration of SO_4^{2-}, higher percentage of coliform bacteria detection and are characterized by unconfined or semi-confined aquifer conditions. These wells may be subject to rapid recharge from preferential pathways and water may originate from shallower groundwater systems. Wells with high positive PC3 scores are located spatially between recharge and discharge areas. One well is shallower than the other one (35 m versus 100 m) which may indicate that SO_4^{2-} also originates from mixing with septic effluents from up-gradient residences where sulphate reduction reactions have not occurred in the water-bearing zone. This component is interpreted to represent local factors.

The fourth component (PC4) accounts for 9% of the variance and consists of positive loadings of Cl^- and SO_4^{2-}, and negative loadings of Mg^{2+} and HCO_3^-. There is no observed pattern in the spatial distribution of PC4 scores. This component potentially may represent the effect of anthropogenic activities on the aquifer and/or mixing between groundwater systems. For example, W26 is relatively shallow (<45 m), located on a topographic high, and shows a high positive score. The well is located in a recharge area

which should lead to lower concentrations of Cl^- and SO_4^{2-}, but the opposite is observed, suggesting mixing with septic effluents. Well W12 also has a high positive score, but is relatively deep (58 m), located in a topographic flat and is interpreted to draw water from a deeper aquifer. This component is a mix of regional and local influences, depending on the location of the well.

Low Risk Months

Table 4.7 presents the results of the PCA for high risk months (RF>40%). The eigenvalues for the first three components are 3.81, 3.05 and 1.39, which explains 75% of the variance. These three new variables (principal components) represent linear combinations of the twelve initial variables reducing the complexity of the analysis and the amount of variables to consider. The loss of information by reducing the original amount of variables is 25%. The spatial distribution of the component scores is shown in Figure 4.14.

The first component (PC1) accounts for 35% of the variance and consists of positive loadings of Na^+, K^+, HCO_3^-, Cl^-, SO_4^{2-}, pH and Mg^{2+}. One well (W2) shows high positive PC1 score and the positive correlations (Table 5) between Na^+, SO_4^{2-} and Cl^- suggest anthropogenic inputs (i.e. mixing with septic effluents). This well is also frequently contaminated by total and faecal coliforms. Positive loadings of Mg^{2+} and HCO_3^- suggest recharge from the overburden. Wells with negative PC1 scores are located mainly in topographic highs, suggesting little dissolution during recharge. This component is interpreted as representing local factors such as recharge processes with a possible influence from anthropogenic activities.

The second component (PC2) accounts for 28% of the variance and consists of positive loadings of Ca^{2+}, NO_3-N, Mg^{2+} and Cl^-, and negative loadings of F^- and pH. The correlations are interpreted to indicate that most of the ions have surficial origins (natural or anthropogenic) and possibly represent the composition of the shallow groundwater system. Most wells with positive PC2 scores are located along recharge pathways whereas wells with negative PC2 scores have a confined aquifer and a higher concentration of F^-. Because this component gives an indication of the travel path and represents the aquifer system, it is considered a regional factor.

The third component (PC3) explains 13% of the variance and consists of positive loadings of SO_4^{2-} and Ca^{2+}, and negative loadings of K^+ and TC. Wells showing high positive PC3 scores are located where the aquifer is unconfined and the presence of TC indicates rapid recharge from surface and runoff water. It appears that K^+ originates from the surface with small-scale application of fertilizers and septic effluents as potential sources. The positive correlation between SO_4^{2-} and Ca^{2+} may indicate that some wells are affected by septic effluents from households using water softeners. This last component is interpreted as a local contributor to the groundwater quality from rapid recharge and mixing from septic effluents.

Table 4.7: Table of component loadings, variance and cumulative variance for high and low risk months. Significant loadings are indicated in bold.

Variables	Loadings				Loadings		
	PC 1	PC 2	PC 3	PC 4	PC 1	PC 2	PC 3
F^-	**0.38**	-0.28	0.02	-0.13	0.17	**-0.46**	0.21
Cl^-	0.13	**0.47**	0.08	**0.38**	**0.35**	**0.30**	-0.13
NO_3-N	-0.25	0.29	0.27	-0.22	-0.03	**0.44**	0.12
SO_4^{2-}	0.25	0.16	**0.42**	**0.44**	**0.35**	-0.01	**0.34**
Ca^{2+}	**-0.37**	**0.30**	0.18	-0.05	-0.04	**0.48**	**0.36**
K^+	0.28	**0.33**	-0.28	-0.03	**0.37**	0.08	**-0.35**
Mg^{2+}	0.01	**0.47**	-0.13	**-0.31**	**0.31**	**0.35**	-0.01
Na^+	**0.46**	0.17	0.08	0.23	**0.47**	-0.10	0.06
HCO_3^-	0.26	**0.30**	0.10	**-0.55**	**0.36**	0.07	0.29
pH	**0.44**	-0.13	0.12	-0.31	**0.32**	**-0.36**	0.09
TC>0	0.12	0.01	**-0.53**	0.06	0.19	0.05	**-0.67**
FC>0	-0.06	0.18	**-0.56**	0.17	0.00	0.00	0.00
Eigenvalues	3.57	2.88	1.87	1.11	3.81	3.05	1.39
% Variance	30	24	16	9	35	28	13
% Cumulative variance	30	54	69	79	35	62	75

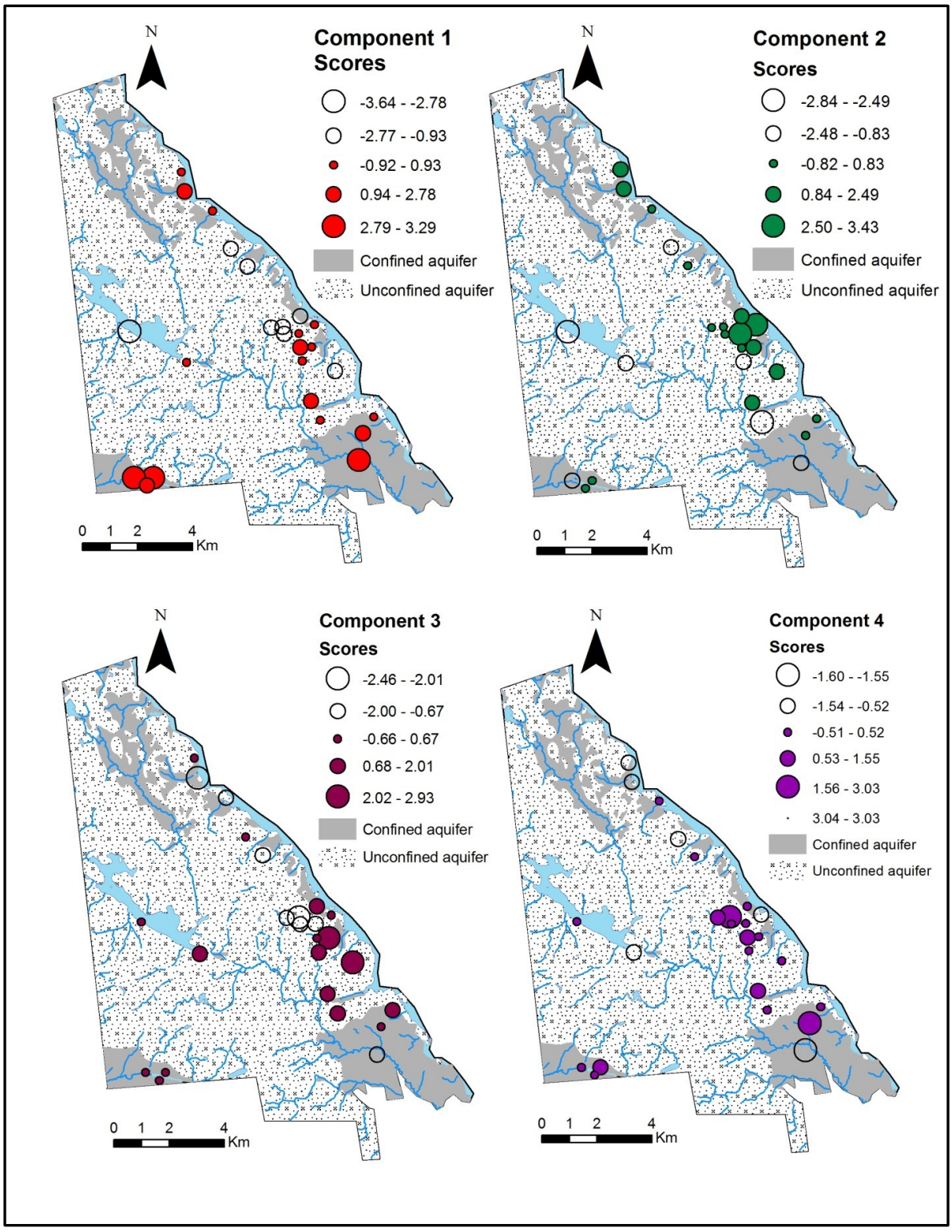


Figure 4.13: Spatial distribution of component scores for higher risk months.

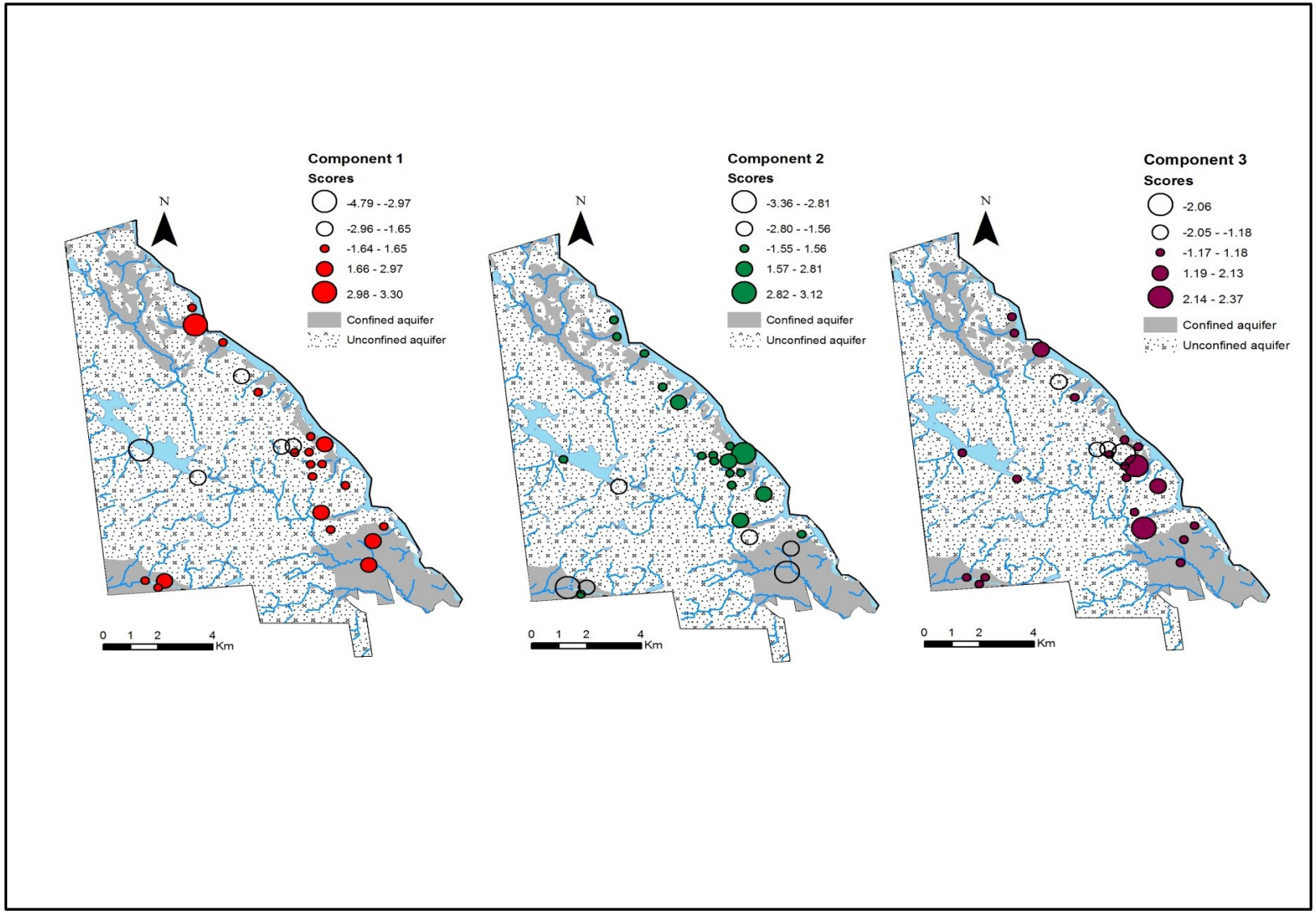


Figure 4.14: Spatial distribution of component scores for lower risk months.

4.5. Discussion

In the Municipality of Chelsea, the lack of significant sources of contamination such as agricultural activities reduces the risk of contamination, but provides an analytical challenge because direct relationships between an obvious source and contamination are not easily observable. Identification of recharge pathways are difficult in the study area because flow in fractured bedrock is dictated by the fracture network (Conboy and Goss, 2000) and recharge is influenced by overburden thickness and the presence of macro-pores (Gleeson et al., 2009). Estimating the specific contribution of recharge is a challenge in this geological environment and often studies that employ isotopic analysis and geophysical tools are necessary to enhance the characterization of the fracture network and recharge pathways. However, these methods are not easily available or affordable to most rural Municipalities. Therefore, it is critical to understand the information obtained from basic monitoring of the ionic concentration of the water and coliform bacteria, and to determine if these data are sufficient to predict vulnerability of a well to contamination. The results of this study have demonstrated that it is possible to identify seasonal variations in coliform bacteria and water chemistry, and link some microbial contamination events to recharge or a change in flow paths. The next step is to assess the importance of seasonality in microbial and chemical water quality; and to determine if the observed variations in water quality are related to rapid recharge and/or if they are influenced by anthropogenic activities. Lastly, the application of multivariate statistical analysis techniques as a tool to assess the influence of extra-regional, regional or local factors such as recharge contribution or the effect of anthropogenic activities, on the water quality is evaluated. The purpose of this analysis is to verify if the information obtained from the underlying structure of an existing data set is sufficient to estimate and identify the contributing factors on water quality without detailed isotopic studies.

4.5.1. Seasonality

Seasonal trends are observed in the monthly results of coliform bacteria and water chemistry analysis. Although concentrations are variable, TC and FC are more frequently detected in the wells from July to December 2008 compared to the remainder of the sampling period. It is interpreted that wells in the study area are more vulnerable to contamination during summer and fall compared to spring and winter seasons. The

frequency of detection did not appear to be significantly affected by the water type, however, the mixed-water type wells generally show higher frequency of contamination compared to the Ca-Mg-HCO_3 and Na-HCO_3 water types. Comparison of factors affecting the presence of coliform bacteria in the wells shows that the "presence of grout" and the "estimated soil depth" are contributors to TC and FC concentrations in October and November 2008, respectively. Both of these physical factors are thought to play a role during recharge events. The well age also affected the presence of coliform bacteria in July and August 2008. Although seasonal effects appear to be the primary contributor to the presence and concentrations of TC and FC, the vulnerability of a well to contamination may increase during certain times of the year depending on a few specific physical characteristics of the site.

Seasonality is observed in the water ionic strength and associated with different stages in the groundwater system (e.g. baseflow or recharge). Different periods are defined based on recharge from snowmelt, summer and winter baseflow (when recharge is virtually non-existent) and fall recharge. Generally, ionic strength values decrease shortly after snowmelt, increase during baseflow periods, and either increase or decrease during fall recharge. A decrease in values represents the dilution effect from recharge, whereas increases are less diagnostic because they may result from variations in the groundwater system (shallow versus deep) or local anthropogenic activities. In many cases, wells showing greater variation in the ionic strength value also show greater relative frequency of coliform bacteria detection in the well. The ionic species Cl^-, NO_3^- and Ca^{2+} contributed the most to the variation independent of the water type and these ions are used to characterize recharge.

The main seasonal contributor to the water composition in the study area is interpreted to be recharge which affects both bacteria concentration and variations in water chemistry. Previously, the wells were classified into four categories based on the relationship between seasonality, coliform bacteria and water chemistry. Wells in the first category are interpreted to be affected by disperse recharge because of consistency in the variation and a source of coliform bacteria is present in the recharge area. In the second category either water chemistry or bacteria show seasonal trends, but not both. Recharge affects seasonal variation in the water chemistry because it is reflected in the composition of the shallow groundwater system. When variations in the chemistry are observed, it is directly related to a recharge event (snowmelt or fall). Disperse recharge in the shallow

groundwater is reflected by lower ionic composition, whereas ionic compositions increase when baseflow is predominant. If a source of coliform was present in the recharge area, the travel time may have been long enough to allow the die-off of coliform bacteria which explains why there is no link between disperse recharge and coliform bacteria for some wells. When seasonality is observed in the bacteria alone, the aquifer and/or the principal source of water in the well becomes contaminated, but mixing processes along the recharge pathway may attenuate variations in the water chemistry. Some of the wells exhibiting this characteristic are located within 100 m of a surface water body (W9 and W10) which may be an active source of coliform bacteria and responsible for mixing and/dilution of water chemistry.

Although category 3 shows a correlation between coliform bacteria and water chemistry, it and category 4 display no relationship with seasonal trends. In category 3, the presence of a bacteria-chemistry relationship combined with the lack of seasonal trends indicate changes in the attenuation potential along the recharge pathway (e.g. activation of a fracture) or periodic variations in the magnitude of a source which are not necessarily driven by climatic control. Only one well (W20) is classified in the fourth category. Neither coliform bacteria nor prominent changes in chemical indicators are detected during the sampling period. This is interpreted to indicate that the groundwater system is fairly non-dynamic and attenuation mechanisms are efficient enough to prevent coliform bacteria from entering the well, presuming there is a source in the proximity of this well. Other local factors, such as anthropogenic activities, recharge pathways and the travel time from the recharge area to the well may attenuate the seasonality signal and are reflected in water quality of wells classified in categories 3 and 4.

4.5.2. Natural recharge pathways

Some authors have used seasonal variations in major-ions to estimate the contribution to recharge by a rapid recharge pathway or disperse recharge. Toran et al. (2007) analysed daily and monthly variations in major-ions in a karstic system in Pennsylvania, U.S.A. The authors found that the contrast in the variation of Ca^{2+}, NO_3^- and Cl^- suggested that both source and recharge were key contributing factors. Toran et al. (2007) also showed that variations in NO_3-N result from a combination of changes in the source and the flow path. Change in the source term was interpreted to be related to the

end of the growing season when plant intake of NO_3-N decreased. A change in flow path was observed when an increase in NO_3-N concentration was linked to decrease in Cl^- concentration and interpreted to represent a groundwater system switch from a deeper to a shallower system. Variation in Ca^{2+} concentration is indicator of storm-water recharge (Toran et al., 2007). When variation occurs concurrently with other ions concentration such Cl^-, then this indicates dilution; however, Ca^{2+} varying alone indicates a change in the equilibrium with respect to calcite in the recharge area. The authors argued that mixing of matrix water with storm-water in the open conduit caused super saturation and outgassing and therefore reducing Ca^{2+} concentrations.

In the study area, consistent lower concentrations of Cl^-, Ca^{2+} or NO_3-N combined with the presence of bacterial contamination during summer or fall may be an indicator of disperse recharge to the well, whereas a sudden decrease in major-ions concentrations combined with an increase in coliform bacteria indicates rapid recharge. At W4 for example, the concentrations of Cl^- and NO_3-N are relatively low during summer months and TC are consistently detected. A rapid decrease in Ca^{2+} concentration is observed in some wells and linked to coliform contamination (e.g. W1, October 2008). The decrease in Ca^{2+} is therefore being attributed to outgassing of CO_2 which precipitates Ca^{2+} (as $CaCO_3$) and implies that a preferential recharge fracture may have become active. One sampling event occurred within 3 days after a storm event with a number of wells exhibiting a higher concentration of TC. The observed lag time, between the September 2008 storm event and the well response, may indicate the activation of a nearby preferential pathway. Coliform bacteria concentration increases significantly in some wells (W1, W6, W12 and W18) whereas others show decreases in ionic strength values (W11 and W15) that are not necessarily linked to the occurrence of coliform bacteria. In the case of W11, the storm may have provided coliform-free water, which may have diluted the observed concentration of TC in that well. The timing of sampling and the amount of precipitation influences the concentration of TC in the well, with the individual well response to the storm event providing a good indication of the presence of nearby active preferential pathways.

Wells showing a seasonal pattern in NO_3-N concentration are interpreted to be more vulnerable to coliform bacteria contamination because rapid recharge events limit the residence time in the soil matrix (or conditions) and therefore, provide insufficient time for denitrification processes to occur. The overall low level of NO_3-N and its lack of strong correlation with FC in the study area indicate it is sourced from natural origins as opposed

to contamination from septic effluents. When NO_3-N is not detected, the infiltration water spends enough time in the soil matrix to allow denitrification. When NO_3-N is sporadically detected, it is interpreted that a change in recharge pathway occurs (i.e. storm event) resulting activation and infiltration through macro-pores.

Activation of alternate flow paths may depend on the initial water content of the soil and the storm duration and/or intensity (Cey et. al., 2005; Sugita et al., 2005). Wells showing a rapid response are highly vulnerable to rapid recharge from fractures or macro-pores with the presence of thin overburden or fractured outcrop contributing to this vulnerability (Gleeson et al., 2009). A thin overburden may have contributed to the vulnerability of W6 and W18 to the storm event. Once the recharge water reaches the fracture network, velocities raging from 2 to 388 m/day have been observed (Novakowsky et al., 2006). The rate of change in water quality and awareness of these changes is a concern because local residents often assume that their water quality does not fluctuate over time.

4.5.3. Effect of faulty well seals as an anthropogenic recharge pathway

Twelve wells in the study area were previously tested to determine their seal integrity with faulty well seals detected in nine of the wells. The relative imbalance in wells with a faulty seal makes it a challenge to provide an absolute determination of the effect of faulty well seals on the seasonal behaviour of water quality. However, a large proportion (6/9) of wells with a faulty seal display seasonal variations of the ionic strength value, whereas only one well (W15) out of the three without a faulty seal shows strong seasonal variation. Although the NO_3-N concentration is variable in wells with a faulty seal, all wells showing sporadic detection have a faulty seal whereas the concentration of NO_3-N is either not detected or consistently detected in those with a proper well seal. These data suggest that in 2/3 (~66%) of the wells tested in the Municipality, the presence or absence of a faulty well seal plays a prominent role in the water quality, especially with respect to the influx of nitrate. In these cases, the annular space in a well with poor seal integrity is acting as a preferential pathway to runoff water infiltration.

4.5.4. Other anthropogenic activities

Chapter 3 demonstrated that local anthropogenic activities contribute to the ionic species concentrations in the groundwater system. Anthropogenic activities in the study area are limited to road salt application on major highways, domestic effluents and residential application of fertilizers. The shallow groundwater system may be impacted by these activities with the resulting effect dependent on the recharge potential in the area. For example, less dilution from recharge may result in higher concentrations of Cl^-, SO_4^{2-}, Na^+, Mg^{2+} or Ca^{2+} during the summer (e.g. W6, W12 and W19) and certain wells showing sporadic increases in ionic concentrations (e.g. W2, W7, W11 and W26) may be linked to mixing with septic effluents. Although, the results show that the impact of anthropogenic activities on water quality may occur over a fairly continuous time interval, more isolated and sporadic events appear to dominate the anthropogenic influence on water quality in the Municipality. The attenuation or contamination potential of anthropogenic inputs along the flow path is controlled by the recharge process, the fracture network and magnitude of the rainfall event.

4.5.5. The applicability of multivariate statistical analysis as a tool to assess groundwater quality

Multivariate statistical analysis techniques (correlations, HCA and PCA) successfully provided new insights on the dominant controls of groundwater quality in the study area, particularly when the well vulnerability is at the highest (high risk months). The correlation matrix and PCA analysis identifies large-scale processes affecting the groundwater quality, whereas the cluster analysis provides details on groups of wells based on their similarities in ionic chemistry and coliform bacteria concentration.

The correlation analysis and PCA show that extra-regional and regional processes are the dominant controls on the chemical groundwater quality during the high risk period. This finding appears somewhat contrary to some of the data presented because recharge is considered a local factor (Korkka-Niemi, 2005) and is interpreted to contribute to the occurrence of coliform bacteria in individual wells in the study area. However, the correlation and PCA analyses demonstrate that groundwater is drawn mainly from a deeper groundwater system with natural origins of the ions. Extra-regional and regional factors (PC1 and PC2) explain 54% of the variance in the data set through the PCA whereas the

opposite is observed during the low risk period where 48% of the variance is associated with local factors (PC1 and PC3). In both periods the influence of local factors, represented by the occurrence of coliforms bacteria, is illustrated through the third component of the PCA. These local factors are clearly linked to the incidence of bacterial contamination; however, during the high risk months when >40% of samples test positive for presence of coliform bacteria, it is the extra-regional and regional factors that control the water chemistry and groundwater quality over the entire study area limiting the contribution of local factors to a minor role. Also during the high risk period a greater number of PCA components are required to explain a similar amount of variance when compared to the low risk months. This means that the inter-relationship structure between the variables is more complex during high risk months and there is possibly more interaction between the different factors.

Examination of the wells individually and grouping them according to their similarities, the cluster analysis allows for more distinction between regional and local factors during the high risk period identifying which specific groups are more prone to the influence from these factors. When comparing the high and low risk periods, it is interesting to observe that some wells always grouped together whereas others clustered differently. For example, the grouping of W9, W23, W10, W25, W12 and W19 is the same in both dendrograms (Fig. 4.12) with the wells in this cluster affected mainly by PC1 during high risk months and negatively affected by PC2 during low risk months; components both related to extra regional and regional factors. The effect of recharge is less prominent on this cluster of wells, resulting in longer water residence times when compared to wells where more seasonal variations in the water chemistry are observed. For this group of wells, located mainly where the aquifer is confined, the main processes affecting the groundwater appear to remain consistent during high or low risk periods and the occurrence of coliform bacteria is potentially the result of variation in the loading at the source and not from a significant change in the flow field.

Seasonal variability in the groundwater system may explain why wells from the other clusters exhibit variations in water chemistry and group differently during the two periods. The distribution of these wells varies within clusters and some wells consistently group together (e.g. W13 and W15; W11, W26 and W5; W14 and W17; W18, W1 and W16) which indicates an overall similarity in water chemistry and coliform bacteria concentration during the entire sampling period. These wells either show little seasonal variation in the water

quality (chemical and bacterial concentration) or comparable magnitude in seasonal variations, but the Euclidian distance between the samples remains more or less similar during the two periods. All of these wells are located where the aquifer is unconfined and located in preferential recharge area and thus, subject to be affected by recharge. Some wells are also spatially close (e.g. W11 and W26) or did not have a uphill neighbour (W14 and W17). This information gives insights on which spatial area over the Municipality is more prone to seasonal variability in groundwater quality.

The results of the multivariate analyses demonstrate their effectiveness at identifying processes which control groundwater quality, but also the importance in incorporating both chemical and bacterial data in order to obtain more robust interpretations. For example, analysis of the chemical data alone may have shown that during the high risk months extra-regional or regional factors control the ionic composition of the water, and thus, wells are technically less prone to the occurrence of bacteria. However, the inclusion of coliform bacteria data in the analysis illustrates the local influence during this period and why these are high risk months for bacterial contamination. In a similar manner, the low risk period may have been interpreted to be more prone to bacterial contamination; however the lower incidence of coliform bacteria during that period may simply reflect the absence of potential sources of coliform bacteria and not necessarily less vulnerability.

Although the multivariate analysis technique performed identify dominant control on groundwater quality, the interpretation is however subjective and more information on the local flow system, the sources and a better understanding of the controlling processes performed with the help of geochemical modelling may have been useful to fully quantify a factor and its relative importance. The understanding of the controlling processes may have been improved by dividing the sampling year based on the periods defined during the individual well analysis (e.g. spring snowmelt, summer baseflow, fall recharge, winter baseflow) instead of high and low risk months. A more complete picture would have potentially been obtained for specific season, but it could have not been used to identify the controlling factors when the vulnerability of the wells is at the highest.

4.6. Conclusions

Twenty-seven wells were sampled for indicator micro-organisms (total and faecal coliforms) and ionic concentrations from April 2008 to May 2009. The objective of the seasonal analysis is to identify contributing factors and determine the role of seasonal variations on the occurrence of coliform bacteria and the hydrogeochemical water quality of domestic wells in Chelsea, Québec.

The microbial analysis results show that some wells are characterized by good water quality because they are consistently free of contamination, but others are frequently contaminated. Seasonal trends are also observed in TC and FC with most wells exhibiting a strong response to summer/autumnal recharge whereas other wells are affected by snowmelt recharge. Variables related to infiltration of runoff water, such as thickness of the soil profile and the presence of grout in the annular space, and other site-specific variables, such as the water level and the well age, also affect the occurrence of coliform bacteria during the summer and fall recharge. The effect of seasonal variations on the occurrence of TC and FC is observed when examining all wells together, but not influenced by any water type in particular (e.g. Ca-Mg-HCO_3, Na-HCO_3, Ca-Cl or mixed) . However, the mixed-water type appears to be the most vulnerable to contamination when compared to the Ca-Mg-HCO_3 types.

Based on climatic controls of recharge events over the Municipality, specific periods (spring recharge, summer baseflow, fall recharge and winter baseflow) are defined to categorize the observed variations in ionic strength values. Strong seasonal variations are observed at some wells whereas others show little seasonal variation. A weak link between ionic variability and coliform bacteria is observed where wells with the most variability generally show a high relative frequency of contamination. From these integrated data, wells are classified into categories based on the seasonal response in both microbial and ionic concentrations. When seasonal variations in water chemistry are associated to variations in bacterial concentration, the source of coliform bacteria may result from diffuse infiltration and not from preferential recharge pathways. When variability is not attributed to specific seasonal patterns, recharge from preferential pathways and contributions from anthropogenic sources are interpreted to explain the water quality anomalies. Seasonal variability in both coliform bacteria and ionic concentrations illustrate seasonal variation in the source of coliform bacteria and in the magnitude and direction of the flow field.

The identification of seasonal trends in coliform bacteria and water chemistry in wells with faulty seals is a challenge because most wells (9/12) exhibit preferential recharge pathways in the annular space. However, all wells showing sporadic detection of NO_3-N have a faulty seal and the annular space may have acted as a preferential pathway to runoff water infiltration. Even though the NO_3-N concentration is within the Québec provincial limit of 10 mg-N/L, it confirms the previous observation on the rapidity with which the water quality may change.

The multivariate statistical analysis techniques (correlation, HCA and PCA) are shown to be useful in evaluating the contribution of extra-regional, regional and local factors which affect the groundwater quality, particularly when wells are the most vulnerable to bacterial contamination (e.g. summer and fall). The correlation and the PCA analysis provide the complete picture on the study area regarding large-scale processes affecting the groundwater, and despite the fact that the analysis is performed when higher percentage of occurrence of coliform bacteria are observed, extra-regional and regional effects control the chemistry when the sampling population is considered as a whole. The cluster analysis allows for more distinction between regional and local factors during the high risk period identifying which specific groups are more prone to the influence from these factors. The discrepancy in the results of the high and low risk months is indicator of seasonal variability in groundwater quality which results from variations in the flow field and in the loading of bacteria. The combination of the chemical and bacterial data illustrates a more complete picture of the factors affecting the groundwater quality.

Arguably, the most important conclusion from this investigation is that it is a combination of factors such as local well characteristics and climatic events that control the occurrence of TC and FC in the study area, although, the dominant factor varies for each well. Various factors appear more or less equally proficient at triggering a contamination event, but this study demonstrates the importance of well construction and rapid recharge which leads to changes in microbial water quality. Communication to local well owners of the role that these two key contributors play in their overall water quality is important because they are factors that residents are able control to a certain extent. Faulty seals and poor well construction are usually fixable at a low to moderate cost. Residents should be informed that microbial water quality changes over time, and they should be encouraged to increase the frequency of testing of their well water during summer and fall, especially after storm events. Although assessing the importance of the numerous factors which

contribute to the occurrence of coliform bacteria in private domestic wells remains a challenge, effective communication to well owner about their well construction, the uniqueness of the local characteristics and the period of the year when it may be more prone to contamination is critical. This will increase the overall awareness about the water quality of domestic wells in the community, particularly in areas susceptible to contamination.

Chapter 5: Assessment of domestic wells vulnerability to bacterial contamination in a crystalline bedrock aquifer, Chelsea, Québec

5.1. Introduction

Crystalline bedrock aquifers are an important source of drinking water as they cover more than 20% of the continental mass (Ayraud et al., 2008) and are the principal source of water for the residents of Chelsea, Québec, Canada. These types of aquifers are vulnerable to contamination because flow in crystalline bedrock is controlled primarily by preferential flow paths through fracture networks (Conboy and Goss, 2000; Boutt et al., 2010). Fractures allow high groundwater velocity (Novakowsky et al., 2006) and depending on the primary porosity, may offer low attenuation potential (Conboy and Goss, 2000). A large proportion of the groundwater in Chelsea is drawn from unconfined crystalline bedrock aquifers with the rate of recharge controlled by the thickness and hydraulic conductivity of the overburden (Gleeson et al., 2009). Overburden thickness is variable in the study area of Chelsea, and thus, water quality is susceptible to contamination and contaminant migration because fractures are potentially acting as preferential pathways combined with poor filtration and rapid infiltration of surface water from the thin soil cover (Cey et al., 2006; Levison and Novakowsky, 2009). Preferential pathways are present in the bedrock aquifer and the overburden, but also may be the product of poor well construction. The well itself may act as a preferential pathway to surficial water and contaminants if its annular space, created during the drilling of the well, is not properly sealed with impermeable material such as concrete or bentonite. The private wells in the study area are characterized by both natural and anthropogenic features that increase their vulnerability to surficial contaminants if a source is located in the proximity of the well.

Groundwater vulnerability has become an important concept in assessing the risk of contamination of groundwater resources (Worrall, 2005). The definitions of groundwater vulnerability and susceptibility are used interchangeably, depending on the author (Frind et al., 2006). Within this chapter, groundwater vulnerability is defined as the propensity of a well to become contaminated from surficial or near-surface contamination sources. This definition is selected because it recognizes that the vulnerability depends on the characteristics of the site, independently of the nature of the contaminant (Worrall, 2005);

and in this sense, it describes the intrinsic susceptibility of the well under normal hydraulic regimes. Many types of methods exist to evaluate the vulnerability of groundwater resources, and range from simple index-based to more complex numerical simulation (Arthur et al., 2007). Statistical methods for vulnerability assessment have the advantage to accommodate for data uncertainty and provide a probability of occurrence (Twarakavi and Kaluarachchi, 2005; Worrall, 2005). Examples include logistic regression (LR) and weight-of evidence (WofE) techniques which have been used in a number of studies to predict groundwater vulnerability to contaminants (e.g. Nolan, 2001; Arthur et al., 2007; Worrall, 2005). The primary goal of these vulnerability assessment methods is to evaluate the risk of contamination in a receptor (aquifer or well) given a combination of physical characteristics along the pathway from the source to the receptor that influence contaminant transport and concentration. In this context, the source includes anthropogenic and land-use activities as well as the potential release of contaminants, whereas the pathway includes all the relevant mechanisms encountered from the source to the receptor, with the well as the receptor (Frind et al., 2006).

In areas where private wells and septic systems co-exist, preferential pathways combined with thin overburden increase the vulnerability of domestic wells to contamination. Chapters 2, 3 and 4 focused mainly on the pathway component of the source-pathway-receptor concept (Frind et al., 2006) and demonstrated its importance and effect on microbial water quality in the study area of Chelsea, Québec. However, preferential pathways are rarely considered in a vulnerability assessment because of the complexity and uncertainty that exists behind these variables. Therefore, there is a need to include their impact when assessing the risk of contamination of residential wells to contamination (Gogu and Dassargues, 2000). The objective of this chapter is to propose a vulnerability assessment model for domestic wells in the Municipality of Chelsea, Québec. The application of data-driven stochastic vulnerability models such as logistic regression and weight-of-evidence are first evaluated, and then an alternative and novel approach based on a simple Poisson distribution analysis is proposed. The model addresses the relative importance of preferential pathways (natural or anthropogenic), seasonal variations and the influence of anthropogenic activities in the probability of contamination in a domestic well. It also attempts to answer simple questions that residential owners may have regarding spatial, seasonal or site-specific characteristics that increase the risk of microbial contamination of drinking water in their well.

5.2. Vulnerability assessment

Three main approaches are commonly used to evaluate vulnerability (Zhang et al., 1996). First, index methods such as DRASTIC (Aller et al., 1987) consist of overlaying various physical attributes of the system using GIS to produce vulnerability maps. These methods are relatively easy to implement, however, weighting factors are often arbitrarily selected, based on an expert opinion (Frind et al., 2006; Worrall, 2005), and not based on observations or measurements. Some studies have also demonstrated that different methods applied to the same system yield different results (e.g. Gogu et al., 2003). Moreover, the indices have to be interpreted against subjective classification schemes which are difficult to assess in the decision making process (Worrall, 2005). As a result, index overlay methods have been criticized by many authors (Frind et al., 2006). The second approach uses physical models to approximate contaminant transport. These tools are powerful, but a proper understanding of the groundwater system is critical and these data are not always available for a region, or are costly to obtain (Twarakavi and Kaluarachchi, 2005). The last approach uses statistics to estimate the vulnerability occurrence based on site characteristics. These methods include logistic regression (LR) or weight-of-evidence (WofE), and have an advantage in their ability to accommodate for data uncertainty by providing a probability of occurrence (Twarakavi and Kaluarachchi, 2005; Worrall, 2005), which is helpful in the decision making process. Vulnerability assessment models are also characterized based on the source of the data and inputs: knowledge-driven models such as DRASTIC are based on expert opinion; whereas data-driven models are based on measured observations (Arthur et al., 2007). The model proposed for the Municipality of Chelsea is based on measured observations.

5.3. Characterization of the source-pathway-receptor model

The vulnerability of domestic wells to contamination depends on the presence a source, the attenuation processes along the flow path from the source to the well (receptor), and the ability of the receptor to dilute the concentration of contaminant (Frind et al., 2006). In this study, the vulnerability of a private well to contamination is assessed by the probability of a failure of the components in the source-pathway-receptor system, which leads to contamination. It combines the probability of an active source occurring near the well with the probability of a failure in natural attenuation processes along the recharge

pathway, and the failure of the receptor (well) to prevent contamination (including the inability to provide sufficient attenuation). The concentration of the contaminant at the end-point is the result of the combination of failure of the components in the source-pathway-receptor model as illustrated in Figure 5.1. The proposed conceptual model highlights the various factors that influence the groundwater quality in Chelsea, Québec and translates the spatial, seasonal and site-specific controls on contamination in terms of a probability that is easy understand by resource managers and, more importantly, by well owners.

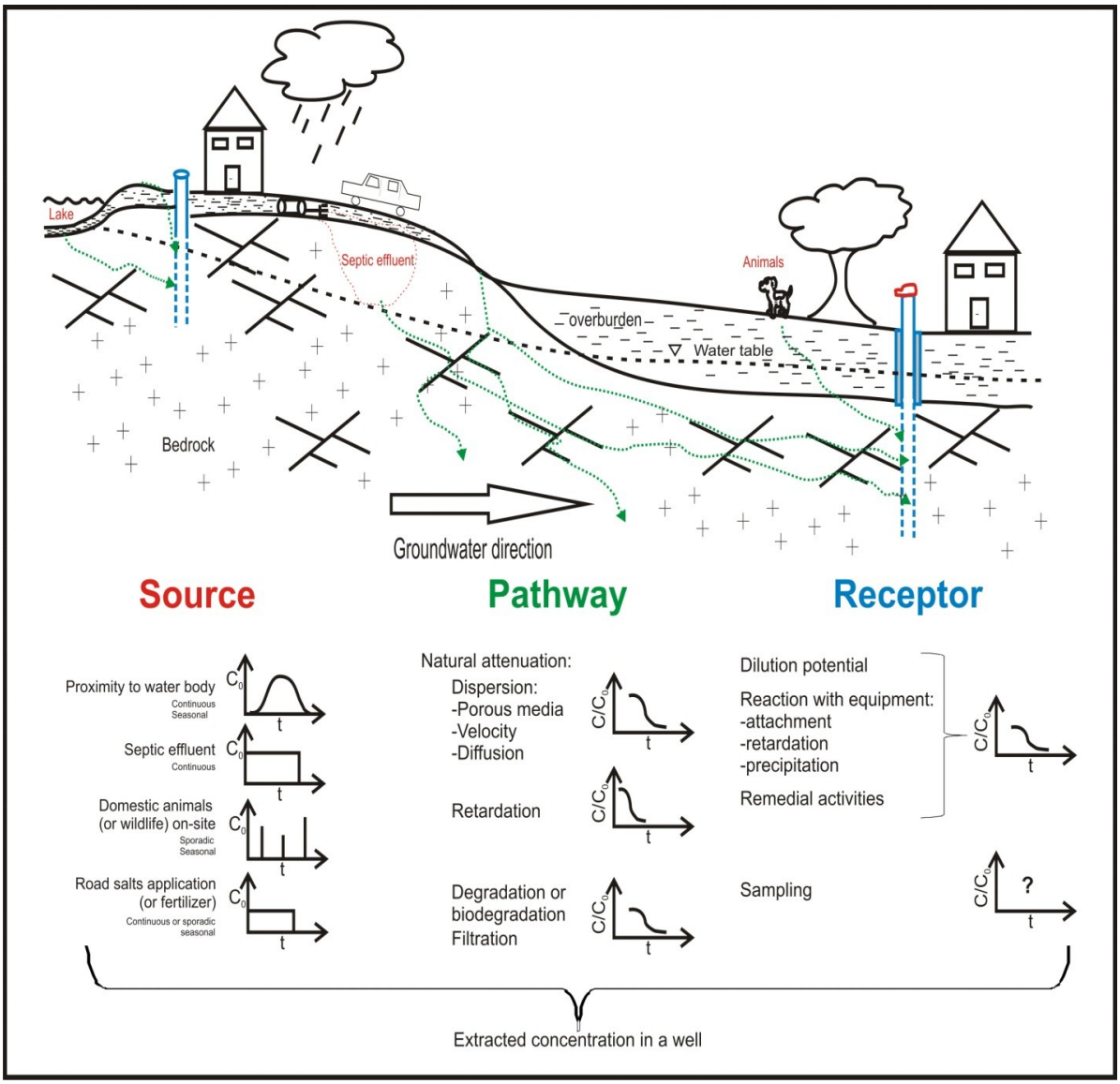


Figure 5.1: Schematic diagram of the conceptual source-pathway-receptor model (Frind et al., 2006) applicable to the Municipality of Chelsea, Québec where the extracted concentration in a well is a combination of source loadings, the attenuation potential along the recharge pathway and at the receptor.

5.3.1. Source

In the study area, agricultural activities are relatively minor and the main anthropogenic sources of coliform bacteria are septic systems. If the septic tank does not leak, is emptied as recommended, and the septic field is well maintained, total (TC) and

faecal coliforms (FC) should be removed from the effluent before the water reaches the shallow groundwater system. The results from Chapters 3 and 4 showed that septic effluents affected water quality in the shallow groundwater system by increasing the concentration of Cl^-, SO_4^{2-} and Ca^{2+} or Mg^{2+}, which are linked to coliform bacteria in some wells. The uncertainty regarding this source of contamination is high because most information on an individual septic system is not public and a confidentiality agreement prohibits the Municipality to share this information without the consent of the homeowner. Residence density and the presence of an uphill neighbour from a well may provide an indication of the risk associated with this source because the risk increases with an increasing number of uphill neighbours. Once in the groundwater system, the extent of the contaminant plume is difficult to determine, especially if little is known of the fracture network. Another source of contamination associated with residence density and the presence of uphill neighbours is that a domestic well may contaminate another well if a hydraulic connection exists between the wells. Other minor anthropogenic sources of contaminants in residential areas include: the presence of a driveway (and proximity to the well); small-scale application of road salts during winter; and fertilizer use during the summer. The presence of domestic animals may also increase the loadings of FC at the surface, and in the well. Natural sources of coliform bacteria include wildlife and surface water bodies, which naturally contains a greater concentration of bacteria because of surface runoff. Sources are generally classified based on their spatial-temporal characteristics, the type of contaminant and the concentrations released (loadings). Figure 5.1 illustrates the different sources that potentially affect domestic wells in the study area and an example of a concentration loading curve specific to the source.

5.3.2. Pathway

Many factors affect the concentration of contaminants along the pathway from the source to the well. As the contaminant passes through the groundwater flow system, it naturally encounters a series of mechanisms that attenuate the observed concentration at the well (Frind et al., 2006). Some of these mechanisms are intrinsic to the aquifer, whereas others depend on the nature of the contaminant. For example, dispersion is a characteristic of the flow system and depends on the type of porous media, the matrix diffusion and the groundwater velocity (Freeze and Cherry, 1979). The nature of the contaminant influences the retardation process and the degradation process, which also

depends on the ambient condition in the aquifer (Freeze and Cherry, 1979). If considering coliform bacteria as a potential contaminant, filtration, sorption and biodegradation are natural attenuation processes that combine to attenuate the concentration of a contaminant as it travels through the groundwater system (Conboy and Goss, 1999). However, conditions may exist that lead to the failure of natural attenuation processes and result in a higher contaminant concentration at the well.

Macro-pores are widely recognized to affect the natural capacity of porous media to attenuate a contaminant, allowing it to travel faster and deeper (Conboy and Goss, 1999; Cey et al., 2006; Levison and Novakowsky, 2009). Development of a preferential pathway increases the potential for rapid recharge and therefore, the vulnerability of a well to rapid infiltration of runoff water. The risk of contamination increases if the runoff water contains a surficial contaminant such as coliform bacteria. Furthermore, the thin soil cover present in some areas may also lead to poor filtration and rapid infiltration of surface water, causing widespread contaminant migration (Cey et al., 2006; Levison and Novakowsky, 2009).

A large proportion of the groundwater in Chelsea is drawn from unconfined crystalline bedrock aquifers with variable overburden thickness. The presence of rapid recharge pathways that lead to high concentrations of TC has been demonstrated in Chapter 4. Preferential pathways are present in the fractured aquifer and in the overburden, but are also the product of poor well construction. Although the well is the receptor, its construction may also lead to it being a pathway. The results from Chapter 2 showed that the annular space of most wells (9/12) investigated in the study area acted as a preferential recharge pathway. Figure 5.1 lists the features affecting the attenuation potential of the groundwater system along a recharge pathway.

5.3.3. Receptor (Well)

The well itself may be an important contributor to the quality of the water, and its vulnerability to surficial contaminants may increase or decrease depending on the type of well, its physical condition and the site characteristics. Figure 5.1 describes the many variables that may affect the vulnerability of a well to contamination. By drawing water at different depths, dilution occurs at the well by mixing with clean water (Frind et al., 2006). The magnitude of the dilution factor appears to depend on the capacity of the well (Einarson and MacKay, 2001) and values of several orders of magnitude have been observed (Bester

et al., 2006). Other mitigation factors may include attachment of the contaminant on the pump and pipes inside the well, reaction with equipment, or precipitation inside the water pipes. The well owner also may decrease the contaminant level by performing remedial activities such chlorination to remove coliform bacteria. However, the effectiveness of this remedial activity depends if microbial colonies are reintroduce in the well (Oliphant et al., 2002). Lastly, the timing of sampling has an impact on the observed concentration (Levison and Novakowsky, 2009; Kozuskanich et al., 2011). The concentration of coliform bacteria in wells over the Municipality was shown to be influenced by climatic control and the time elapsed between an important rainfall event and the sample collection may impact the observed concentration (Chapters 3 and 4). Kozuskanich et al. (2011) demonstrated that the amount of water purged from the well before collecting the sample influences the extracted concentration, but this impact was not considered during the sample collection process of this study.

5.4. Microbial contamination in Chelsea, Québec

One of the most important conclusions from the spatial and seasonal analyses (Chapters 3 and 4) was that, although the dominant factor varied for each well, it was a combination of factors that controlled the occurrence of TC and FC in the study area. These factors include local well characteristics, climatic events, a source loading, natural attenuation processes along the pathway, the effect of the receptor, remedial action, and error introduced during sampling (Fig. 5.1). Chapter 4 also showed that some wells were vulnerable to rapid recharge after rainfall events, which led to temporary degradation of the water quality. The extracted concentration is considered a probability of observing a given concentration in a specific volume of water and the data are used in this context to assess vulnerability of a well to microbial contamination (Frind et al., 2006).

5.5. Vulnerability assessment approach

The statistical approaches of logistic regression (LR) and weight-of-evidence (WofE) are increasingly being employed in groundwater vulnerability assessments, and their application to construct probabilistic contamination maps is evaluated for the Chelsea dataset. Subsequently, the potential of an alternative method, using a simple Poisson

distribution is considered, to translate the findings from the previous chapters in terms of probability of contamination.

Logistic regression is a common method to estimate aquifer vulnerability based on the relationship between a response variable and influencing variables (Twarakavi and Kaluarachchi, 2005). LR analysis relates the probability of a binary response variable to be less than a threshold value due to one or more explanatory variables (Twarakavi and Kaluarachchi, 2005). LR is modelled as a linear function when the log of the odd ratio is taken; where the odd ratio represents the probability of obtaining a response of 1 (exceeding the threshold) over the probability of obtaining a response of 0 (not exceeding threshold). Binary logistic regressions give the probability of response to one threshold only, whereas ordinal logistic regressions give the probability of response to more than one threshold, such as the background and maximum concentration limit in the aquifer (Helsel and Hirsch, 1995; Twarakavi and Kaluarachchi, 2005). Multivariate logistic regressions are performed to estimate probabilities based on the occurrence of the influencing variable which quantifies the vulnerability.

Logistic regression (LR) analyses have been used to predict the probability of nitrates and bacterial contamination in domestic wells in Ontario (Goss et al., 1998; Conboy et Goss, 2000). The LR technique also has been used by many researchers in the USA to evaluate vulnerability of aquifer to nitrates, pesticides and volatile organic compounds (Tesoriero et Voss, 1997; Nolan, 2002; Aelion and Conte, 2004) and to predict the occurrence of arsenic (Winkel et al., 2008; Amini et al., 2008). This technique represents an improvement over the index overlay methods because the weighting of the independent variables are assigned using the slope coefficient of observed data and not based on expert-knowledge (Nolan, 2002).

Another modeling technique to assess vulnerability is weight-of-evidence (WofE), which generates a data-driven, predictive model that uses spatial data to describe and analyze the interactions between physical features and a known occurrence of a target variable (Bonham-Carter, 1994). The WofE model is a log-linear form of the Bayesian model with an assumption of conditional independence (Bonham-Carter, 1994). The model quantifies the relationship between a target and a predictor variable. A set of training data is needed to implement the model in addition to knowledge of significant associations between the target variable and predictor classes (evidence maps). Based on the location

of the known occurrence (training data) and the class of evidence maps, statistical calculations build maps from weighted input data layers. The method has the advantage to reduce some bias associated with knowledge-driven method because it is based on data and not on an expert opinion (Arthur et al., 2007).

Weight-of-evidence modeling techniques historically have been used in the context of mineral exploration mapping (Bonham-Carter, 1994) and it is only recently that the technique has been applied to aquifer vulnerability assessment (Masetti et al., 2005). For example, Arthur et al. (2007) implemented the WoE modeling technique to evaluate the relative vulnerability of aquifers in Florida. The authors used dissolved nitrogen data as a training point and indication of vulnerability because it is present naturally at the surface and in a relatively low concentration in confined aquifer systems. Soil hydraulic conductivity, karst features, thickness of the aquifer confinement, and hydraulic head difference between the water table and potentiometric surface, were the evidential themes used in the model. The modeling technique was successful in identifying the intrinsic vulnerability of the aquifer system, but did not account for anthropogenic activities. However, future studies would have the ability to combine the results with known contaminant sites to further assess vulnerability.

Initially, the application of LR and WofE modeling techniques towards the Chelsea, Québec dataset appeared promising, however, difficulties exist to properly implement the models in GIS and evaluate probabilities of contamination. The primary challenge for both LR and WofE was related the failure of detecting significant factors (influencing variables) which contributed to the presence of coliform bacteria in wells over the entire Municipality, and thus, no conclusive association between bacterial contamination and spatial attributes was established (Chapter 3). Furthermore, the complexity existing within the dataset made the isolation of a specific factor that caused contamination difficult and an exhaustive list of events was not obtained. Moreover, WofE is based on Baye's rule of Probability with the assumption of conditional independence between the variables (Bonham-Carter, 1994). The variables considered in this study did not satisfy this rule of independence and implementation of the model with the existing dataset violates this assumption because the observed concentration depends on the presence of a source combined with a failure in the pathway and at the receptor, to attenuate the contaminant. For example, the dilution potential of a well depends mainly on the fracture network, which is also a component of the pathway. The difficulties encountered in the identification of specific factor to contamination

and the lack of conditional independence within the obtained Chelsea dataset requires a simplification to the assessment of vulnerability and the computation of probabilities by employing an alternative approach.

The Poisson distribution has been broadly applied in research fields such as accident statistics, earth sciences, and biology (Gibbons, 1987; Davis, 2002; Fowler et al., 1998). The Poisson distribution is a binomial probability distribution function used to calculate the probability of obtaining a specific value from a discrete variable based on the population mean. The Poisson distribution is determined by a single parameter lambda (λ), which is equal to the population mean, μ, and also equal to the variance, σ^2, (Davis, 2002) as shown by Equation [1]. Lambda is the mean count rate per unit time or, in this case, per unit volume of water. The probability of obtaining a specific count (x) per unit time or volume is given by Equation [2] (Davis, 2002).

$$\lambda = \mu = \sigma^2 \qquad [1]$$

$$P(x) = e^{-\lambda}\left(\frac{\lambda^x}{x!}\right) \qquad [2]$$

Classic applications include radioactive decay in Bq or disintegration per unit time or lightning strikes per unit time (Fowler et al., 1998). With regards to water quality evaluation, it has been used to determine the enumeration of total coliforms in water samples by a membrane-filtering procedure (Hass and Haller, 1986). An investigation by Goss et al. (1994) on water-well contamination and farm family health confirmed that coliform bacteria plate counts conformed to a Poisson distribution.

The Poisson distribution is considered an appropriate model to use in the study area because the coliform bacteria concentration represents a count of colonies per 100mL, which are discrete variables (Fowler et al., 1998). Furthermore, the contamination events are considered “rare” and independent since more than one event cannot occur at the same time (Davis, 2002). The observed coliform bacteria concentration in the well follows a Poisson distribution that is interpreted as a probability, which results from a failure in the source-pathway-receptor concept. Therefore, this distribution is used to estimate the

probabilities of a well being contaminated (TC≥10 CFU/100mL and FC >0 CFU/100mL) in Chelsea based on the population mean.

The first step in the process is to verify that these data conform to the Poisson distribution. The "goodness of fit" for both total and faecal distributions is performed following the Kolmogorov-Smirnov technique described by Davis, (2002). The results show that the distribution of TC or FC does not follow the Poisson distribution when considering all samples altogether; which means the deviation is larger than expected in a true Poisson distribution (Davis, 2002). However, this is due mostly to a few outliers and not entirely surprising since true Poisson distributions are rare in nature (Fowler et al., 1998). If sampling is random, the sample means of coliform bacteria counts are normally distributed based on the Central Limit Theorem (CLT), which states that if samples are obtained at random, then the sample means will tend to be normally distributed irrespective of the underlying population distribution (Davis, 2002). In this study, an attempt at random sampling was undertaken, however, the site selection process was based, in a large part, on the willingness of a well owner to participate in the research. Therefore, although the site selection process partially violates the assumption of randomness, it is an unavoidable consequence of conducting a study of private water wells with volunteer well owners. Furthermore, the CLT is relatively robust against violations of the randomness assumption (Snedecor and Cockran, 1980). Although the microbial data in this study do not follow a Poisson distribution, a Poisson model is still applied to infer probabilities of contamination over the municipality of Chelsea in order to answer simple questions from a well owner perspective and to semi-quantify the importance of well-site attributes on the probability of contamination.

The normal deviate is used to test the significance of the Poisson probability obtained, comparing the mean of the annual average when wells are classified based on the site-specific characteristics at the well, following Equation 3 (Detre and White, 1970):

$$\frac{(x_2 - x_1)}{\sqrt{\left(\frac{x_2}{n_2} + \frac{x_1}{n_1}\right)}} \geq z_{1-\alpha/2} \qquad [3]$$

where x_2 and x_1 represent the mean of the annual averages of TC and FC counts in the defined categories and n the number of observations in each category. In the Poisson distribution, the variance equals the mean and the standard error on the mean of n observations is given by the square root of (x/n). In this study, all statistical tests are carried

out at the 95% confidence level (α=0.05). The use of the normal distribution is justified based on the CLT, which is applicable on any distribution.

5.6. Results and Interpretation

The privately owned wells in the study area are characterized by both natural and anthropogenic features such fractures in the crystalline bedrock, thin overburden and/or faulty well seals that increase their vulnerability to surficial contaminants if a source is located in the proximity of the well. This section translates the findings from Chapters 2, 3, and 4 into a probability in order to help the residents of Chelsea better understand the spatial, seasonal and site-specific influences on the risk of TC and FC contamination. The spatial and seasonal probabilities calculated provide a general overview of the TC and FC contamination trends over the Municipality and they are intended for residents of Chelsea with limited knowledge of their well or for those interested in having a general idea on the risk of contamination. However, most well owners are often aware of some specific information on their well and its location, such as the presence of clay or a domestic animal, which are components of the source-pathway-receptor concept. It is important to point out that only one factor is considered at a time and each is evaluated against the combined effect of the other contributing factors. The importance of a factor is statistically tested to evaluate its significance on the risk of contamination and the relative importance of site-specific characteristics, including preferential pathways (natural or anthropogenic), on TC and FC contamination in domestic wells over the study area.

The Poisson distribution is first used to assess the probability of a drilled well to become contaminated with TC at any time during the year and at any location within the Municipality of Chelsea. This calculation is performed using the individual annual concentration average. Two monthly samples (W1-September 2008 and W2-October 2008) were removed because the TC and FC counts obtained are outliers (65 000 and 1980 CFU/100mL), which significantly affect the annual average and probabilities of contamination. The annual average of the distribution is 8 CFU/100mL and the probability of a well exceeding the Quebec DWO of 10 CFU/100mL is 0.33 (Equation 4). Figure 5.2a illustrates the Poisson distribution for TC using the annual contamination average whereas Figure 5.2b shows the cumulative probability for the distribution. For a well owner, this

means that if a water sample is collected at any time during the year, at any location over the Municipality, the probability that the TC count exceeds the DWO is 33%.

$$P(TC\ count \geq 10\ CFU\ 100mL^{-1}) = 1 - P(TC\ count \leq 9) = 0.33 \quad [4]$$

Similarly, the probability of contamination (i.e. FC> 0CFU/100mL) on a yearly basis is also calculated. The annual average of the distribution is 0.66 CFU/100mL, and the Poisson distribution is illustrated in Figure 5.2c and the cumulative probabilities in Figure 5.2d. The probability of any well in Chelsea characterized by a greater count than the FC DWO is 48%, at any time during the year (Equation 5). Interestingly, the probability of occurrence for FC is greater than the probability for TC. This is explained by the difference in the provincial DWO, which is 10 CFU/100mL and 0 CFU/100mL for TC and FC, respectively. Although relatively low, the average for FC is greater than the FC DWO, which contrasts the TC average that is lower than the TC DWO. Even if a lower number of wells are contaminated by FC during the sampling period, an annual average greater than the DWO influences the probability of contamination with the Poisson distribution.

$$P(FC\ count > 0\ CFU\ 100mL^{-1}) = 1 - P(FC\ count = 0) = 0.48 \quad [5]$$

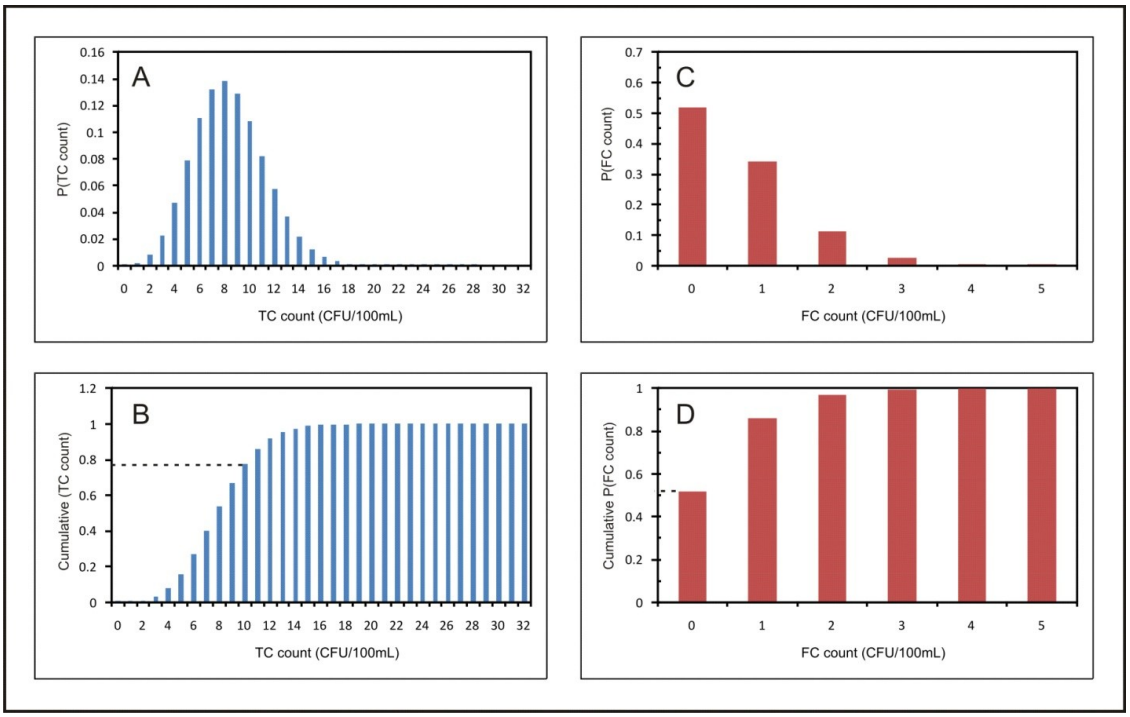


Figure 5.2: A) Poisson distribution for TC with mean of 8 CFU/100mL; B) Cumulative probability of obtaining a given TC count; C) Poisson distribution for FC with mean of 0.66 CFU/100mL; and D) Cumulative probability of obtaining a given FC count.

Although the yearly probability of contamination provides an overview of the risk in the study area, Chapter 4 demonstrated the effects of seasonal variations on the occurrence of coliform bacteria. Well owners may be interested to learn when their well is at its highest risk for TC and FC contamination in order to increase the surveillance of water quality during these specific times. The probabilities of contamination are calculated for important seasonal events such as spring snowmelt, and during summer and fall, which represent periods of recharge. Figure 5.3 shows that the probability of TC contamination is close to 1 from July to October and relatively low during the remainder of the year, whereas the probability of FC contamination is close to 1 in July and August, decreases in September and is close to 0.1 in December, February and May. Seasonal effects are responsible for changes in the risk of contamination classification during the study timeframe: high during summer and fall, which appears to result from seasonal recharge from rainfall events; moderate during the spring, which appears to depend on the presence of a source and the timing and length of snowmelt; and low during the remaining months of the sampling period. The high contamination risk during summer and fall is thought to result

from rapid recharge through preferential pathways created by fractures and by the presence of thin overburden (Chapter 4). The minor peaks in the probability of FC contamination in December, February and May demonstrate that the possibility of contamination is present even during periods of lower risk when climatic control is minimal, and that year-round surveillance of the water quality should be maintained. Although spatial and seasonal controls are contributors to contamination events, the results of this study (Chapters 2, 3 and 4) show that the unique site characteristics are usually the more important factors which lead to individual well vulnerability in the Municipality of Chelsea.

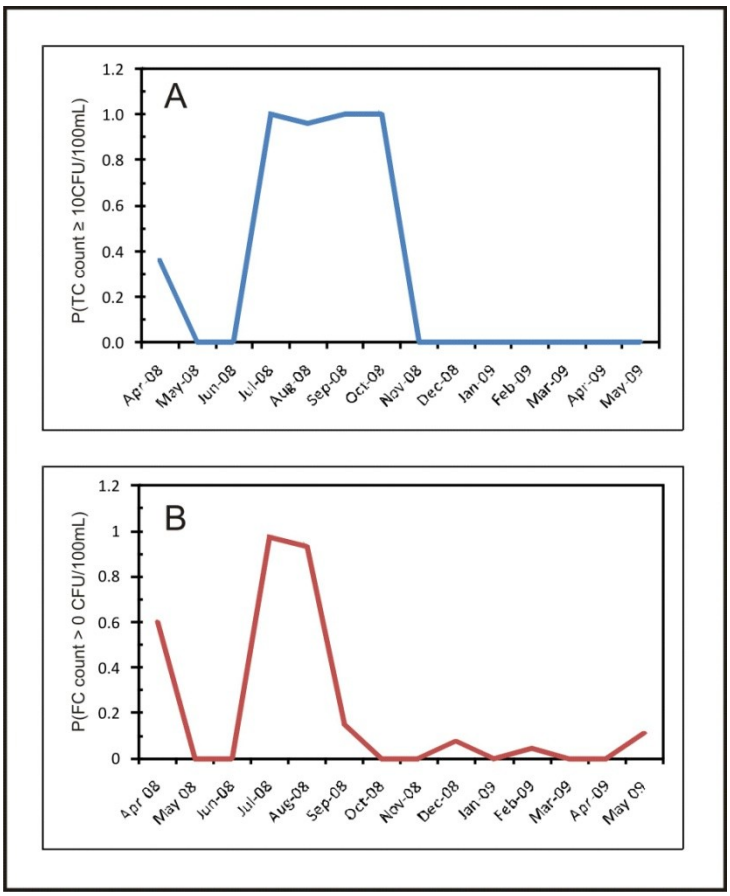


Figure 5.3: Probability of bacterial contamination in a well during the year: A) Probability for TC contamination; and B) Probability for FC contamination.

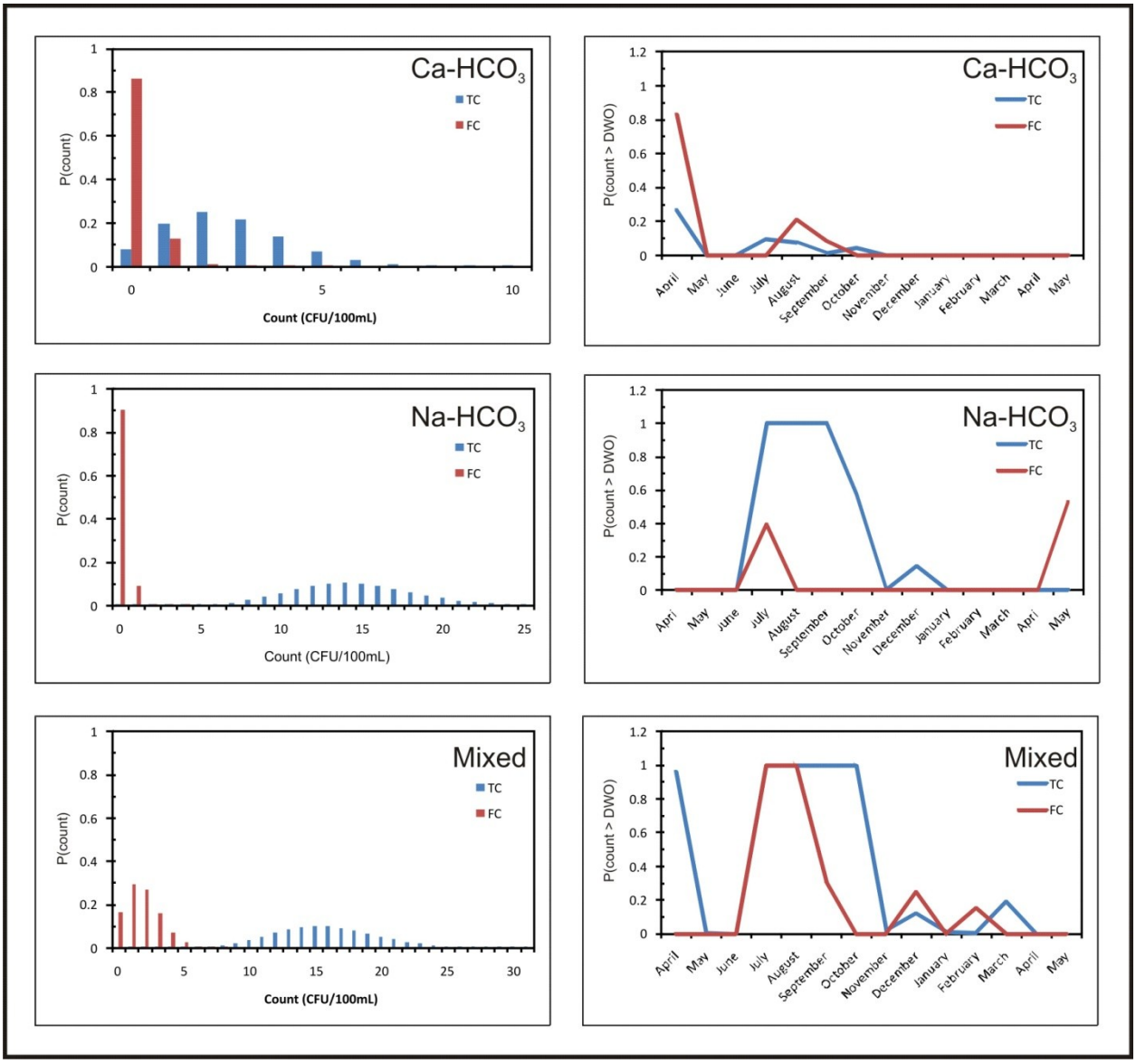


Figure 5.4: The left hand column of the figure represents Poisson distributions for both TC and FC for wells classified in the Ca-HCO_3, Na-HCO_3 and mixed-water types whereas the right hand column represent the monthly probabilities of contamination based on monthly Poisson distribution for each water type.

The “yearly probability of contamination”, that is, the probability of contamination over a period of one year for a well in the Ca-HCO_3 water type is <0.005, whereas it is 0.91 and 0.95 for wells classified in the Na-HCO_3 and mixed water types, respectively. Therefore, wells in the Na-HCO_3 and mixed water types are at greater risk for contamination over the study area compared to the Ca-HCO_3 water type. For FC contamination, the

yearly probabilities are 0.13, 0.09 and 0.83 for Ca-HCO_3, Na-HCO_3 and mixed water types, respectively, with the mixed water type exhibiting the highest risk. Seasonally, similar probabilistic trends are observed during summer and fall when the risk of contamination (both TC and FC) is relatively lower in wells from the Ca-HCO_3 water type compared to the other two water types (Fig. 5.4). The probabilities of TC contamination during spring are variable depending on the water type, with the mixed-water type more affected by the spring 2008 recharge compared to the Na-HCO_3 or Ca-HCO_3 water types. However, the probability of contamination with FC is higher in the Ca-HCO_3 for spring 2008, whereas it is higher in spring 2009 for the Na-HCO_3 water type. Similar to previous findings in Chapter 4, an examination of the probabilities shows that the effect of snowmelt does not appear to be reproducible year-to-year. This is interpreted to indicate that infiltration of snowmelt water is not the only factor controlling the occurrence of coliform bacteria during this timeframe.

Compared to the findings of Chapters 3 and 4, the use of a Poisson distribution enhances the identification of site-specific variables related to the source-pathway-receptor concept, that are found to increase significantly the probability of coliform bacteria contamination (Table 5.1). An example of a source of contamination is the presence of a domestic animal on-site which increases the probability of FC contamination. The proximity to a surface water body also increases the probability of contamination for both TC and FC and may indicate the existence of a hydraulic connection between the surface water body and the well. The presence of an uphill neighbour significantly increases the risk of FC contamination, whereas it does not affect the probability of TC contamination. Examples of pathways include drainage towards the well, which influences the probability of TC contamination. This variable also has been shown to significantly affect the proportion of wells exhibiting TC in the study area (Chapter 3). A water level that is below the casing shoe is also a component of the pathway and appears to increase significantly the probability of TC contamination. The water level influences the risk of contamination if the presence of TC is the result of fracture activation during a rainfall event and the fracture connects to the well above the water level, runoff water may seep directly into the well without dilution provided by the water table or a higher water level. Lastly, the well age is an example of a receptor component, but the effect of this variable is the opposite of the expected result. The finding of Chapter 4 showed that older wells (>10 years old) tend to be more contaminated than younger wells (<10 years old) and are more vulnerable to contamination from summer recharge.

Table 5.1: Yearly probabilities of TC and FC contamination based on the site-specific characteristics, for wells in the Municipality of Chelsea, Québec. Significant difference between the probabilities are indicated in bold (p-value<0.05).

	Site-specific characteristics		n	Mean (CFU/100mL) TC	Mean (CFU/100mL) FC	P(TC≥10)	P(FC>0)
Source	Domestic animal on-site	**Yes**	13	8.30	1.28	0.33	**0.72**
		No	13	8.22	0.02	0.31	**0.02**
	Surface water body within 130 m	**Yes**	9	10.45	1.75	**0.60**	**0.83**
		No	17	7.16	0.06	**0.19**	**0.06**
	Insect proof cap	**Yes**	5	7.85	0.62	0.11	0.39
		No	21	8.91	0.72	0.38	0.49
	Presence of uphill neighbour (s)	**Yes**	14	10.56	1.13	0.41	**0.68**
		No	6	10.95	0.14	0.65	**0.13**
Pathway	Confined condition at the well	**Yes**	9	8.17	1.01	0.30	0.63
		No	17	8.37	0.46	0.33	0.37
	Faulty Seal	**Yes**	9	12.31	1.29	0.78	0.73
		No	3	9.21	1.70	0.44	0.82
	Known presence of grout in annular	**Yes**	6	11.28	1.74	**0.69**	0.82
		No	20	7.41	0.32	**0.21**	0.27
	Drainage towards the well	**Yes**	19	9.51	0.61	**0.48**	0.46
		No	7	5.03	0.74	**0.03**	0.52
	Water level above casing shoe	**Yes**	12	6.30	0.60	**0.11**	0.45
		No	14	10.01	0.69	**0.54**	0.50
	Flowers of trees within 2 feet	**Yes**	12	8.69	0.76	0.35	0.53
		No	14	8.08	0.55	0.29	0.42
Receptor	Well age < 10 years old (in 2008)	**Yes**	8	8.57	1.31	0.36	**0.73**
		No	18	8.18	0.35	0.31	**0.30**

Other site-specific characteristics increase the probability of TC or FC contamination, but the difference between probabilities is not statistically significant (Table 5.1). For example, the presence of a faulty well seal increases the probability of contamination but, the difference is not statistically significant. However, it is a challenge to

make firm conclusions on the relative importance of a faulty seal to contamination events because of the low statistical resolution (12 wells).

As with many statistical treatments of data, it is important to determine if the resulting probabilistic relationship is logical within the context of the site-specific characteristics. For example, the presence of grout appears to significantly increase the probability of TC contamination, however, its presence should enhance attenuation processes, and thereby decrease the probability of contamination. Similarly, the probability of contamination with FC is significantly higher for younger (<10 years) wells compared to older wells, which is the opposite of the expected result. In these situations, it is possible that the wells with these features are also characterized by another, more dominant variable such as proximity to a surface water body, which significantly increases the probability to contamination and thus, mask the impact of the other features.

The significant site-specific characteristics that increase the probability of TC contamination in a well are: the drainage towards the well, the water level, the presence of grout in the annular space and the proximity to a surface water body; whereas for FC, they are: the well age, the proximity to a surface water body and a domestic animal.

These significant factors were combined two at a time, to further assess their relative importance in the probability of contamination. This analysis results in six combinations for both TC and FC (Tables 5.2 and 5.3) summarized as follows:

1) Presence of grout, combined with the drainage towards the well or with the proximity to surface water body significantly increases the probability of TC contamination.

2) Water level below casing shoe (>6 m from ground surface) combined with the presence of grout or with the proximity to a surface water body increases the probability of TC contamination.

3) Absence of the variable drainage towards the well combined with water level below casing shoe (>6 m from ground) or the proximity to a surface water body increases the risk of TC contamination.

4) Presence of uphill neighbour(s) combined with the presence of a domestic animal on-site or the proximity to a surface water body increases the probability of FC contamination.

5) The presence of a domestic animal on-site increases the probability of contamination with no distinction to the well age classification, which may signify that this site-specific characteristic is a dominant factor of FC contamination.

6) The probability of FC contamination generally increases when two or more significant factors classified as a source are combined, but does not necessarily increase when two or more components classified as a pathway are combined.

Table 5.2: Combinations of significant factors which influence TC contamination in Chelsea, Québec. Significant combinations are indicated in bold (p-value<0.05).

1st level		n	mean (CFU/100mL)	P(TC≥10)	2nd level		n	mean (CFU/100mL)	P(TC≥10)
Known presence of grout in annular space	Yes	6	7	**0.69**	Drainage towards the well	Yes	5	14	**0.87**
						No	1	0	**0.00**
	No	20	0	**0.21**		Yes	14	8	0.29
						No	6	6	0.07
Drainage towards the well	Yes	19	10	**0.48**	Water level above casing shoe	Yes	7	6	0.09
						No	12	7	0.13
	No	7	5	**0.03**		Yes	2	11	**0.71**
						No	5	1	**0.00**
Known presence of grout in annular space	Yes	6	7	**0.69**	Water level above casing shoes	Yes	3	3	**0.00**
						No	3	20	**0.99**
	No	20	0	**0.21**		Yes	9	7	0.22
						No	11	7	0.21
Drainage towards the well	Yes	19	10	**0.48**	Surface water body within 130 m	Yes	7	9	0.48
						No	12	10	0.48
	No	7	5	**0.03**		Yes	2	14	**0.88**
						No	5	2	**0.00**
Known presence of grout in annular space	Yes	6	7	**0.69**	Surface water body within 130 m	Yes	3	20	**1.00**
						No	3	7	**0.15**
	No	20	0	**0.21**		Yes	9	8	0.24
						No	11	7	0.20
Water level above casing shoe	Yes	12	6.3	**0.11**	Surface water body within 130 m	Yes	6	7	0.22
						No	6	5	0.04
	No	14	10.0	**0.54**		Yes	3	16	**0.96**
						No	11	8	**0.32**

Table 5.3: Combinations of significant factors which influence TC contamination in Chelsea, Québec. Significant combinations are indicated in bold (p-value<0.05).

1st level		n	mean (CFU/100mL)	P(FC>0)	2nd level		n	mean (CFU/100mL)	P(FC>0)
Well age < 10 years old (in 2008)	Yes	8	1.3	**0.73**	Domestic animal on-site	Yes	3	3.48	**0.97**
						No	5	0.00	**0.00**
	No	18	0.4	**0.30**		Yes	10	0.62	**0.46**
						No	8	0.03	**0.03**
Well age < 10 years old (in 2008)	Yes	8	1.3	**0.73**	Surface water body within 130 m	Yes	2	5.22	**0.99**
						No	6	0.00	**0.00**
	No	18	0.4	**0.30**		Yes	7	0.76	0.53
						No	11	0.10	0.09
Presence of uphill neighbour (s)	Yes	14	1.1	**0.68**	Well age < 10 years old (in 2008)	Yes	4	2.61	0.93
						No	10	0.53	0.41
	No	6	0.1	**0.13**		Yes	2	0.00	0.00
						No	4	0.21	0.19
Presence of uphill neighbour (s)	Yes	14	1.1	**0.68**	Domestic animal on-site	Yes	8	1.95	**0.86**
						No	6	0.03	**0.03**
	No	6	0.1	**0.13**		Yes	1	0.75	0.53
						No	5	0.01	0.01
Presence of uphill neighbour (s)	Yes	14	1.1	**0.68**	Surface water body within 130 m	Yes	5	3.10	**0.96**
						No	9	0.03	**0.03**
	No	6	0.1	**0.13**		Yes	1	0.00	0.00
						No	5	0.16	0.15
Domestic animal on-site	Yes	13	1.3	**0.72**	Surface water body within 130 m	Yes	7	2.25	**0.89**
						No	6	0.14	**0.13**
	No	13	0.0	**0.02**		Yes	2	0.00	0.00
						No	11	0.02	0.02

5.7. Discussion

A substantial proportion of the groundwater in Chelsea is drawn from unconfined crystalline bedrock aquifers, which have been shown to be vulnerable to rapid recharge in areas of thin overburden (Gleeson et al., 2009). The results from Chapters 2, 3 and 4 demonstrated that the privately owned wells in the study area are characterized by both natural and man-made features that may increase their vulnerability to surficial contaminants. This study shows that it is possible to calculate probabilities of contamination using a Poisson distribution by considering the observed count of coliform bacteria as an indicator of the overall risk that results from a source, the attenuation potential along the

pathway and the effect of the receptor well to reduce the concentration. As a result, a well owner in the Municipality of Chelsea, Québec is able to readily assess the potential vulnerability of their well from a number of perspectives:

- From a spatial perspective, "what is the probability of contamination for a drilled well in Chelsea?" Based on the collected data for TC and FC, the probability of contamination for a well in Chelsea is 33% for TC and 48% for FC.

- From a seasonal perspective, "during which seasons is the probability of contamination increased and why?" The probability of TC contamination is at the highest from July to October and relatively minor during the remainder of the year. The probability of FC contamination is high in July and August, decreases in September and peaks in December, February and May. Overall, the contamination risk for the Municipality of Chelsea is characterized as: high during summer and fall, which result from seasonal recharge from rainfall events; moderate during the spring, which may depend on the presence of a source and the timing and length of snowmelt; and low during the remaining months of the year. However, minor peaks in the probability of contamination during lower risk periods illustrate that year-round surveillance of water quality should be maintained.

- From a site-specific perspective, "what characteristics of my residence and well increase the probability of contamination?" Wells exhibiting a mixed-water type generally show greater probabilities of TC and FC contamination, but the probability of contamination also depends on seasonal variation. Based on the physical features at the site, the probability of TC contamination in a well is influenced by the drainage towards the well, the water level and the proximity to a surface water body; whereas the well age, the proximity to a surface water body and a domestic animal on-site affect the probability of FC contamination. The combination of site-specific characteristics (physical characteristics at the site only) provides additional and useful information for well owners to better understand the probabilities of contamination and how the risk is influenced. The probability of FC contamination generally increases when two or more significant factors classified mostly as a source are combined, however, the probability does not necessarily increases when two or more pathway component are combined.

The probabilistic vulnerability assessment shows the characteristics that increase the risk of TC and FC contamination in private water wells and their respective component in the source-pathway-receptor concept (Table 5.1). Interestingly, the failure in the source is mainly indicated by FC contamination whereas a failure in the pathway is indicated by TC contamination. For example, the proximity to a surface water body and the presence of a domestic animal on-site are classified in the source component and increase the risk of contamination. Sources of TC are generally associated with soil, vegetation or insects and are more abundant compared to sources of FC which are generally from, manure spreading, septic effluents and the presence of wildlife (Conboy and Goss, 1999; Macler and Merkle, 2000). The potential for a source of TC at the surface is high, and thus, TC are an adequate indicator of a failure in the pathway (or receptor) component. Certain components of the pathway (e.g. water level and drainage towards the well) are found to significantly affect the risk of TC contamination, but require the presence of a source in addition to a relatively low potential of dilution at the receptor. Assessing the influence of the receptor component represents a challenge since it difficult to quantify the potential of dilution or the impact of remedial mitigation from the well owners. The only receptor variable considered in this study is the well age, which provides an indication of the general maintenance of the well itself. The importance of this last variable was surprising because younger wells have higher probability of contamination. This may indicate that other variables, such as drainage towards the well, are dominant controls on domestic well contamination in the study area. The combination of site characteristics also helps the well owner to identify which component of the source-pathway-receptor concept is the most applicable to their site.

Knowing if the contamination is resulting from a failure in the pathway only or in the source may help well owner to take appropriate action in order mitigate contamination. The combination of significant factors demonstrates that the number of potential sources in the proximity of a well increase the probability of FC contamination, whereas the presence of more than one pathway does not necessarily increase the risk. Homeowners have a control on some of these sources such the presence of a domestic animal on-site. To mitigate the impact of the animal (domestic or wildlife), a fence may be installed around and uphill the well to limit the animal access. Rapid recharge is an important contributor to microbial contamination in the study area (Chapter 4). Although the annular space of a well may act

as a pathway, the presence of natural preferential pathways may have a greater influence on the risk of contamination in the study area. This component is harder to mitigate to reduce the probability of contamination, but a homeowner may perform year-round surveillance of the water quality, especially during summer and fall, to reduce the impact on human health.

The use of a Poisson distribution in this simple fashion to assess well vulnerability has not been previously documented in the literature. Recently, Poisson-based models, such as Poisson regressions have been used by Francisque et al. (2009) to explain and predict heterotrophic bacteria count in water distribution system; and were successfully used by Montenegro et al. (2009) to understand spatial and temporal variability in citizen complaints concerning water quality. The potential of Poisson regression techniques was not assessed in this current research and further assessment on the use of Poisson-based model in the context of well vulnerability assessment is recommended. Additional data on well contamination that incorporate a greater number of wells and a longer time frame are needed to rigorously test the applicability of the Poisson distribution.

The Municipality of Chelsea is a suitable study area to further develop this assessment tool. In 2003, a volunteer based-water surveillance program was initiated in the Municipality which has resulted in the creation of a comprehensive database to assist in the proper management and decision-making process with regards to the sustainability of its groundwater resources (H_2O Chelsea, 2010). Most residents of Chelsea are already aware of the importance of protecting their well water quality and some regularly test their water through the H_2O Chelsea program. Thus, it would be feasible for the Municipality, with the help of their residents, to gather more information on the site-specific characteristics of private wells over the Municipality through the distribution of a short questionnaire with the sampling bottles. This will improve the H_2O database and provide additional information to assist in the further clarification of significant factors that contribute to contamination in the study area. A larger dataset may provide additional information on significant factors influencing microbial contamination in the Municipality; and the implementation of the significant factors with logistic regression and GIS techniques for instance, may allow the construction of probability maps to determine specific areas at greater risk of contamination. Although the developed model would be specific to the Municipality, the modeling methodology may be used for any rural Municipality for which valid information on coliform bacteria is available.

5.8. Conclusions

The proposed vulnerability assessment model is designed to highlight various factors that influence the groundwater quality in Chelsea, Québec, where the fractures in the crystalline bedrock combined with variable overburden thickness increase the potential for rapid recharge. Preliminary work on the applicability of a Poisson distribution in well vulnerability assessment demonstrates that is possible to predict probabilities of TC and FC contamination in residential wells in the study area.

The overall probability of contamination for a well in Chelsea is 33% for TC and 48% for FC. The distribution is also applicable to assess vulnerability at different periods during the year (i.e. snowmelt and summer recharge) and the effect of site-specific characteristics. The probability of contamination is higher (and close to 1) from July to October (TC) and in July and August (FC) which illustrates that drilled wells in the study area are subject to rapid recharge from preferential pathways. Well characterized with mixed-water type show greater probability of contamination compared to wells with a Ca-HCO_3 water type. Wells characterized in the Na-HCO_3 water type exhibit higher probability of contamination during the summer period compared to the remainder of the sampling period. Irrespective of the water type, probability of contamination is generally higher during late summer and fall, when recharge occurs.

The probability of TC contamination in a well is influenced by the presence of site characteristics such as the drainage towards the well, the water level, the presence of grout in the annular space and the proximity to a surface water body. The well age, the proximity to a surface water body and a domestic animal affect the probability of FC contamination. Furthermore, the combination of these significant factors shows that drainage towards the well, the proximity to a water body and the presence of an on-site domestic animal appear to increase the probability of well vulnerability to TC or FC contamination in the study area.

The presence of two or more sources in proximity to a well increases significantly the probability of FC contamination, whereas the presence of two or more pathways does not necessarily increase the risk. Well owners have the potential to control the presence of some sources and should concentrate their mitigation actions towards this component. Since controlling the impact of natural recharge pathway is challenging, year round surveillance of the water quality is recommended with a particular awareness during summer and fall seasons.

The application of a Poisson distribution in this simple manner to assess well vulnerability has not been previously documented in the literature and more comprehensive studies, with a greater number of contaminated wells are required to fully determine its potential utility for these types of studies. The findings from this research may be used as a guideline for more detailed analyses, such as sensitivity tests of the Poisson distribution or the applicability of Poisson regression model for the study area.

With the results from this study quantified in terms of probability, the model may help residential owners answer simple questions they have regarding spatial, seasonal or site-specific characteristics, which potentially increase the risk of microbial contamination in their drilled well. The assessment of vulnerability of domestic wells in Chelsea, Québec, assists in the source water protection component of a multi-barrier approach (CCME, 2004) which may assist individual well owners to take actions to protect the water quality of their well.

Chapter 6: Thesis summary

Groundwater is an important source of water for Canada as 30% of its inhabitants depend on it for household usage (Environment Canada, 2010a). In the rural Municipality of Chelsea, Québec (Canada), groundwater is critical because it is the primary source of water for most of the residences. In most Canadian provinces, responsibility for the monitoring of private water supplies for microbes and chemicals resides with the user since there are no regulations for the monitoring of water quality in domestic wells. Consequently, little is known on the proportion of wells that do not follow the jurisdiction guidelines. This lack of regulation makes local private water supplies vulnerable to microbial contamination since rural residents are often unaware that water quality may change over time.

The majority of the residences in Chelsea draw their water from private, drilled wells, in crystalline bedrock aquifers with variable thickness of overburden. These types of aquifers are vulnerable to contamination because flow in the bedrock is controlled primarily by preferential flow paths through fracture networks (Boutt et al., 2010); and the rate of recharge is influenced by the thickness and the hydraulic conductivity of the overburden (Gleeson et al., 2009). These characteristics offer low potential for attenuation, and given the activation of preferential pathways during a storm, rapid recharge may occur, which may allow spreading of the surficial contaminant over wide areas (Cey et al., 2006). Preferential pathways are found in the bedrock aquifer and in the overburden; but also may be the product of poor well construction, if the well annular space is not properly sealed with impermeable material such as concrete or bentonite. The privately owned wells in the study area are characterized by both natural and anthropogenic features that increase their vulnerability to surficial contaminants if a source is located in the proximity of the well.

There is an overall paucity of comprehensive investigations in the Municipality of Chelsea, and consequently, a need to better understand the processes controlling the groundwater chemistry and evolution, and the impact of anthropogenic activities on the groundwater system. The three main goals of this research are to: 1) develop a practical method that allows the detection of faulty well seals and to characterize their importance as preferential pathways; 2) spatially and temporally characterize the groundwater quality in Chelsea over a 14 month period, and assess the importance of physical factors, including the role of faulty well seals, in the microbial contamination of domestic wells in the Municipality; and 3) educate the residents of Chelsea on the risk associated with microbial

contamination in their well through the development of a vulnerability model that integrates spatial, temporal and site-specific controls on contamination in the Municipality of Chelsea.

The actual extent of well seal problems are not well documented because there has been no practical method of testing the integrity of the surface seal, and as a result the relative importance of a faulty well seal as a preferential pathway is poorly understood. This research presents such a method for detecting faulty well seals using a comparison of near-surface vertical hydraulic conductivity (K) measurements and the injection of a sodium chloride solution at the wellhead. The K values obtained from single-ring infiltrometers around the well and in its surroundings are compared statistically using single factor ANOVA. In addition an estimate of the time of travel (TOT) from ground surface to the well is calculated using the K value at the well and then compared to the measured TOT, obtained from the tracer arrival time. The applicability of the faulty seal detection method was tested in three different geological settings across Canada (Hobbema, Alberta; Lindsay, Ontario and Chelsea, Québec). The method was successful at detecting faulty well seals in different geological settings, however, it appears to work best where local geological heterogeneity is minimal and where the surficial geology is composed of fine-grained sediments.

Alternate scenarios were considered in order to assess the relative importance of the well construction (presence of a preferential path in the annular space) compared to the local characteristics with respect to the infiltration of runoff water. The impact from the well construction is greater than the local characteristics of the geological system when a faulty seal is inferred from significantly higher K measurements at the well. In the cases where the K values were statistically significantly higher, the tracer was detected in the well water column within a short period of time, which demonstrates the presence of a preferential pathway through the annular space. However, when there is no significant difference between the well and the surrounding K, a tracer test was necessary to evaluate the possible connection between the surface and the well water. If the tracer test demonstrated a hydraulic connection through the annular space, it is concluded that the well construction and the local characteristics are equally important contributors to contamination from the infiltration of surface water. The ability of the technique to detect a proper seal was not tested because there are no wells in this study where the K value at the well is significantly smaller than the K values in the surrounding area. Further research is needed to test the technique for the detection of sound well seals. The faulty seal detection method was

subsequently employed in the Municipality of Chelsea in order to assess the importance of faulty well seals in contamination events as part of a larger study in the area to understand the pathways and the factors that influence the composition of the water in domestic wells.

The results of the spatial investigation on the presence of coliform bacteria in well water suggests that although there is a relatively low level of agricultural activities in the area, sources of bacterial contamination exist near the wells. The results also demonstrate that residences located in proximity to one another may experience a different microbial water quality than their neighbour. The variable "drainage towards the well" is shown to correlate with increased vulnerability of wells to surface water infiltration, but preferential pathways must be present near the wellhead for rapid infiltration to occur. The effect of seasonal variations on bacterial contamination events was not considered in the spatial analysis, which may explain why no strong significant factors were found to influence the presence of TC and FC in domestic wells in Chelsea.

Hydrogeochemical facies of the Chelsea area were classified with a Piper diagram. Groundwater type vary broadly from Ca-HCO_3, Na-HCO_3 or mixed cations-HCO_3 type to Ca (or mixed cations)-Cl or Ca-mixed anions, with Ca-HCO_3 as the predominant water type. The spatial distribution of hydrogeochemical facies suggests that the groundwater composition is affected by water-rock interactions processes, the confining aquifer conditions and anthropogenic activities. As water infiltrates in preferential recharge areas (higher elevations), it dissolves carbonates present in the thin layer of till overlying the bedrock. The groundwater evolves from a Ca-HCO_3 towards a Na-HCO_3 facies as it flows from unconfined to confined aquifers and appears to also be influenced by the Na-Ca cation-exchange process. Generally, concentrations of HCO_3^-, Cl^- and SO_4^{2-} increase from recharge areas to discharge areas near the Gatineau River. Increases in these concentrations are attributed mainly to water-rock interaction processes such as weathering, but also to anthropogenic activities such as septic effluents. The influence of anthropogenic activities may also explain why the mixed groundwater facies are observed in areas where residences are clustered.

Monthly microbial analysis results show that although some wells are characterized by good water quality, and consistently free of contamination, others are frequently contaminated. Total (TC) and faecal (FC) coliforms also display seasonal trends with most wells exhibiting a strong response to summer/autumnal recharge, with others affected by

snowmelt recharge. Variables related to infiltration of runoff water (i.e. thickness of the overburden and the presence of grout in the annular space), and other site-specific variables, such as the water level and the well age, also affect the incidence of coliform bacteria during the summer and fall recharge.

Seasonal variations are observed in the water chemistry and are linked to the presence of coliform bacteria in the wells. Specific periods (spring recharge, summer baseflow, fall recharge and winter baseflow) are defined to categorize the observed variations in ionic strength values. Some wells exhibit strong seasonal variations whereas others show little seasonal variation. The wells that display the most variability in water chemistry generally show a higher relative frequency of contamination. From the integration of ionic concentration and microbial data, wells are categorized to explain the seasonal response in the water composition. Seasonal association between water chemistry and bacterial concentration indicates that the source of coliform bacteria may result from diffuse infiltration and not from preferential recharge pathways. Deviations from seasonal trends are interpreted to reflect either rapid recharge from preferential pathways or contributions from anthropogenic sources. Seasonal variability in both coliform bacteria and ionic concentrations not only demonstrate seasonal variations in sources of coliform bacteria, but also in the magnitude and direction of the flow field. Unfortunately, the unique attributes of the wells, the complexity of bedrock geology, the presence of septic systems and the multiple origins for most ions make it difficult to isolate the primary spatial and seasonal influences on the presence of coliform bacteria and ionic chemistry.

Two multivariate statistical techniques, principal components analysis (PCA) and hierarchical cluster analysis (HCA) were performed in an attempt to better elucidate the factors that control the hydrodynamic evolution and the quality of the groundwater. Both PCA and HCA were first performed using the yearly dataset and then, subdivided into two seasonally classified datasets based on the occurrence of TC: high risk months (July to December 2008) and low risk months (remainder of study period). As coliform bacteria may give indication on water residence times, the integration of microbial data into the multivariate analysis is key towards the identification of local factors that affect water quality such as rapid infiltration through preferential pathways. For the Chelsea dataset, the PCA supplies information regarding the large-scale processes that affect groundwater whereas the HCA allows for more distinction between regional and local factors. The discrepancy in the results from the comparison analysis of high and low risk months further demonstrates

how seasonal variability in groundwater quality is the combined effect from variations in the flow field and in the loading of bacteria. It is only through the integration of both the chemical and bacterial data that a more complete picture of the factors affecting the groundwater quality is obtained.

The findings from the spatial and seasonal analysis are translated into probabilities in order to quantify the risk associated with the factors that influence groundwater quality. Using the Poisson distribution and the average bacterial count rates, probabilities of exceeding guideline values were calculated under different scenarios. The purpose of this work is to help residential owners in Chelsea to answer simple questions they may have regarding spatial, seasonal or site-specific characteristics that increase potentially the risk of microbial contamination in their drilled well. Overall, the probability of contamination (i.e. of exceeding provincial guidelines) for a well in Chelsea is 33% for TC and 48% for FC. The seasonal assessment shows that the probability of contamination is higher generally during late summer and fall, when recharge occurs. This suggests that drilled wells in the study area are subject to rapid recharge from activated preferential pathways. The water type is also an indicator of the risk of contamination as wells characterized with Na-HCO_3 and mixed-water type show greater probability of contamination, especially during summer and fall. The risk of TC contamination also increases with the presence of some site characteristics such as the drainage towards the well, the water level and proximity to a surface water body. The well age, proximity to a surface water body and the presence of domestic animals are also found to increase the probability of FC contamination. Furthermore, the combination of the significant contributing factors shows that drainage towards the well, the proximity to a water body and the presence of an on-site domestic animal further increase the vulnerability of wells in the study area TC and FC contamination. A key finding from this assessment is that the combination of more than one source of contamination in proximity to a well increases significantly the probability of FC contamination, whereas the presence of more than one pathway does not necessarily increase the probability of contamination.

From a well owner's perspective, this research shows that it is a combination of factors such as local well characteristics and climatic events that control the occurrence of TC and FC in the study area, although, the dominant factor varies for each well. Communication to local well owners of the role played by key factors in the source-pathway-receptor concept towards their overall water quality is important because residents are able

to control and mitigate the risk of contamination from these factors (i.e. presence of domestic animals, application of road salts near a well and faulty well seal). Residents should be informed that microbial water quality changes over time, and they should be encouraged to increase the frequency of testing of their well water during summer and fall, especially after storm events. The simple probabilistic model proposed will help small municipalities to promote the importance of local groundwater monitoring and more importantly, to effectively communicate with well owners about their well construction, the uniqueness of the local characteristics and the period of the year when it may be more prone to contamination.

One of the primary objectives of this research was to assess the role of a faulty seal as a significant factor affecting the water quality of domestic water wells (Chapter 2). The limited dataset (a total of twelve wells with nine characterized by a faulty seal) makes it a challenge to fully assess its role in surface water infiltration. Future work could include well drillers, municipalities or conservation authorities conducting the faulty seal detection technique to collect more information on a greater dataset of wells. These data combined with measurements fo indicator variables such as coliform bacteria and nitrate would assist in the further assessment of the role of faulty seals on contamination. In a similar fashion, increasing the size of the well database with a greater range in physical or chemical features (e.g. surface vs. drilled wells, wells with known septic contamination vs. clean wells) may provide more definitive results in identifying the spatial and seasonal factors affecting microbial contamination in Chelsea, Québec and increase the robustness of the multivariate analyses (Chapters 3 and 4). And finally, the application of logistic regression rather than the Poisson distribution (Chapter 5) on the dataset presented in this dissertation may provide a better method to predict the probability of contamination in the Municipality of Chelsea, Québec.

References

Aelion, C.M. and Conte, B.C., 2004. Susceptibility of residential wells to VOC and nitrate contamination. Environmental Science & Technology, 38(6): 1648-1653.

Alberta Geological Survey, 2002. Quaternary Geology of Central Alberta – Deposits V.2. Digital Data. DIG 2007-0018, Edmonton, Alberta, Canada. http://www.ags.gov.ab.ca/publications/DIG/ZIP/DIG_2007_0018.zip

Aller, L., T. Bennett, J. Lehr, R. Petty, and G. Hackett. 1987. DRASTIC: A standardized system for evaluating ground water pollution potential using hydrogeologic settings. EPA-600/2-87-035. Ada, Oklahoma: National Water Well Association.

Amini, M. et al., 2008. Statistical modeling of global geogenic arsenic contamination in groundwater. Environmental Science & Technology, 42(10): 3669-3675.

Appelo, C. and Postma, D., 2005. Introduction to Groundwater Geochemistry, Geochemistry, Groundwater and Pollution, Second Edition. Taylor & Francis.

Arthur J.D, Wood, A.R., Baker, A.E., Cichon, J.R. and Raines, G.L., 2007. Development and Implementation of a Bayesian-based Aquifer Vulnerability Assessment in Florida. Natural Resources Research, 16(2).

Ayraud, V. et al., 2006. Physical, biogeochemical and isotopic processes related to heterogeneity of a shallow crystalline rock aquifer. Biogeochemistry, 81(3): 331-347.

Ayraud, V. et al., 2008. Compartmentalization of physical and chemical properties in hard-rock aquifers deduced from chemical and groundwater age analyses. Applied Geochemistry, 23(9): 2686-2707.

Bailey G. 2007, Personal interview, June 7, Lindsay, Ontario.

Barrett, M.H. et al., 1999. Marker species for identifying urban groundwater recharge sources: A review and case study in Nottingham, UK. Water Research, 33(14): 3083-3097.

Bester, M.L., Frind, E.O., Molson, J.W. and Rudolph, D.L., 2006. Priority substances list assessment report: Road salts. Ground Water, 44(2): 165-175.

Bonham-Carter, G., 1994. Geographic information systems for geoscientists : modelling with GIS. New York : Pergamon, 1994

Boutt, D.F., Diggins, P. and Mabee, S., 2010. A field study (Massachusetts, USA) of the factors controlling the depth of groundwater flow systems in crystalline fractured-rock terrain. Hydrogeology Journal, 18(8): 1839-1854.

CCME (Canadian Council of Ministers of the Environment), 2004. From source to tap: Guidance on the multi-barrier approach to safe drinking water. Winnipeg: CCME

Cey, E., Rudolph, D. and Therrien, R., 2005. Dynamics of groundwater recharge through structured soils and the influence on water quality. In: N.R. Thomson (Editor), Bringing Groundwater Quality Research to the Watershed Scale. Iahs Publication, pp. 89-96.

Cey, E., Rudolph, D. and Therrien, R., 2006. Simulation of groundwater recharge dynamics in partially saturated fractured soils incorporating spatially variable fracture apertures. Water Resources Research, 42(9).

Cey, E.E., Rudolph, D.L. and Passmore, J., 2009. Influence of macroporosity on preferential solute and colloid transport in unsaturated field soils. Journal of Contaminant Hydrology, 107(1-2): 45-57.

Chapuis, R.P., and D. Chenaf. 1998. Detecting a hydraulic short-circuit along a monitoring well with the recovery curve of a pumping test in a confined aquifer: method and example, *Canadian Geotechnical Journal* 35, no. 5: 790-800.

Chapuis, R.P. and Sabourin, L., 1989. Effects of Installation of Piezometers and Wells on Groundwater Characteristics and Measurements. Canadian Geotechnical Journal, 26(4): 604-613.

Charrois, J.W.A., 2010. Private drinking water supplies: challenges for public health. Canadian Medical Association Journal, 182(10): 1061-1064.

Chesnaux, R., and R.P. Chapuis. 2007. Detecting and Quantifying Leakage Through Defective Borehole Seals: A new Methodology and Laboratory Verification, *Geotechnical Testing Journal* 30 no 1: 17-24

Chesnaux, R., R.P. Chapuis, and J.W Molson. 2006. A New Method to Characterize Hydraulic Short-Circuit in Defective Borehole Seals, *Ground Water* 44, no. 5: 676-681.

Clark I. and Fritz P., 1997. Environmental Isotopes in Hydrogeology. Lewis Publisher. New York

Corkal, D., Schutzman, W.C. and Hilliard, C.R., 2004. Rural water safety from the source to the on-farm tap. Journal of Toxicology and Environmental Health-Part a-Current Issues, 67(20-22): 1619-1642.

Cloutier, V., Lefebvre, R., Savard, M.M., Bourque, E. and Therrien, R., 2006. Hydrogeochemistry and groundwater origin of the Basses-Laurentides sedimentary rock aquifer system, St. Lawrence lowlands, Quebec, Canada. Hydrogeology Journal, 14(4): 573-590.

Cloutier, V., Lefebvre, R., Therrien, R. and Savard, M.M., 2008. Multivariate statistical analysis of geochemical data as indicative of the hydrogeochemical evolution of groundwater in a sedimentary rock aquifer system. Journal of Hydrology, 353(3-4): 294-313.

Cloutier, V., Lefebvre, R., Savard, M.M. and Therrien, R., 2010. Desalination of a sedimentary rock aquifer system invaded by Pleistocene Champlain Sea water and processes controlling groundwater geochemistry. Environmental Earth Sciences, 59(5): 977-994.

Conboy, M.J. and Goss, M.J., 1999. Contamination of rural drinking water wells by fecal origin bacteria - Survey findings. Water Quality Research Journal of Canada, 34(2): 281-303.

Conboy, M.J. and Goss, M.J., 2000. Natural protection of groundwater against bacteria of fecal origin. Journal of Contaminant Hydrology, 43(1): 1-24.

Conboy M.J. and Smith S., 2005. Well Wise: A comprehensive consumer's guide for private wells. ISBN 0-9780387-0-3

Davis John, C., 2002. Statistics and data analysis in geology. New York : Chichester : Wiley, c2002 3rd ed. 638 p

Detre, K. and White, C., 1970. Comparison of 2 Poisson-Distributed Observations. Biometrics, 26(4): 851-&.

Dunnivant, F.M., I. Porro, C. Bishop, J. Hubbel, J.R Giles, and M.E Newman. 1997. Verifying the Integrity of Annular and Back-Filled Seals for Vandose-Zone Monitoring Wells, *Ground Water* 35, no. 1: 140-148

Edmunds, W.M., Shand, P., Hart, P. and Ward, R.S., 2003. The natural (baseline) quality of groundwater: a UK pilot study. Science of the Total Environment, 310(1-3): 25-35.

Einarson, M.D. and Mackay, D.M., 2001. Predicting impacts of groundwater contamination. Environmental Science & Technology, 35(3): 66A-73A.

Environment Canada (a) 2010 Groudwater website, (accessed November 5th 2010) http://www.ec.gc.ca/eau-water/default.asp?lang=En&n=300688DC-1

Environment Canada (b) 2010. Daily Data for 2003 to 2009. National Climate Weather and Data Information Archive. From http://www.climate.weatheroffice.gc.ca [Accessed June, 2010]

Ermineskin Tribal Enterprises, 2005. Long Term Water Supply Study. Final Report prepared by *ISL group*, Edmonton Alberta.

Focazio, M.J., T.E. Reilly, M.G. Rupert, and D.R. Helsel. 2002. Assessing ground-water vulnerability to contamination: Providing scientifically defensible information for decision makers. USGS Circular 1224. Reston, Virginia: USGS.

Fowler Jim, J.P., Cohen Louis , 1998. Practical statistics for field biology. Chichester ; New York : Wiley, 2nd ed. 259 p

Francisque, A., Rodriguez, M.J., Miranda-Moreno, L.F., Sadiq, R. and Proulx, F., 2009. Modeling of heterotrophic bacteria counts in a water distribution system. Water Research, 43(4): 1075-1087.

Freeze, A.R., and J.A. Cherry. 1979. *Groundwater*. Prentice Hall.

Frind, E.O., Molson, J.W. and Rudolph, D.L., 2006. Well vulnerability: A quantitative approach for source water protection. Ground Water, 44(5): 732-742.

Fulton, R.J., compiler 1995: Surficial materials of Canada, Geological Survey of Canada, Map 1880A, scale 1:5000000

Gaillardet, J., Dupre, B., Louvat, P. and Allegre, C.J., 1999. Global silicate weathering and CO2 consumption rates deduced from the chemistry of large rivers. Chemical Geology, 159(1-4): 3-30.

Geological Survey of Canada 2008. Urban Geology of the National Capital Area. Online data. http://gsc.nrcan.gc.ca/urbgeo/natcap/geoserv_e.php [Accessed June 2009]

Gibbons, R.D., 1987. Statistical-Models for the Analysis of Volatile Organic-Compounds in Waste-Disposal Sites. Ground Water, 25(5): 572-580.

Glanville, T.D., J.L. Baker, and J.K Newman. 1998. Evaluation of Methods for Diagnosing Contamination in Rural Wells, *Transaction of the ASAE* 41, no. 6: 1625-1633.

Gleeson, T., Novakowski, K. and Kyser, T.K., 2009. Extremely rapid and localized recharge to a fractured rock aquifer. Journal of Hydrology, 376(3-4): 496-509

Gogu, R.C. and Dassargues, A., 2000. Current trends and future challenges in groundwater vulnerability assessment using overlay and index methods. Environmental Geology, 39(6): 549-559.

Gogu, R.C., V. Hallet, and A. Dassargues. 2003. Comparison of aquifer vulnerability assessment techniques. Application to the Neblon River basin (Belgium). Environmental Geology 44, no. 8: 881–892.

Golder Associates Ltd., 1990. Élaboration d'une étude hydrogéologique sur les installations privées, Municipalité de Chelsea, Québec.

Gonzales T. R., 2008. The effects that well depth and wellhead protection have on bacterial contamination of private water well in the Estes Park valley, Colorado. Journal of Environmental Health, 71(5): 17-23

Goss, M.J., Barry, D.A.J. and Wilson, J.B., 1994. A study to identify the seasonal variations in well-water contamination and survey farm family health. Final Report to Agriculture Canada on Project No. 7932.

Goss, M.J., Barry, D.A.J. and Rudolph, D.L., 1998. Contamination in Ontario farmstead domestic wells and its association with agriculture: 1. Results from drinking water wells. Journal of Contaminant Hydrology, 32(3-4): 267-293.

Güler, C., Thyne, G.D., McCray, J.E. and Turner, A.K., 2002. Evaluation of graphical and multivariate statistical methods for classification of water chemistry data. Hydrogeology Journal, 10(4): 455-474.

H2O Chelsea 2010. http://www.h2ochelsea.ca/introduction.htm [Accessed June 2010]

Halim, M.A. et al., 2010. Arsenic in shallow aquifer in the eastern region of Bangladesh: insights from principal component analysis of groundwater compositions. Environmental Monitoring and Assessment, 161(1-4): 453-472.

Hammer, Ø., Harper, D.A.T., and P. D. Ryan, 2001. PAST: Paleontological Statistics Software Package for Education and Data Analysis. Palaeontologia Electronica 4(1): 9pp. http://palaeo-electronica.org/2001_1/past/issue1_01.htm

Haas, C.N. and Heller, B., 1986. Statistics of Enumerating Total Coliforms in Water Samples by Membrane-Filter Procedures. Water Research, 20(4): 525-530.

Helsel Dennis R, H.R.M., 1995. Statistical methods in water resources [electronic resource].

Jalali, M., 2007. Hydrochemical identification of groundwater resources and their changes under the impacts of human activity in the Chah basin in western Iran. Environmental Monitoring and Assessment, 130(1-3): 347-364.

Jiang, Y.J., Wu, Y.X., Groves, C., Yuan, D.X. and Kambesis, P., 2009. Natural and anthropogenic factors affecting the groundwater quality in the Nandong karst underground river system in Yunan, China. Journal of Contaminant Hydrology, 109(1-4): 49-61.

Jiang, Y.J. and Yan, J., 2010. Effects of Land Use on Hydrochemistry and Contamination of Karst Groundwater from Nandong Underground River System, China. Water Air and Soil Pollution, 210(1-4): 123-141.

Jolliffe, I.T., 2002. Principal component analysis New York : Springer. 2nd ed. 487 p

Jones, A.Q. et al., 2006. Public perceptions of drinking water: a postal survey of residents with private water supplies. Bmc Public Health, 6.

Jury, W.A., W.R. Gardner, and W.H Gardner. 1991. *Soil Physics*. 5th ed. New York: John Wiley and Sons.

Korkka-Niemi, K., 2005. Cumulative factors affecting groundwater quality in domestic wells in Finland. In: N.R. Thomson (Editor), Bringing Groundwater Quality Research to the Watershed Scale. Iahs Publication, pp. 19-28.

Kozuskanich, J., Novakowski, K.S. and Anderson, B.C., 2011. Fecal Indicator Bacteria Variability in Samples Pumped from Monitoring Wells. Ground Water, 49(1): 43-52.

Kreutzwiser, R. de Loe, R., Imgrund, K., Conboy, M. J., Simpson, H., Plummer, R., 2011. Understanding stewardship behaviour: Factors facilitating and constraining private water well stewardship. Journal of Environmental Management, 92(4): 1104-1114.

Levison, J. and Novakowski, K., 2009. The impact of cattle pasturing on groundwater quality in bedrock aquifers having minimal overburden. Hydrogeology Journal, 17(3): 559-569.

Litaor, M.I., Brielmann, H., Reichmann, O. and Shenker, M., 2010. Hydrochemical analysis of groundwater using a tree-based model. Journal of Hydrology, 387(3-4): 273-282.

Lutenegger, A.J. and J.D. DeGroot. 1994. Hydraulic Conductivity of Borehole Sealants in *Hydraulic Conductivity and Waste Contaminant Transport in Soil*, ASTM STP 1142. American Society for Testing and Material, Philadelphia, PA, USA

Macler, B.A. and Merkle, J.C., 2000. Current knowledge on groundwater microbial pathogens and their control. Hydrogeology Journal, 8(1): 29-40.

Malard, F., Reygrobellet, J.L. and Soulie, M., 1994. Transport and Retention of Fecal Bacteria at Sewage-Polluted Fractured Rock Sites. Journal of Environmental Quality, 23(6): 1352-1363.

Masetti, M., Poli, S. and Sterlacchini, S., 2005. Acquifer vulnerability assessment using weights of evidence modelling technique: Application to the Province of Milan, Northern Italy. In: Q. Cheng and G. BonhamCarter (Editors), GIS and Spatial Analysis, Vol 1and 2, pp. 499-504.

Mencio, A. and Mas-Pla, J., 2008. Assessment by multivariate analysis of groundwater-surface water interactions in urbanized Mediterranean streams. Journal of Hydrology, 352(3-4): 355-366.

Meiri, D. 1989. A tracer test for detecting cross-contamination along a monitoring well column. *Groundwater Monitoring Review* 9, no. 2: 78-81

MDDEP 2002. Ministère du développement durable de l'Environnement et des Parcs du Québec. Groundwater Catchment Regulations, Environment Quality Act.

Montenegro, P., Rodriguez, M.J., Miranda, L., Joerin, F. and Proulx, F., 2009. Occurrence of citizen complaints concerning drinking water: a case study in Quebec City. Journal of Water Supply Research and Technology-Aqua, 58(4): 257-266.

Moore, P.J., Martin, J.B. and Screaton, E.J., 2009. Geochemical and statistical evidence of recharge, mixing, and controls on spring discharge in an eogenetic karst aquifer. Journal of Hydrology, 376(3-4): 443-455.

Natural Resources Canada,1997. Geomatics Canada. GeoAccess Division. NATIONAL ATLAS DIGITAL DATA 1:7500000 http://www.geogratis.gc.ca

Natural Resources Canada 2005, Centre for Topographic Information, 031G12. CanMatrix (georeferenced) 1.1. Sherbrooke, Quebec, Canada. http://www.GeoGratis.gc.ca

Natural Resources Canada 2008, Earth Sciences Sector, Mapping Services Branch, Centre for Topographic Information , 031G12. CanVec 1.0. Sherbrooke, Quebec, Canada. http://www.geogratis.gc.ca

Nolan, B.T., 2001. Relating nitrogen sources and aquifer susceptibility to nitrate in shallow ground waters of the United States. Ground Water, 39(2): 290-299.

Nolan, B.T., Hitt, K.J. and Ruddy, B.C., 2002. Probability of nitrate contamination of recently recharged groundwaters in the conterminous United States. Environmental Science & Technology, 36(10): 2138-2145.

Natchem 2010. Canadian National Atmospheric Chemistry Precipitation Database *(July 29th 2010)*. Environment Canada, Meteological Service of Canada, 4905 Dufferin Street, Toronto, Ontario, Canada M3H 5T4 http://www.msc.ec.gc.ca/natchem/precip/index_e.html

Novakowski K., B. Beatty, M.J. Conboy, and J. Lebedin. 2006. Expert Panel Report: Water well sustainability in Ontario. Prepared for the *Ontario Ministry of Environment*, Sustainable Water Well Initiative. Final Report January 2006.

Novakowski, K., Bickerton, G., Lapcevic, P., Voralek, J. and Ross, N., 2006. Measurements of groundwater velocity in discrete rock fractures. Journal of Contaminant Hydrology, 82(1-2): 44-60.

NRC (United States National Research Council). 1993. Ground Water Vulnerability Assessment: Predicting Relative Contamination Potential under conditions of Uncertainty. Washington, D.C.: National Academy Press.

Oliphant, J.A., Ryan, M.C., Chu, A. and Lambert, T.W., 2002. Efficacy of annual bacteria monitoring and shock chlorination in wells finished in a floodplain aquifer. Ground Water Monitoring and Remediation, 22(4): 66-72.

Ontario Ministry of Environment. 1990. (amended 2003) Regulation 903: Ontario' Wells Regulation, *Ontario Water Resources Act.*

Piper, A.M., 1944. A graphic procedure in the geochemical interpretation of water-analyses. Transactions-American Geophysical Union, 25: 914-923.

Pronk, M., Goldscheider, N. and Zopfi, J., 2006. Dynamics and interaction of organic carbon, turbidity and bacteria in a karst aquifer system. Hydrogeology Journal, 14(4): 473-484.

Reid, D.C., Edwards, A.C., Cooper, D., Wilson, E. and McGaw, B.A., 2003. The quality of drinking water from private water supplies in Aberdeenshire, UK. Water Research, 37(2): 245-254.

Reynolds, W. D. 1993. In: Carter, M. R. (ed), *Soil Sampling and Methods of Analysis*, Canadian Society of Soil Science, Lewis Publishers, Ann Arbor, MI, USA.

Reynolds, W. D. 2007. In: Carter, M. R and Gregorich E.G. (ed), *Soil Sampling and Methods of Analysis*, *Second Edition*, Canadian Society of Soil Science, Lewis Publishers, Ann Arbor, MI, USA.

Richardson, H.Y., Nichols, G., Lane, C., Lake, I.R. and Hunter, P.R., 2009. Microbiological surveillance of private water supplies in England - The impact of environmental and climate factors on water quality. Water Research, 43(8): 2159-2168.

Robertson, W. D. Cherry, J. A. Sudicky, E. A. 1991. Groundwater Contamination from 2 Small Septic Systems on Sand Aquifers. Ground Water 29 (1), 82-92.

Rudolph, D.L., Barry, D.A.J. and Goss, M.J., 1998. Contamination in Ontario farmstead domestic wells and its association with agriculture: 2. Results from multilevel monitoring well installations. Journal of Contaminant Hydrology, 32(3-4): 295-311.

Scanlon, B.R., 1989. Physical Controls on Hydrochemical Variability in the Inner Bluegrass Karst Region of Central Kentucky. Ground Water, 27(5): 639-646.

Scanlon, B.R., 1990. Relationships between groundwater contamination and major-ion chemistry in a karst aquifer Journal of Hydrology, 119: 271-291.

Simpson, H., 2004. Promoting the management and protection of private water wells. Journal of Toxicology and Environmental Health-Part a-Current Issues, 67(20-22): 1679-1704.

Singer, S. N, C.K Cheng, and M.G Scafe. 2002. The Hydrogeology of Southern Ontario, Second Edition. Volume 1. Hydrogeology of Ontario Series. Report. Ontario Ministry of the Environment.

Singh, C.K., Shashtri, S. and Mukherjee, S., 2011. Integrating multivariate statistical analysis with GIS for geochemical assessment of groundwater quality in Shiwaliks of Punjab, India. Environmental Earth Sciences, 62(7): 1387-1405.

Snedecor, George W. and William G. Cockran, 1980. Statistical Methods 7th Ed. The Iowa State University press. 507p.

Statistics Canada. 2009. Domestic water use: the relevance of rurality in quantity used and perceived quality. *Rural and Small Town Canada Analysis Bulletin.* Cat. no. 21-006-X, 2009; 7:1-31. Available:www.statcan.gc.ca/bsolc/olc-cel/olc-cel?catno=21-006-X&CHROPG=1&lang=eng (Accessed 2010 Oct. 28)

Statistics Canada; 2007: *Households and the environment*. Ottawa (ON):. Cat. no. 11-526-X:1-102. Available: www.statcan.gc.ca/pub/11-526-x/11-526-x2009001-eng.htm (Accessed 2010 Oct. 28)

S-Plus software (version 8.0). 2008. TIBCO Software Inc.

Sugita, F., Kishii, T. and English, M., 2005. Effects of macropore flow on solute transport in a vadoze zone under repetitive rainfall events. In: N.R. Thomson (Editor), Bringing Groundwater Quality Research to the Watershed Scale. Iahs Publication, pp. 122-129.

Swistock, B.R. and Sharpe, W.E., 2005. The influence of well construction on bacterial contamination of private water wells in Pennsylvania. Journal of Environmental Health, 68(2): 17-22.

Taylor, R., Cronin, A., Pedley, S., Barker, J. and Atkinson, T., 2004. The implications of groundwater velocity variations on microbial transport and wellhead protection - review of field evidence. Fems Microbiology Ecology, 49(1): 17-26.

Tesoriero, A.J. and Voss, F.D., 1997. Predicting the probability of elevated nitrate concentrations in the Puget Sound Basin: Implications for aquifer susceptibility and vulnerability. Ground Water, 35(6): 1029-1039.

Toth, J., 1999. Groundwater as a geologic agent: An overview of the causes, processes, and manifestations. Hydrogeology Journal, 7(1): 1-14.

Toran, L. and White, W.B., 2005. Variation in nitrate and calcium as indicators of recharge pathways in Nolte Spring, PA. Environmental Geology, 48(7): 854-860.

Toran, L., Herman, E.K. and White, W.B., 2007. Comparison of flowpaths to a well and spring in a karst aquifer. Ground Water, 45(3): 281-287.

Twarakavi, N.K.C. and Kaluarachchi, J.J., 2005. Aquifer vulnerability assessment to heavy metals using ordinal logistic regression. Ground Water, 43(2): 200-214.

U.S. EPA. 1993. Guidelines for delineation of wellhead protection areas. EPA-440/5-93-001.

Valdes, D. et al., 2007. A spatial analysis of structural controls on Karst groundwater geochemistry at a regional scale. Journal of Hydrology, 340(3-4): 244-255.

Valenzuela, M. et al., 2009. Fecal Contamination of Groundwater in a Small Rural Dryland Watershed in Central Chile. Chilean Journal of Agricultural Research, 69(2): 235-243.

Vrba, J. and A. Zoporozec, ed. 1994. Guidebook on Mapping Groundwater Vulnerability. International Contributions to Hydrology. Hannover, Germany: H. Heise Publishing.

Wang, Y., Ma, T. and Luo, Z., 2001. Geostatistical and geochemical analysis of surface water leakage into groundwater on a regional scale: a case study in the Liulin karst system, northwestern China. Journal of Hydrology, 246(1-4): 223-234.

Wilcoxon, F., 1945. Individual Comparisons by Ranking Methods. Biometrics Bulletin, 1(6): 80-83.

Winkel, L., Berg, M., Amini, M., Hug, S.J. and Johnson, C.A., 2008. Predicting groundwater arsenic contamination in Southeast Asia from surface parameters. Nature Geoscience, 1(8): 536-542.

Worrall, F. and Besien, T., 2005. The vulnerability of groundwater to pesticide contamination estimated directly from observations of presence or absence in wells. Journal of Hydrology, 303(1-4): 92-107.

Yesiller, N., B.E. Tuncer, C.H. Benson. 1997. Ultrasonic Method for Evaluation of Annular Seals for Well and Instrument Holes, *Geotechnical Testing Journal* 20, no 1: 17-28.

Yidana, S.M. and Yidana, A., 2010. Assessing water quality using water quality index and multivariate analysis. Environmental Earth Sciences, 59(7): 1461-1473.

Zhang, R., Hamerlink, J.D., Gloss, S.P., Munn, L., 1996. Determination of non-point source pollution using GIS and numerical models. J. Environ. Qual. 25, 411–418.

Zimmerman, T., Zimmerman, M. and Lindsey, B. 2001. Relation Between Selected Well-Construction Characteristics and Occurrence of Bacteria in Private Household-Supply Wells, South-Central and Southeastern Pennsylvania. U.S. Geological Survey Water Resources Investigations Report 01-4206.

Appendices

Appendix A: Well Seals Integrity: Pilot Project

Well Seal Integrity Study: Pilot Project

Final Report



December 29, 2006

Report Prepared for:

First Nations and Inuit Health Branch (FNIHB), Health Canada

Report prepared by:

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Summary

The purpose of the pilot project was to test a methodology developed at the University of Ottawa to detect faulty well seals. Four domestic wells were evaluated on the Hobbema Reserve (Cree Nations) in Alberta. The results of the research are presented in this report.

Faulty well seals and improper well abandonment are believed to be a threat to groundwater because they offer direct pathways for surface contaminants, particularly pathogens, to enter the groundwater system. The well seal is the material that fills-in the space between the well casing and the surrounding geological material. In most provinces, well drillers must now use a sealing material that will not allow infiltration; but it was common practice in the past to backfill the space with the drill cuttings, or other nearby materials. As a result older seals are not very effective. Some new well seals can also be faulty because of improper placement.

The hypothesis of this study was that a faulty seal can be detected by statistically comparing the vertical hydraulic conductivity (K) at the well to the K in the vicinity. A series of steady-state, single-ring infiltrometer measurements were carried out and the resulting K values were used to infer possibly faulty seals. Since the seal should have a lower K value, a K value at the well that was greater than in the surrounding area was inferred to indicate a strong possibly faulty seal; and a K value similar to the surroundings was inferred as moderate evidence for a faulty seal. A tracer solution of NaCl was used to confirm the results; the tracer results were conclusive in all four of the pilot sites. This methodology appears extremely promising for detecting faulty seals at ground surface. The next phase of this research will be to continue the development of a retrofitting technique and to test the results with the technique tested in this project. This will have the potential to eradicate contamination problems at the source, rather that relying on water treatment techniques (which are often bypassed in First Nations households). Consequently, these developments have the potential to increase the quality of life for people on domestic wells and in particular for remote communities that depend on groundwater as a source of potable water.

Purpose and Scope

The purpose of this pilot project is to evaluate a methodology developed at the University of Ottawa for detecting faulty well seals of domestic wells. Dr. Michel J.L. Robin and PhD candidate, Pascale St-Germain, at the University of Ottawa, were mandated to evaluate the status of the seal of four wells on the Hobbema Reserve (Cree Nations), which is located between Red Deer and Edmonton, Alberta. The results of the research are presented in this report.

Background

Surface water and groundwater are the source of drinking water for Canadian First Nations, and for a number of Health Canada Facilities across Canada. Contamination of water supplies by harmful pathogens is a chronic problem: In the period from December 2005 to November 2006, 74 boiling water advisories have been issues for First Nation communities (COC, 2006). This number does not include the number of drinking-water advisories for households relying on domestic wells as their source of drinking water. Advisories are often issued as a precaution and the percentage of wells that are actually contaminated by pathogens is not known. The number of advisories is, nevertheless, an indication of chronic contamination problems. Contamination of a groundwater supply by pathogens can take place in a number of ways, but the main cause is thought to be via direct pathways from the surface to the aquifer.

Direct pathways are problematic because they allow rapid movement of contaminants to deep groundwater systems without the filtering benefits of the soil. The most obvious candidate for a direct pathway is along the well casing of poorly sealed wells (the casing is the steel pipe, usually around 15 cm in diameter, that extends from the aquifer to ground surface).

The well seal in an integral part of well construction, which was commonly neglected in past water-well drilling practices. During well construction, the annular space between the surrounding geologic material and the well casing must be sealed with a low permeability material. If the casing is not properly sealed, a preferential flow path can be created along the casing, thereby enhancing the transport of surface waters to the aquifer system. Even when properly installed during construction, seals tend to deteriorate over time, again providing a preferential flow path for surface water. Surface water is an issue because it often contains bacteria that are harmful to people. “The importance of applying an adequate seal was not always understood” (e.g. MOE, 2006). Figure 1 illustrates the difference between an efficient seal and faulty seal. The efficient seal forces the infiltrating water

through the surrounding soil allowing time for contaminant breakdown; whereas the faulty seal allows the surface water to enter directly into the well at the bottom of the casing. As mentioned earlier, providing a diagnostic method to detect poorly sealed wells is the purpose of this work.

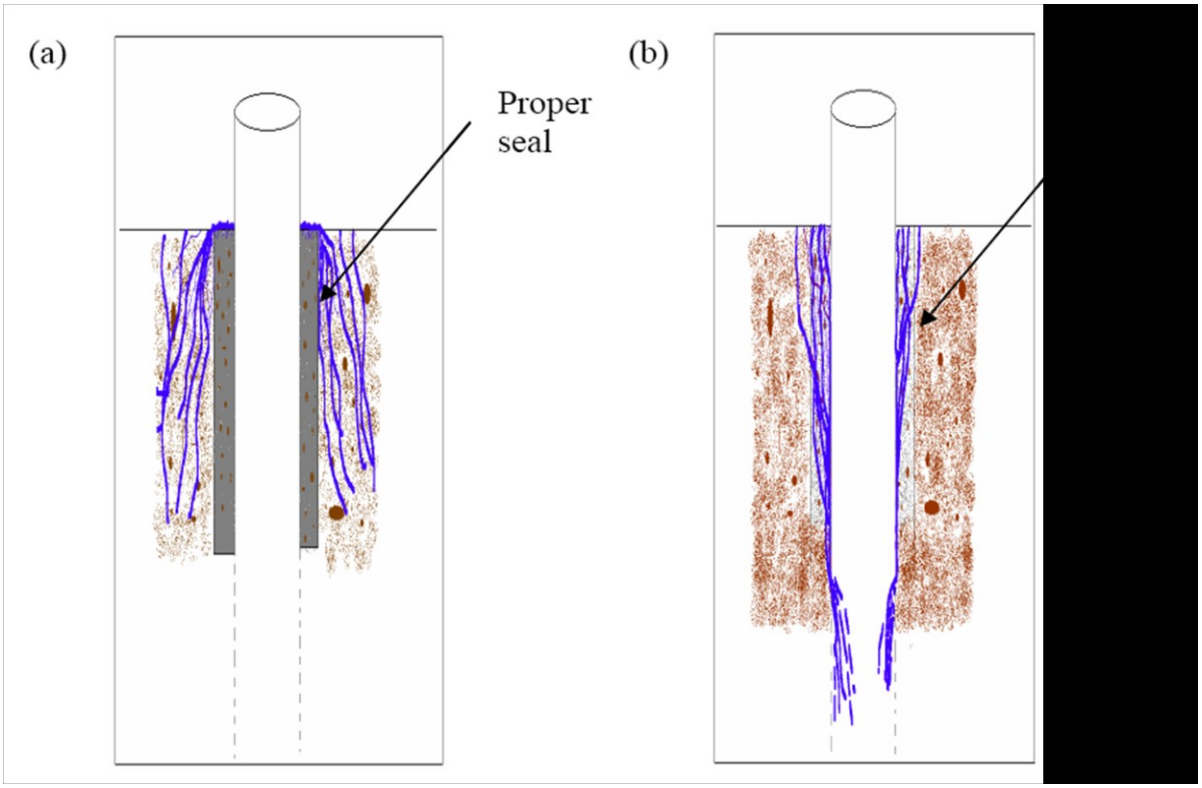


Figure 1: Schematic diagram of a well with a proper seal (a) showing infiltration water percolating through the soil; and a faulty seal (b) showing surface water flowing along the casing.

Study sites

The study took place on land managed by the Ermineskin Band, the second largest of four First Nations bands on the Hobbema Reserve between Edmonton and Red Deer, Alberta. There are approximately 405 water wells on the Ermineskin lands. In this pilot study, four sites were examined; three of the four sites were private wells and the other was located near Pigeon Lake, at the Ermineskin Health Center, a building managed by the First Nation and Inuit Health Branch of Health Canada. A description specific to each site is given in the Results section. Figure 2 shows the relative location of each study well.

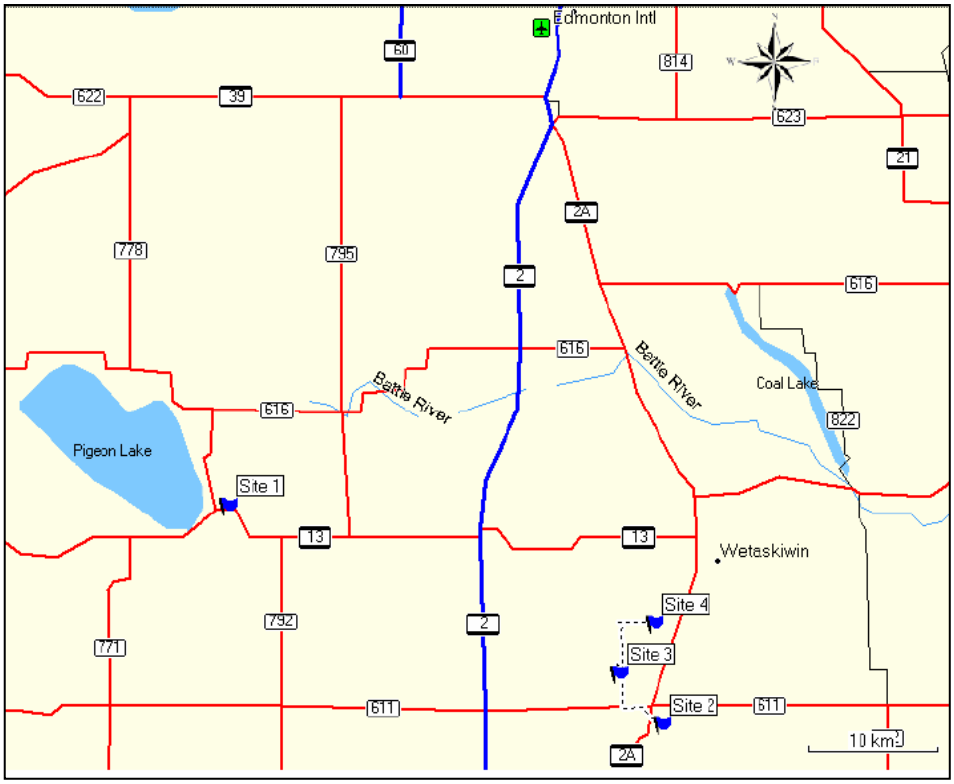


Figure 2: Map showing the locations of the four study sites, South of Edmonton, Alberta

Methodology

The procedure for testing seal integrity is actually fairly simple and safe. It consists in measuring the ease with which water can infiltrate the soil, which is described by a parameter called the vertical hydraulic conductivity (K). The hydraulic conductivity is measured on the land near the well and compared statistically to the hydraulic conductivity around the well casing. The hydraulic conductivity is measured by a simple instrument called a single ring infiltrometer. The technique is described in detail by Reynolds et *al*. (1993). Briefly, the method consists of inserting a cylinder (the infiltrometer ring) into the soil and measuring the rate at which water infiltrates while maintaining a constant water level inside the cylinder. Figure 3 illustrates the procedure. The infiltration rate typically increases and reaches a "steady-state" rate, when it no-longer changes in time. The mathematical formulae described by Reynolds et *al*. (1993) can then be used to calculate the vertical hydraulic conductivity, based on the infiltration rate at steady-state and on the geometry of the system. A statistical procedure called ANOVA is then used to decide if the K measured on the adjacent land is greater than the K measured at the well casing. If the K measured at the well is greater than or equal to the K on the adjacent land, then the well seal is possibly faulty.

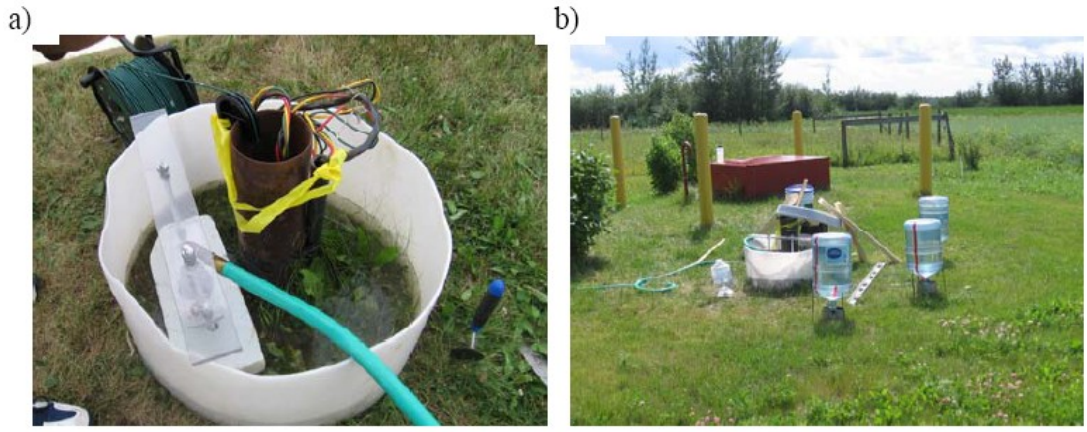


Figure 3: a) Large ring infiltrometer at the well showing the float-valve system used to maintain the water level constant; and b) small ring infiltrometers in the vicinity of the well using Mariotte siphons to maintain the water levels constant.

A tracer test was used to verify the infiltration technique for detecting faulty seals. For the tracer test, water from the well was spiked with table salt (NaCl) and used in the infiltrometer at the well. Salty water can easily be detected with an electrical conductivity (EC) probe, so a recording EC probe was used to measure the EC all along the water column in the well before, and at various times following the infiltration test. A change in the EC of the water in the well confirmed that the well seal was faulty.

Results and Discussion

Site 1: Pigeon Lake, Health Center (Health Canada building)

The infiltration tests at Pigeon Lake were done from July 28 to July 30th 2006. A follow up, to monitor the tracer arrival, was done every day following the infiltration test until August 12, 2006. The hydraulic conductivity value at the well (1.0×10^{-5} m/s) was significantly higher than elsewhere at this site (3.7×10^{-6} m/s), by a factor of approximately 3, indicating a faulty seal.

For the tracer test, a total of 380 L of tracer solution was infiltrated at the well. The EC profiles along the water column in the well are shown in Figure 4. The horizontal axis gives the EC values and the vertical axis the depth from the ground surface. The level of water in the well is indicated by a line and an upside down triangle. The initial EC profile is left-most on the figure. Arrival of the tracer is manifested by a shift of the EC profile to the right at day 8 (EC profiles for days 2 to 7 were omitted for clarity). Shifting continues until day 12 and begins to revert back the original profile by day 15.

At the end of day 8 (August 4th) the EC probe malfunctioned and was replaced on day 12. No reading could be made over that period. The probes (old and new) were duly calibrated every day against a standard solution, and it is therefore unlikely that shifts in EC of the magnitude observed could be accounted by the use of a different probe; but the switch may nevertheless have induced a small discrepancy. Figure 4 clearly indicates that surface water infiltrates readily into the well since the shift in EC occurred while the old probe was still functioning.

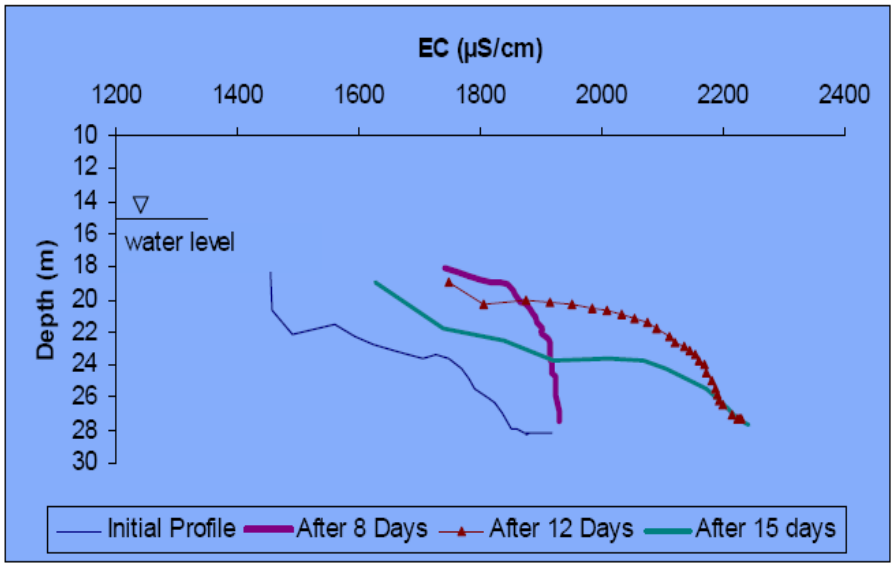


Figure 4: Electric conductivity (EC) as a function of depth

Conclusions and Recommendations for Site 1, Pigeon Lake

The infiltration tests show that the well seal was compromised, which was also corroborated by the tracer test. The presence of a clear and direct pathway for surface water to enter the well make it vulnerable to wet periods of the year such as snowmelt in the spring or prolonged periods of rain. This also explains the chronic recurrent bacterial contamination problems in this well. It is highly recommended that this well not be used for drinking water or any other activity where bacterial contamination may be a problem (e.g. making coffee, brushing teeth, washing hands for medical purposes, etc). This well is a good candidate for a resealing technique presently being developed at the University of Ottawa.

Site 2: Ermineskin, house # 220

The infiltration tests at house #220 were done on July 31st, 2006. A follow up, to monitor the tracer arrival, was done every day following the infiltration test until August 12, 2006. At this site the

hydraulic conductivity value at the well was approximately the same as in the surrounding area (around 3.0 x 10^{-5} m/s), giving mild evidence of a faulty seal. However, as it is shown on figure 5, the tracer reached the well in 6 to 10 days after the injection of the tracer. No monitoring could be done between days 6 and 10 because of a defective EC probe. The large amount of variability at this site reduced the statistical resolution of the test (i.e. the ability to detect a difference if there is one), pointing to the need for more infiltration tests. Because of the large number of tests to be performed, the infiltrometers used in the vicinity of the well are smaller – providing results in a shorter time and with less water. As a result, the tests only represent the hydraulic conductivity in the near surface, in contrast to the larger ring infiltrometer, which produce measurements that extend much deeper, because of the large volumes of water infiltrated. The difference between infiltrometers was found to be negligible at other sites in Québec, but it could explain the large variability at this site. Another plausible explanation for the lack of difference in the K values is that the tracer might be able to reach the aquifer at the same rate if the tracer test were to be performed away from the well. To verify these hypotheses is not feasible at this time as it would require additional tests at the site.

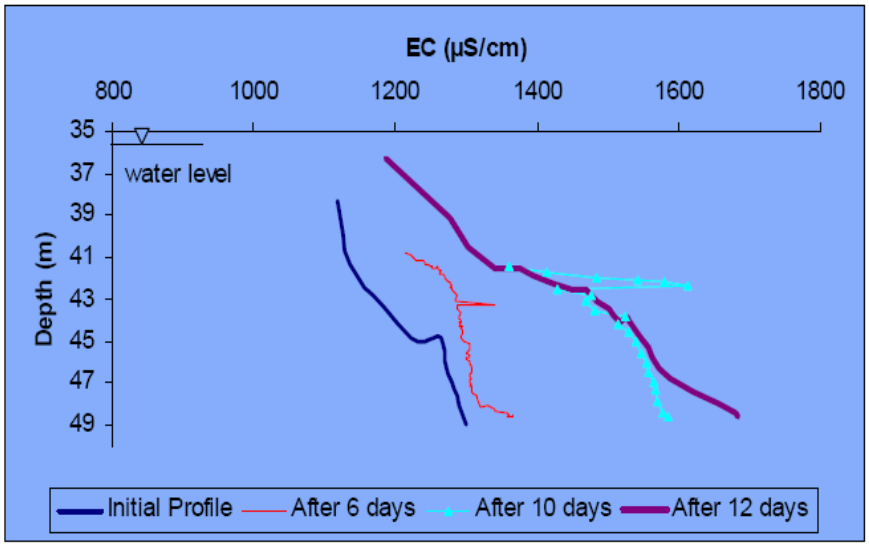


Figure 5: Electric Conductivity (EC) as a Function of depth

Conclusions and Recommendations for Site 2, House #220

The infiltrometer tests showed mild evidence of a faulty seal at this site but the tracer reached the well within 10 days, which indicated the possible presence of a defect in the seal, or that the soil will allow infiltration to 30 m in less than 10 days (which is somewhat unlikely). This well is less

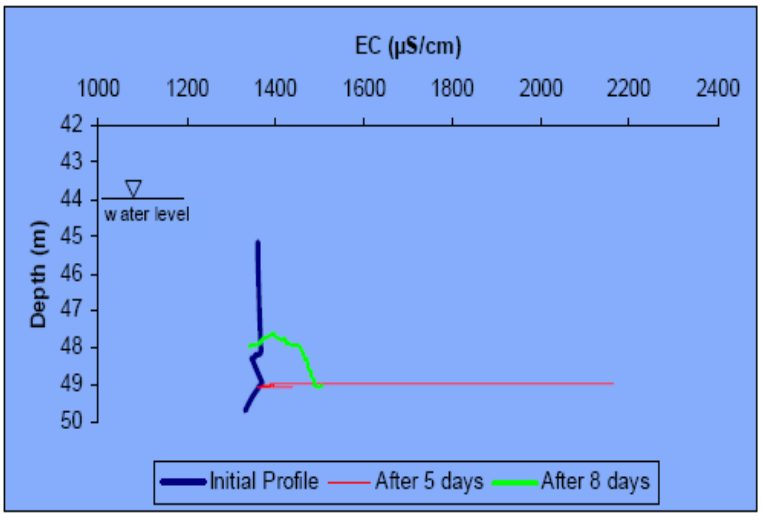
susceptible to surface water contamination because of the great depth to the water level in the well (which is assumed to correspond to the water table). Thus the geological formation around the well might offer a sufficient barrier to contamination. However the well could get contaminated from very large infiltration events (such as spring melt waters or large rainfall events). The well has not shown contamination in the past, but little is known of its past history and of the proximity of contamination sources. Since the well is not use as a drinking water source for human, only horses, it is of no risk to human health unless its use is changed, and then it would be considered a risk.

Site 3: Ermineskin house # 304

The infiltration tests at this location were done on August 1st, 2006. A follow up, to monitor the tracer arrival, was done every day following the infiltration test until August 12, 2006. The infiltration tests showed that the K value at the well (7.0×10^{-5} m/s) was twice as high as in the vicinity (3.5×10^{-5} m/s), but this difference could not be shown to be significant because of the large variability. Again this constitutes mild evidence for a faulty seal. Figure 6(a) shows the initial EC profile and at days 5 and 8 after the tracer infiltration. The figure shows that the tracer arrived in the well in less than 5 days. The large EC peak at a depth of 49 m on day 5 prompted us to monitor the EC at that depth over approximately 10 minutes. The results, in Figure 6(b), show short spikes of EC, typical of unstable flow carrying tracer into the well.

Considering the depth to the water level in the well (assumed to be the level of the water table), a tracer travel time of 5 days is a clear indication of a faulty well seal or an extremely high hydraulic conductivity in the area.

a)



b)

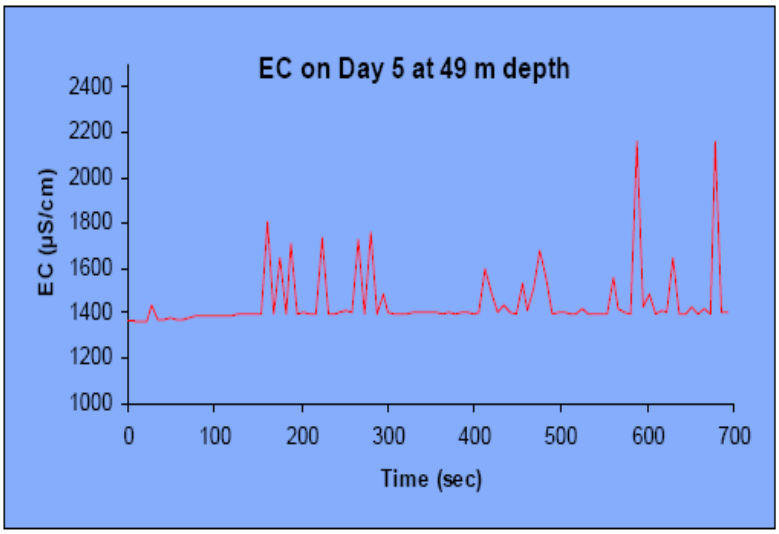


Figure 6: Electric Conductivity (EC) as a function of a) depth, b) time for the profile after 5 days at depth = 49 m.

Conclusions and recommendations for Site 3, House # 304

The infiltration tests gave mild evidence for a faulty seal, but the tracer test corroborated the results with strong evidence. With the proximity of contamination sources and a likely faulty seal, this well can be a threat to human health if water is drank directly, without treatment. But since this well is not used because of contamination and supply issues, the associated risk is small. It is important to mention, however, that the well may be a significant threat to groundwater quality in that area, because it could act as a direct pathway from surface water to enter the aquifer without natural

filtration or attenuation. This well is a good candidate for further testing of the diagnostic methodology and for testing a resealing technique presently being developed at the University of Ottawa. Once this work is done the well should be decommissioned properly, with sealant inside and out of the casing to avoid contaminating the aquifer.

Site 4: Ermineskin, house # 141

The infiltration tests at house 141 were done on August 3 and 4th, 2006. A follow up, to monitor the tracer arrival, was done every day following the infiltration test until August 12, 2006. There was no significant difference between the K values in vicinity of the well and the K values at the well (both around 2.5 x 10^{-5} m/s); giving mild evidence of a faulty seal. The tracer test results, in Figure 7, show that the tracer reached the well in less than 6 days. Because of EC probe malfunction, no monitoring was done between 2 and 6 days after the injection of the tracer (the probe was replaced on Day 7 and, as was discussed above, the impact of replacing the probe is believed to be negligible).

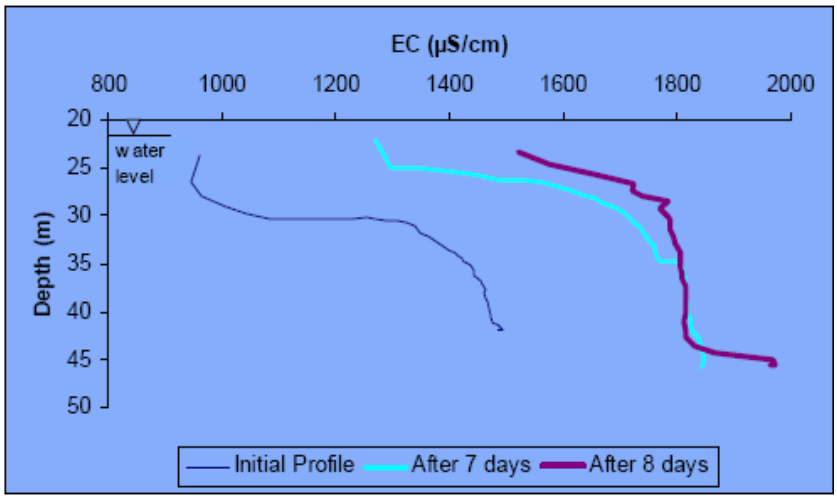


Figure 7: Electric Conductivity (EC) as a Function of depth

Conclusions and recommendations for Site 4, House # 141

Here again, the infiltration tests gave mild evidence for a faulty seal, but the tracer test corroborated the results with strong evidence. Since the casing of this well extended only about 10 cm above the ground, recommendations were made directly to the home owner to have the casing extend. The well is used as a drinking water source for a family with young children. The water from this well should not be used for drinking without disinfection. The well is a good candidate for further testing of the diagnostic methodology and for testing a resealing technique presently being developed at the

University of Ottawa.

Conclusions

It is argued in the literature that "a seal should have a K lower than the native soil" (Lutenegger and DeGroot, 1994). The infiltration tests showed that faulty or inexistent seals could be inferred at all sites: At the Pigeon Lake the K values were much higher at the well than in the surrounding area, which were quite low; but at the Ermineskin sites the K values were relatively high everywhere. The conclusion is therefore that the infiltration technique alone may be sufficient to detect a faulty seal. The technique offers the advantage that it is simple, cost effective and requires limited know-how. The technique can be verified with tracer tests, but more specialized equipment is required (EC probe). All sites showed tracer arrival in the well in a matter of days, indicating that the wells were at risk of surface water contamination (because of the short residence times). Since there were no site with K values smaller at the well than in the surrounding areas the ability of the technique to detect good seals could not be tested. The large variability at the Ermineskin sites reduced the statistical resolution, which made statistical inference more difficult. This can be fixed in future sites by increasing the number of infiltration measurements. Another difficulty at the Ermineskin sites is likely the result of the great depth to the water table (> 25 m): surface measurements of hydraulic conductivity may simply not be a good representation of the hydraulic conductivity at those depths.

The tracer technique that was used to verify the infiltration methodology turned out to be very successful at detecting rapid pathways to the well, which we infer to be the result of faulty seals. It is important to point out, however, that rapid pathways may exist even in the presence of an effective seal: surficial geology and preferential pathways in the proximity of the well may be responsible for bacterial contamination in the well. Testing this hypothesis will be the subject of further work.

Recommendations for well owners:
(1) Owners at all four sites should refrain from using their well water for drinking water purposes (including cooking and hygiene). The rapid tracer movement to the wells indicated that all sites are vulnerable to surface water contamination. The well water may be free of bacterial contamination for part of the year, but it is likely to be contaminated after large infiltration events, such as spring melt and heavy rainfalls.

(2) Leakage problems at the wells pit-less adaptors cannot be ruled out, however, because of the tracer arrival times, the leakage is more likely due to an improper or inexistent seal around the casing. Therefore replacing the pit-less adapter is not likely to be the solution.

(3) All wells are good candidates for retrofitting (resealing) using a technique being developed at the University of Ottawa.

(4) Boil water advisories should be issued as a precaution any time there is a large infiltration event in a territory.

(5) Water sampling should take place after large infiltration events (e.g. spring melt).

Recommendations for future work:

(6) Both the infiltration and the tracer technique should be used simultaneously to detect faulty seals when possible.

(7) The well seal testing methodology is easy to perform and programs could be created to teach the methodology locally to senior high school students.

(8) A down-hole camera should be used to inspect the casing and determine the exact length of the casing. The lack of knowledge about the well construction geometry (length of casing, screen length, etc) was a major impediment in this pilot study. The use of a down-hole camera would allow us to inspect the casing and casing welds, and pinpoint the exact length of the casing.

(9) A tracer test should also be done beside the well to determine if the rapid pathway is through the formation itself or through the well seal.

(10) Development of a retrofitting (resealing) technique should be completed and tested as soon as possible. Testing should be complemented with the seal-detection technique and with the excavation of retrofitted seals.

(11) A detailed cost analysis of the retrofitting technique should be made (preliminary estimates

indicate that the technique could be 10 to 80 times cheaper than drilling a new well, depending on the depth of the new well).
(12) Suspected faulty seals should be repaired and retested to see if the method can detect effective seals.

(13) The detection and resealing techniques should be tested in a number of geological settings across the country.

Importance for First Nations

- The vast majority of First Nation people depend on groundwater for drinking water. On the Hobbema reserve alone, there are approximately 2,540 water wells (ISL report, 2005). It is likely that the majority of these wells are not maintained adequately, and that the wells are poorly sealed because of their age. These wells may be at risk for contamination by surface water.
- Water treatment is the last barrier to contamination. It is well known that water treatment systems on First Nation territories have not been very successful in the long run, mostly because of the specialized knowledge required. Consequently, contamination prevention, possibly through proper well seals, becomes paramount.
- The resealing technique being developed at the University of Ottawa has the potential to eliminate the problems caused by leaky well seals, and possibly eliminate the contamination problem all together. The resealing technique has tremendous potential, considering the magnitude of the problem, the inconvenience, the current costs of maintaining the present water systems, and most importantly the potential harm that can come to people.

Acknowledgments

This pilot project was funded by the First Nations and Inuit Health Branch of Health Canada. Special thanks to Mudher Al-Khafaji for his indispensable field assistance during the summer 2006. Also thanks to Joan Yee and Skattar Sandhu (Health Canada) for logistical help in Alberta. Thanks to Verona Omeasoo for the field assistance and to the First Nations People of the Hobbema Region for their hospitality.

References

Council of Canadian web site, visited Nov 29, 2006
http://www.canadians.org/water/issues/policy/index.html

Ermineskin Tribal Enterprises, 2005. Long Term Water Supply Study. Final Report prepared by ISL group, Edmonton Alberta.

Indian and Northern Affairs Website, visited on November 29, 2006
http://www.ainc-inac.gc.ca/nr/prs/m a2003/02304bk_e.html

Lutenegger, A.J., J.D. DeGroot., "Hydraulic Conductivity of Borehole Sealants" in Hydraulic Conductivity and Waste Contaminant Transport in Soil, ASTM STP 1142. American Society for Testing and Material, Philadelphia, 1994

Reynolds W.D. from "Soil Sampling and Methods of Analysis" 1993, M.R Carter for Canadian Society of Soil Sciences, Lewis, Chapter 56 p 605-611.

Appendix B: Faulty well seal detection at Fleming College, Lindsay, Ontario

Introduction

The faulty seal detection method was tested on six representative wells at the Sir Sandford Fleming College in Lindsay, Ontario. This college has a drilling training program and wells are drilled for educational instruction. There were two main goals for the 2007 field season: 1) further develop the faulty seal detection method; and 2) to develop a retrofitting technique to repair a well where a seal integrity problem occurred. This location was chosen because of the accessibility to the wells and their proximity to each other. Also, it is possible to obtain information on the characteristics of the annular space (cutting and properly grouted). Lastly, because these wells are not used for drinking water consumption, it is an ideal site to test the grout injection method which aims to recreate an efficient seal in the annular space.

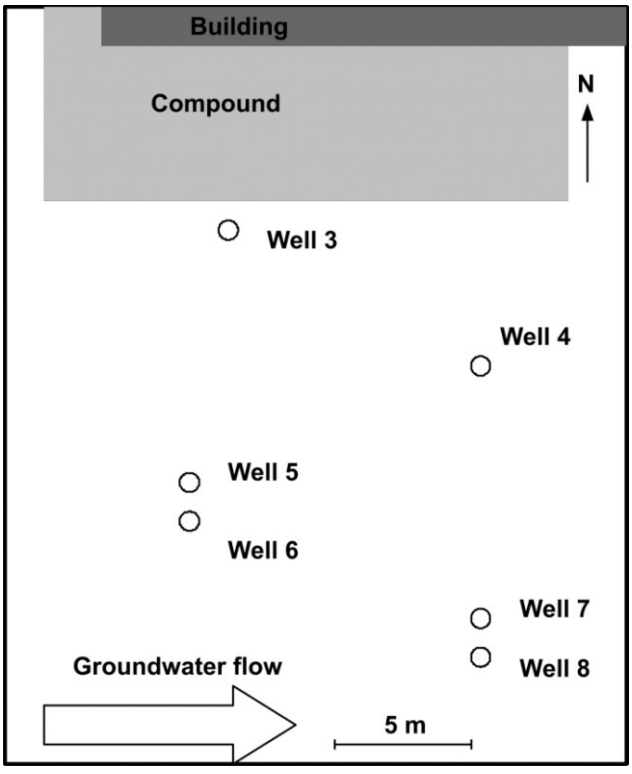


Figure B1: Map of the Fleming College test-site with the location of the wells.

Study site

From June to August 2007, fieldwork was conducted on the Fleming College property in Lindsay, Ontario. The surficial geology of the first 5 m consists of compact till, mainly composed of clay and silt. Underlying the till, dissolved limestone is found from 5 to 6 m. The water table is located at a depth of approximately 5 m below the surface. Groundwater is flowing from northwest to southeast, towards the Scugog River.

Methods

Faulty seal detection

Six representative wells were used to further develop the faulty seal detection method. At each well-site, a small ring infiltrometer test was carried out. The location of the small ring around the well was randomly chosen. The purpose of doing these small ring tests is to verify if a faulty seal is detected by testing only one area of the annular space while being more water efficient. A large ring infiltration test was performed at three of the six well-sites (W4, W6 and W8). At these well-sites, the small ring test potentially detected a faulty seal. Small ring infiltration tests were also carried out at sixteen locations in the surrounding area of the well. Two small ring tests were rejected because water leaks occurred around the ring.

Retrofitting technique

Three wells (W4, W6 and W8) were used to develop the retrofitting method. The method consists of the injection of grout using a high pressure grout injection pump and attempting to fill void space left by an improper seal. At each well-site, steel rods were inserted at two locations into the annular space using a hammer (Jackhammer or 2-handle hammer). The steel rods each have a length of 6 feet and screw together from inside tread. The rods were inserted one at a time until the appropriate depth was reached. The depth of insertion varied at each well, but an attempt was made to insert the rods to the depth of the casing shoe. The exact depth for each well-site is provided in Table B1. The pump is attached to the steel rod by a proper connector. The pump pushes the grout into the

annular space through the rods. The rods were slowly lifted (few cm/sec) using a manual jack. The sealant material is mixed and placed into the pump reservoir.

Calculations determined the amounts of cement, bentonite, and water required to create the proper ratios for our grouting mixture. The calculations are provided by the Fleming College Drilling and Blasting Program reference material (Fleming College sealing wells for Ontario well technicians, 2005). Three different mixtures have been used for the injection.

- Cement mixture: Portland Cement only

  Mixing directions: base on manufacturer's specifications: 18.5 L of water per 88.1 lb bag

- Bentonite (20% by weight, Ontario Regulation 903 acceptable solids ratio) : Baroid Quick-grout is (Granular sodium-based bentonite grout)

  To obtained a 20% solid grout: 91 L of water is required for every 50 lbs of bentonite pellets

- Cement-Bentonite (20% by weight of bentonite, 5% bentonite by weight of cement slurry)

Example of calculations:

20% by weight of bentonite

Fill volume	100 L			
20% by weight bentonite slurry (Using Quick-Grout)				
Volume Yield	=	1.98	L of slurry /lb of bentonite	
	=	4.39	L of slurry/kg of bentonite	
Specific gravity	=	2.6	kg/L	
Specification for 20% by weight (91L of water required per 50lb sack)	=	4.01	L of water/kg of bentonite	
Required kg of bentonite	=	22.79	kg	(=Volume needed/Volume yield)
Required water	=	91.38	L	(kg of bento*amount of water required per kg)

Cement-Bentonite mixture (20% bentonite by weight, 5% by weight of cement)

for 100L of cement slurry

Volume Yield	=	31.04	L of slurry/40 kg bag
	=	0.78	L of slurry per kg of cement
density	=	4.12	lbs/L
density	=	1.87	kg/L
mixing ratio of cement		4.749326	lb of dry cement/L of water

(18.55L of water required per 88.1lb sack)

for 100L	283.85	lbs of cement required
	59.76737	L of water required

For 5% dry bentonite by weight of mixture

kg of bento = 5%*density of cement slurry
= 0.05*1.87kg/L

for 1L=	0.09	kg bento	
=	0.38	L water	(4.009L per kg of dry bento)
For 100L=	9.37	kg bento	
=	37.55	L water	

***Add these amounts to the 100L of the cement slurry

Validation of the technique

To verify the efficiency of the proposed retrofitting technique, an infiltration test was conducted and the difference between the before and after hydraulic conductivity was statistically compared. A tracer (NaCl) was also injected to detect hydraulic connection. The infiltration test follow the same procedure as described in Chapter 2.

Complete details on the amount of grout injected at each well, depth of insertion and hydraulic conductivity measurement are given in the “Result from infiltration and tracer tests” section.

Results-Infiltration and tracer tests (summary)

Well information, infiltration test data and tracer results are summarized in Tables B1 and B2. Electrical conductivity figures showing the tracer monitoring and tracer test analysis are grouped by individual tests performed at each well.

Table B1: individual site characteristics and tracer test description.

Well#		Well age (yrs)	Well depth (m)	Water level (m)	Annular space material	Casing length (m)	Date	Type of test	Tracer	Tracer EC (µS/cm)	Test duration (hrs)	Total L of water (pre-tracer+tracer+chaser)
3F		7	14	4.5	grouted	6	June 19th 2007	small ring	tap water	500	8	60+40+40
4F	1	8	61	4.5	cuttings	6	July 9th 2007	small ring	tap water	500	8	60+0.3+0
	2						July 12th 2007	large ring	NaCl	12 000	6	360L tracer
	3				well upgrade		August 2nd 2007	large ring	NaCl	12 000	6	180 L of tracer
5F		7	74	4.5	grouted	6	June 23rd 2007	small ring	tap water	500	8	60L+120L
6F	1	6	40	4.5	grouted	6	July 11th 2007	small ring	NaCl	10 000	8	80+40+20
	2						July 16th 2007	large ring	NaCl	11 000	8	380+380 (tracer)
	3				well upgrade		August 1st 2007	large ring	NaCl	13 000	8	190+190+190
7F		15	45	4.5	grouted	6	June 21st 2007	small ring	tap water	500	8	40+1.5+0.5
8F	1	2 months	8	4.5	cuttings	6	July 10th 2007	small ring	tap water	500	8	60+60+40
	2						July 15th 2007	large ring	NaCl	12 300	8	380+380+560
	3				well upgrade		August 3rd 2007	large ring	NaCl	11 000	8	380+380+570

Table B2: Results from infiltration and tracer tests. The verdict indicates if the well seal was classified as faulty (F) or not faulty (NF). TOT refers to time of travel and K to the hydraulic conductivity. The test #3 for W4, W6 and W8 is the infiltration test performed after grout injection.

Well#		K (m/s)	p-value	TOT calculated (hrs)	tracer observed	verdict
3F		3.75E-06	0.75	315	No	NF
4F	1	2.43E-05	0.0007	48.5	possibly	F
	2	1.70E-05	0.01585	67	7 days	F
	3	2.94E-06	0.62	401	??	NF
5F		2.07E-05	0.0035	56	No?	P
6F	1	1.33E-05	0.08	86	Yes?	P
	2	8.21E-06	0.51	144	3 days	F
	3	2.11E-06	0.99	23 days	??	NF
7F		2.08E-07	0.28	5679	Pre-tracer?	F then NF
8F	1	1.64E-05	0.02	72	8hrs	F
	2	2.14E-05	0.002	55	48	F
	3	3.02E-06	0.63	391	??	F

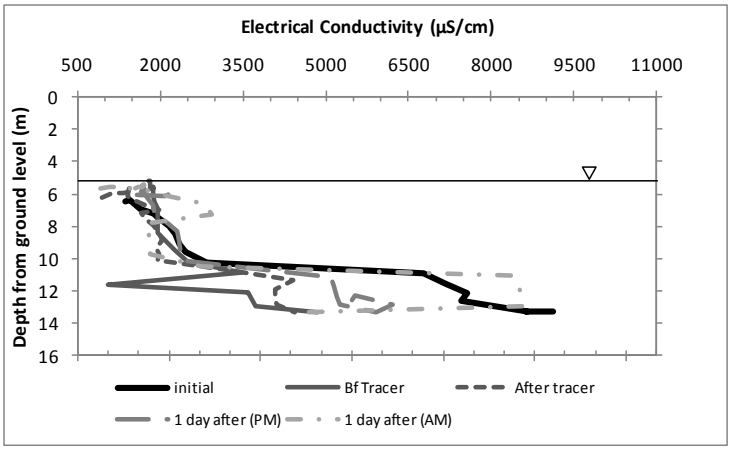
Conclusions from retrofitting method

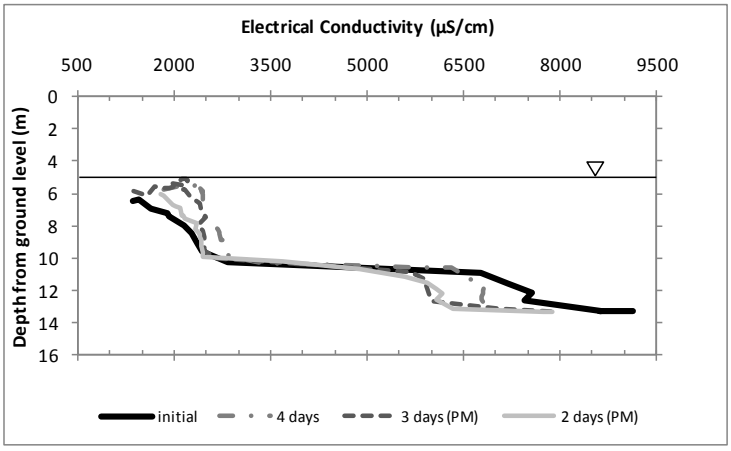
Overall, the grout injection process works well. Injecting the grout at three locations around the well may improve the efficiency and increase the quantity of grout injected. Since these are only preliminary tests, follow-up studies would be required to further refine the method. For example, future work may include excavating the annular space to evaluate the underground distribution of grout because it is difficult to determine if the grout is properly in place or escaped through cracks.

The infiltration tests conducted after the grout injection show that the retrofitting method reduced the hydraulic conductivity at the well. However, the results of the tracer test are inconclusive because of possible mixing between the tracer tests at each well. Since the same tracer have already been injected at the wellhead prior to the upgrade, it is difficult to determine if the tracer detected in the well is from the current tracer test or a previous one.

Result from infiltration and tracer tests-complete dataset

Well 3: Small ring infiltrometer





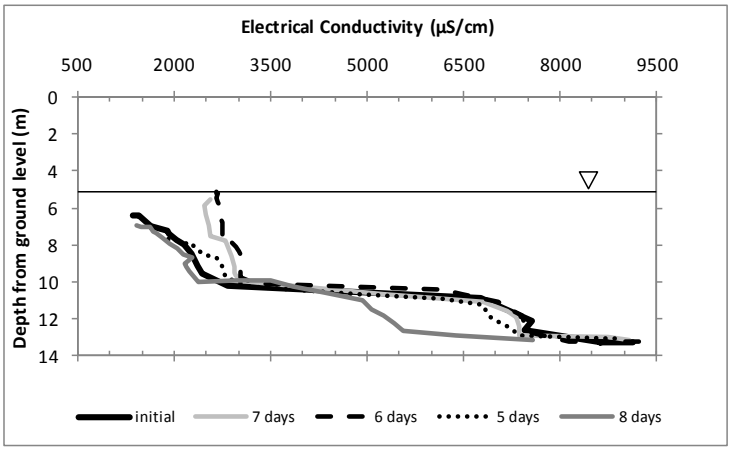
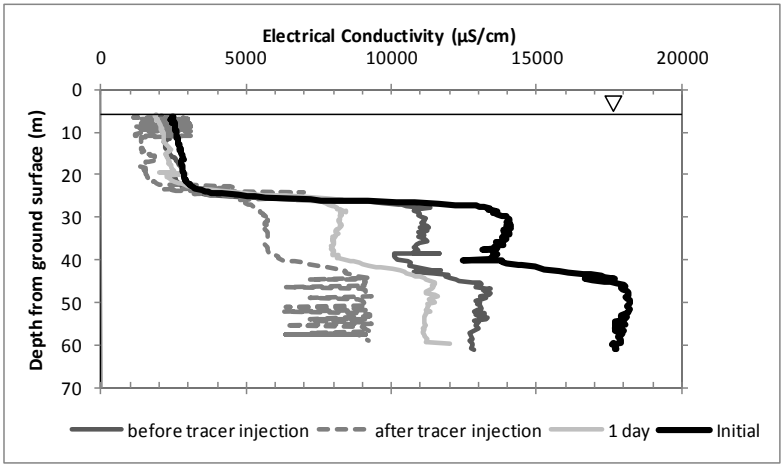


Figure B2: Electrical conductivity of the water column during tracer monitoring at W3. The tracer is not observed during the monitoring period and variations of EC values are interpreted to be the result of various rainfall event.

Well 4: Small ring infiltrometer



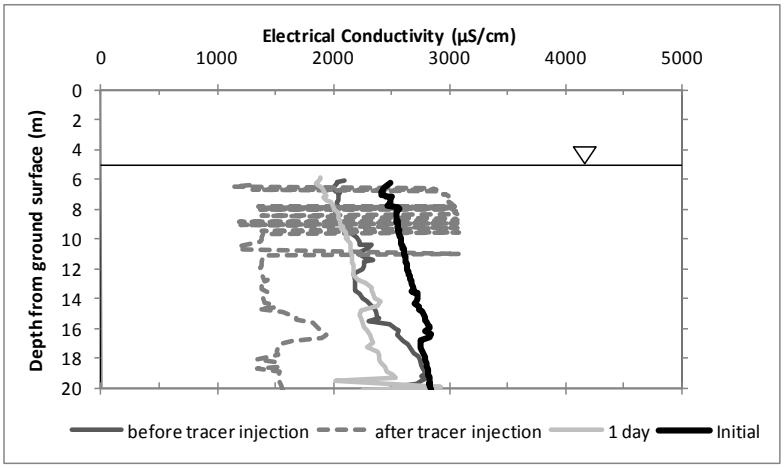


Figure B3: Electrical conductivity of the water column during tracer monitoring at W4, small ring infiltrometer. The tracer is observed shortly after the tracer injection when instabilities in EC values are observed in the first 5 m of the water column.

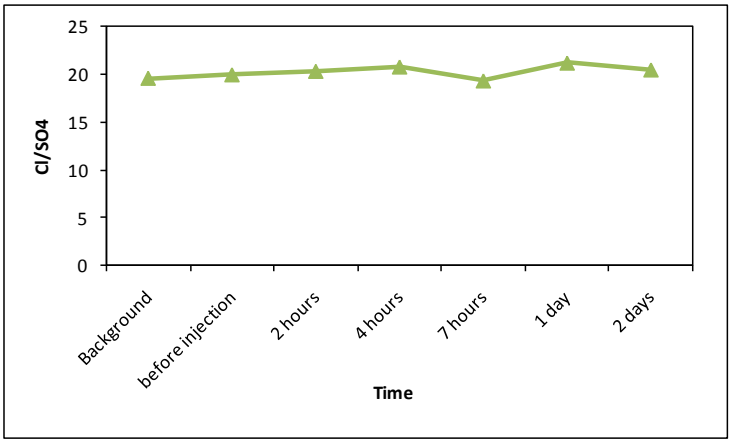
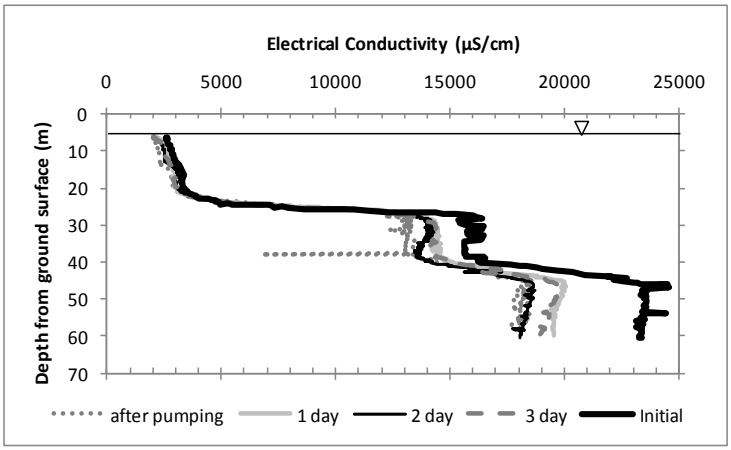
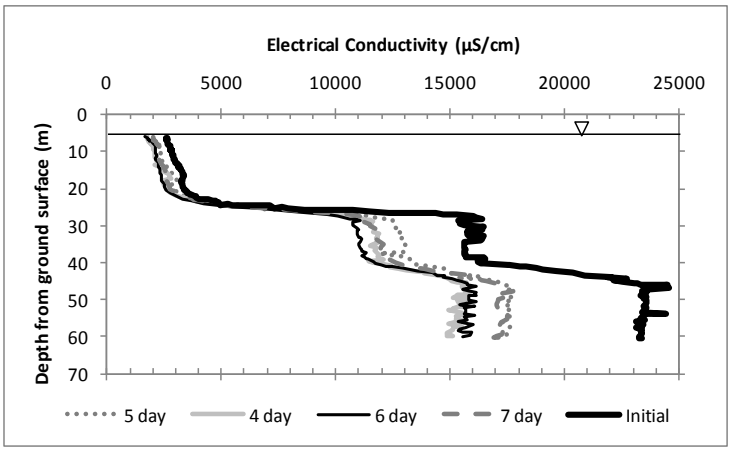
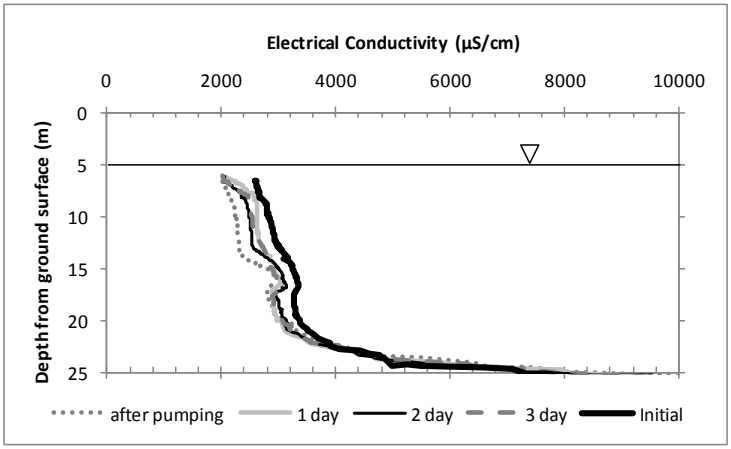


Figure B4: Water chemistry (Cl/SO_4) of the W4 during tracer monitoring.

Well 4: Large ring infiltrometer







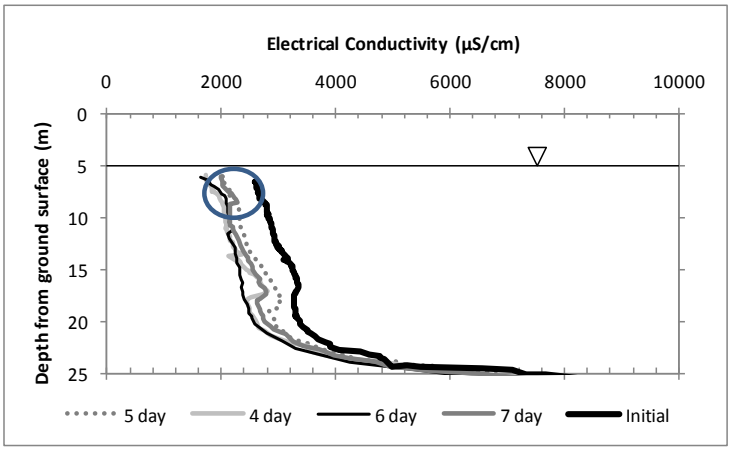


Figure B5: Electrical conductivity of the water column during tracer monitoring at W4, large ring infiltrometer. The tracer is observed 7 days after the tracer injection when an increase in EC value is observed at the casing shoe.

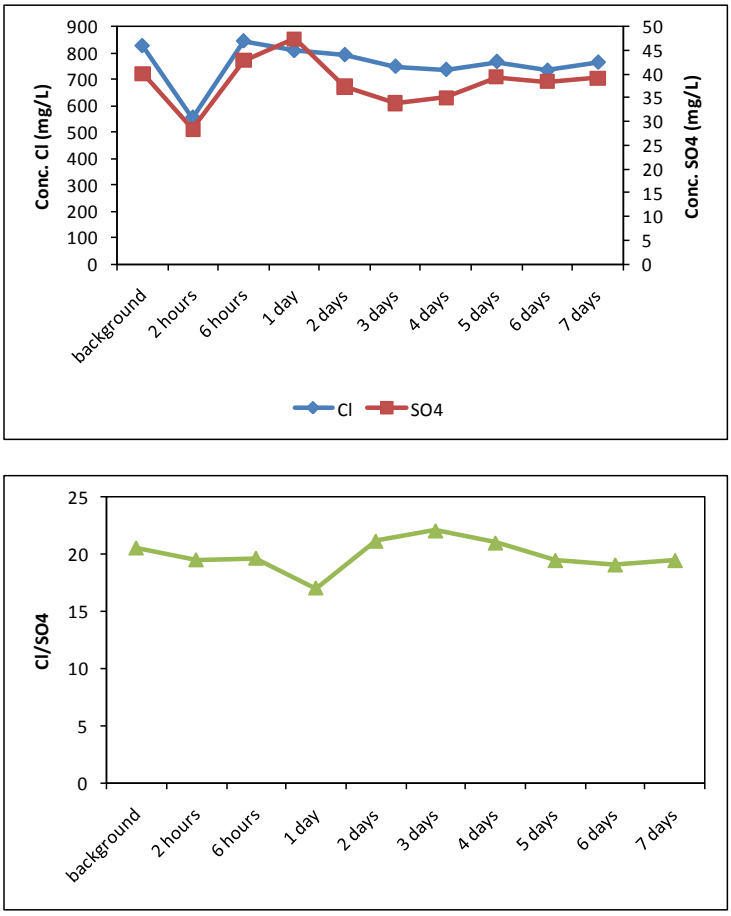


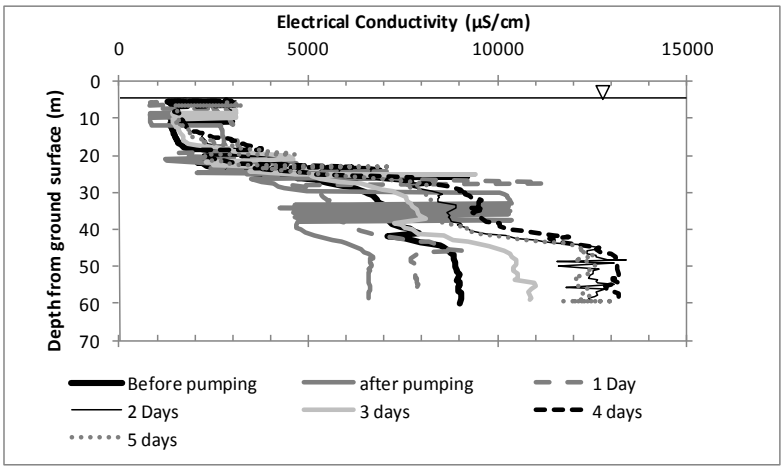
Figure B6: Water chemistry of the W4 during tracer monitoring. There is a small increase of the Cl/SO_4 concentration ratio after 2 days which appears to result from a decrease in the SO_4 concentration.

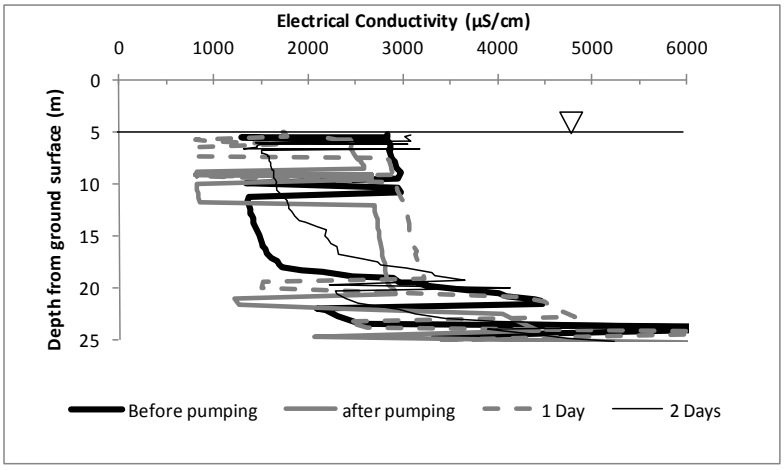
Well 4: Large ring infiltrometer (after grout injection)

Well upgrade

Grout was injected into the annular space as a test for the installation of a proper well-seal. The grout injection follows this protocol:

- Rods were inserted at 2 opposite locations (east and west) into the annular space.
- East (July 23, 2007):
    - Rod at a depth of 17 feet
    - From -17 ft to -9 ft: cement grout (3 Gal)
    - From -9 ft to surface: 30 L of bentonite grout
- West (July 24, 2007):
    - Rod at a depth of 12.5 feet
    - From -12.5 to -3ft: 3 gal of cement grout were injected
    - From -3ft to surface: 10 L of bentonite grout





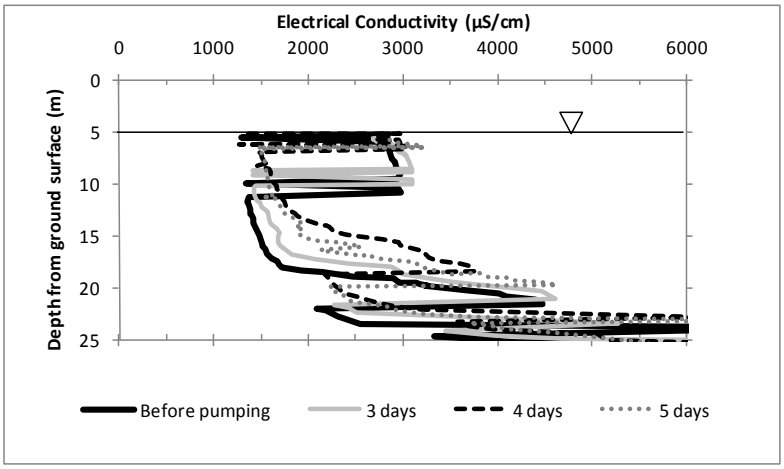


Figure B7: Electrical conductivity of the water column during tracer monitoring at W4, large ring infiltrometer after the well upgrade. Tracer test is not conclusive because the tracer from the previous tracer test was not flushed from the system.

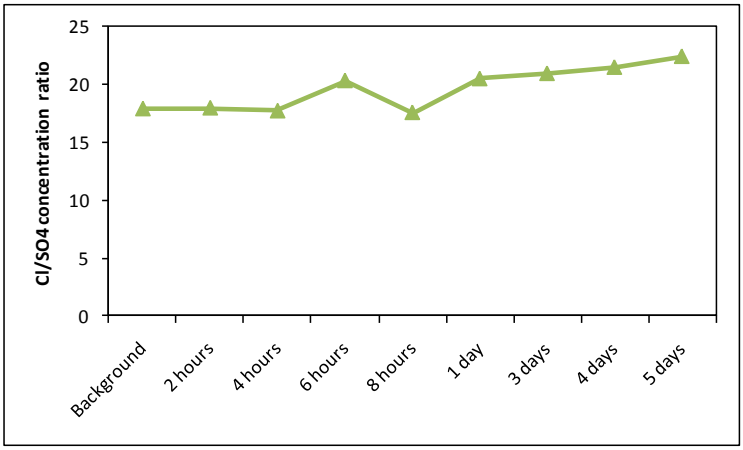


Figure 8B: Cl/SO_4 ratio in water samples after the well upgrade.

W4 Conclusion/summary

Hydraulic conductivity comparison (K):

- There is no significant difference between K at the well and K in the vicinity (p-value 0.62)

EC profile of the water column:

- There is a significant increase of the EC values within the first few metres of the water column. The increases are observed even before the tracer injection and it is

not clear whether the increase results from the previous tracer test or the tracer test following the grout injection.
- One day following the injection of the tracer, the Cl/SO_4 concentration ratio starts to increase.

Verdict regarding the well seal:

- Based on K measurement only, the hydraulic conductivity at the well decreases. However, there is no significant difference between the K before, and the K after the well upgrade (p-value =0.12).
- The tracer test is inconclusive
- Difficult to make firm conclusions regarding the retrofitting method at this well.

Well 5: Small ring infiltrometer

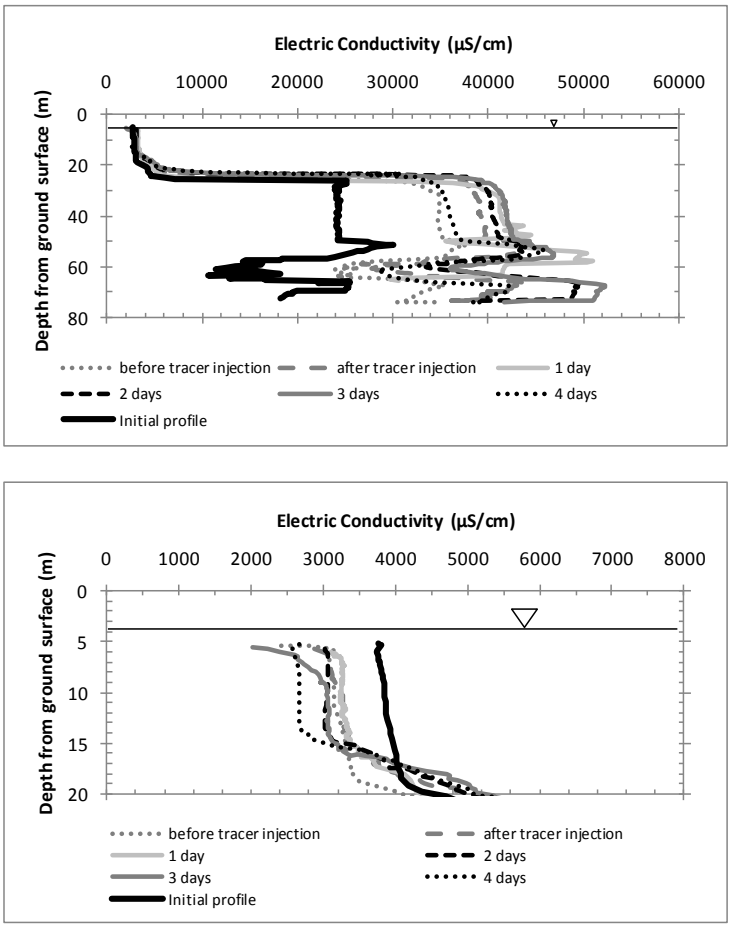


Figure B9: Electrical conductivity of the water column during tracer monitoring at W5.

Well 6: Small ring infiltrometer

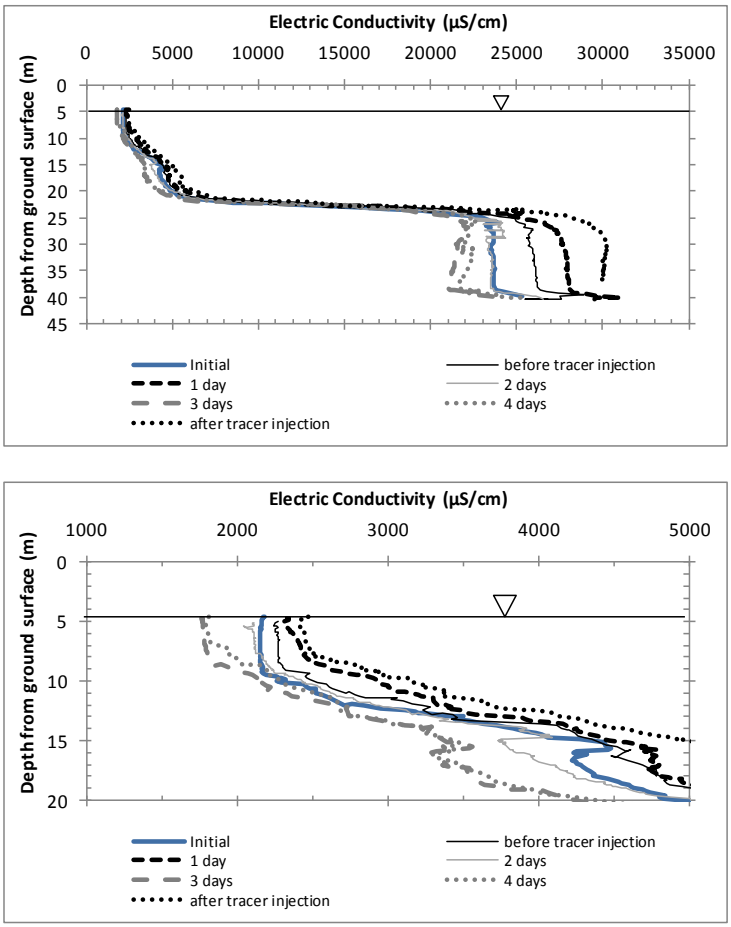


Figure B9: Electrical conductivity of the water column during tracer monitoring at W6.

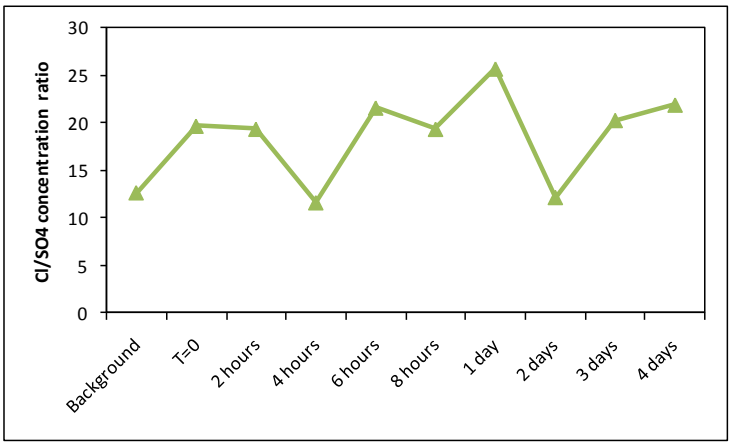


Figure B10: Cl/SO_4 ratio in water samples during tracer monitoring.

Well 6: large ring infiltrometer (complete analysis)

Hydraulic Conductivity

The infiltration tests at this site were conducted from July 15 to 17, 2007. The tracer was monitored until July 22, 2007. Prior to the large-ring infiltration test, a small-ring infiltration test was done directly at the well head. The results are not presented here, but are similar to the large-ring test. No flushing of the system was done between the infiltration tests and there is some evidence of this previous small-ring test in the electrical conductivity profiles. During the test period, rain events were monitored on July 15, 16, 18, 19 and 20.

Tracer Test

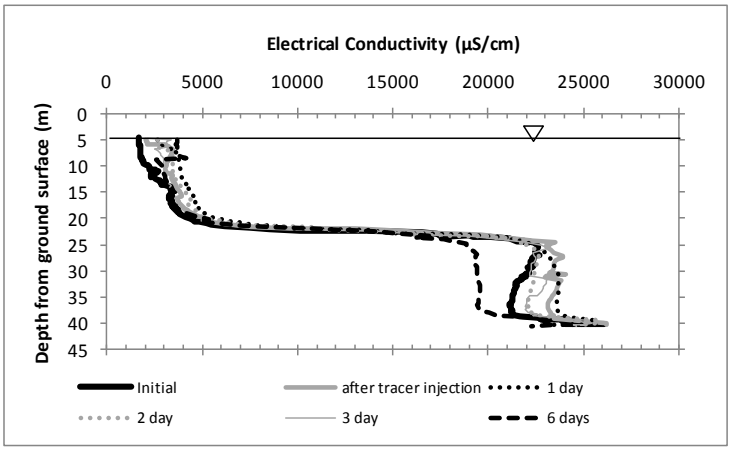
Two barrels (380 L) of municipal tap water were used as pre-tracer at this location. During the test, electrical conductivity for Lindsay tap water was measured at 500 µS/cm. The tracer, a sodium chloride (NaCl) solution, has an EC of 11 000 µS/cm. The total amount of tracer was 380 L. During the tracer injection, the well was pumped at an average rate of 0.156 L/min for 8 hours. Following the injection, two barrels of municipal tap water, acting as chaser water, were infiltrated. The depth of the infiltration front was estimated to be between 7.5 and 10 m, which was thought to cover the casing length. The well was purged every day after profiling and sampling with a purging rate of about 3 L/min. A total of 45 L was removed from the borehole everyday. EC profiles of the water column and water samples were taken up to 6 days following the tracer injection.

Hydraulic conductivity (K) measurement at the well was done using a large ring infiltrometer. Since the well was grouted, the choice of the alpha value was0.01. A steady state infiltration rate of 14.5 cm^3/s was measured during tracer injection. The calculated hydraulic conductivity value at this well was 8×10^{-4} cm/sec, which gives an estimate of the time of travel (TOT) of 6 days. When comparing the K at the well and in the vicinity, no significant difference is observed (p-value=0.51). One explanation is the size of the ring, which is larger than the annular space and included some of the vicinity in the K measurement. An alternate explanation is that the well was grouted, leading to bentonite particle swelling during the pre-tracer infiltration, and subsequently reducing the surface hydraulic conductivity. The resulting K value is similar to the vicinity values. The tracer test results are important because they provide insight on the status of the seal and the hydraulic connection with the surface.

EC profiles of the water column

The EC profiles of the water column are shown in figures 6 and 7. In figure 6, instabilities and EC increase are observed before, and after the tracer injection, between 6 and 8 meters. The casing shoe is located between these depths. These instabilities are thought to result from the previous tracer test completed at this well (July 11) and are the effect of not flushing the system between the tests. The pre-tracer water may have pushed the residual salt water in the ground into the well. An increase of EC is also observed in the profile after the tracer injection. This increase corresponds to 6 days after the previous test tracer injection. Therefore, the tracer TOT for this site seems to be less than 6 days. From figure 7, decreases of EC are observed around the casing shoe a few days following the injection. These decreases most likely result from the pre-tracer arrival into the well. The arrival of the tracer is clearly demonstrated in the Day 3 profile, where there is a significant increase of the electrical conductivity around the casing shoe. Because of technical difficulties, no monitoring was done during Day 4 and 5, but it is assumed that the tracer was still reaching the well because a significant increase is still observed in the Day 6 profile. The geochemical analysis of the major anions and cations is similar to the results observed from the profiling of the water column.

The tracer arrival is further demonstrated using the analysis of the major anions and cations. Figure 8 shows an increase of chloride (Cl^-) concentration, after 8 hours of pumping. There is already an increase in EC, at this time, which is not thought to be from this test. This increase in Cl^- concentration corroborates with the EC increase attributable to the previous small-ring infiltration test. The Cl^- concentration decreases in the following days, matching the EC profiles, but still decreases on Day 3 and 6, whereas the EC profiles show an increase. This discrepancy in the data may result from the water sample collection because samples were collected after profiling of the water column. This profiling action induces mixing and the water collected is no longer representative of the depth. Another possibility is that too much (or not enough) water was pumped prior to sampling. Thus, the samples collected no longer represent a snap shot of the depth.



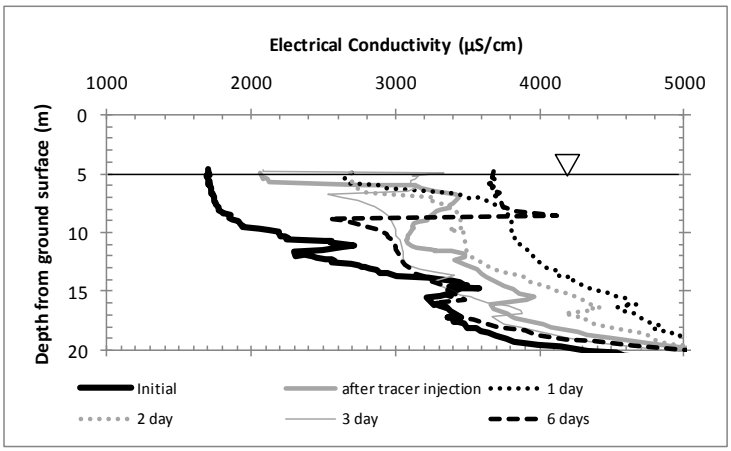


Figure B11: Electrical conductivity of the water column during tracer monitoring at W6, large ring infiltrometer.

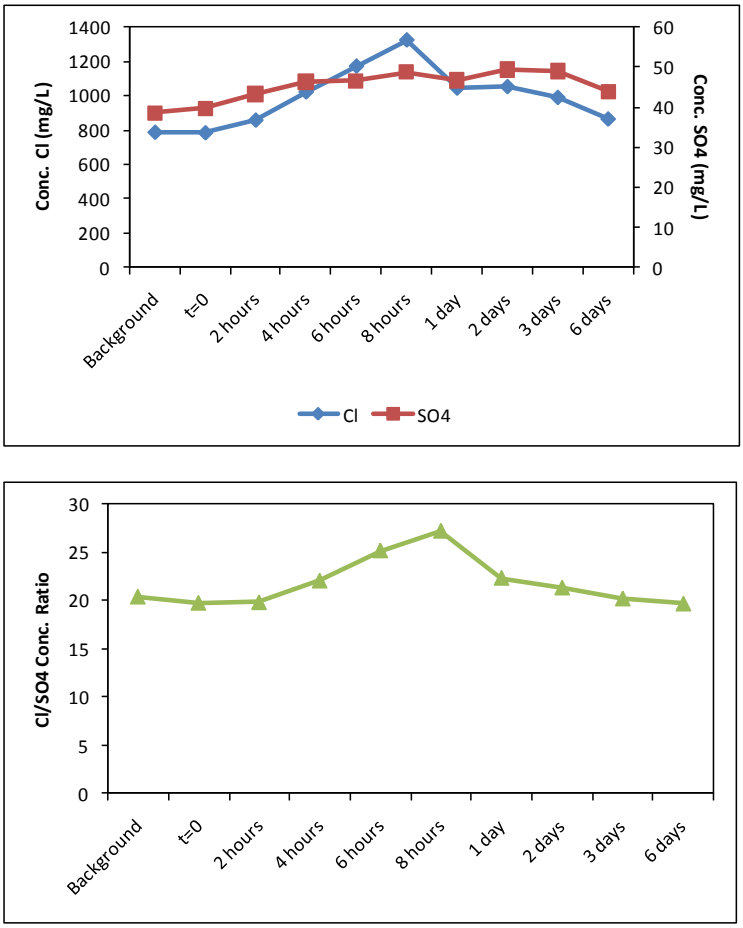


Figure B12: Cl/SO_4 ratio in water samples during tracer monitoring. The increase in the ratio results from an increase in the Cl^- concentration.

W6 Conclusion/summary (before grout injection)

There are no significant differences between the K measurements from the well and from the vicinity. Using K analysis alone, it is challenging to identify a faulty seal. However, the EC profiles show evidence of tracer arrival three days after its injection. Furthermore, the tracer TOT of 3 days is slightly faster than the 6 days TOT estimate with the K results. This indicates the presence of preferential pathways in the annular space. From the EC profiles of the water column, it is also possible to observe the presence of a previous test tracer, which is corroborated by the geochemical analysis of the water samples. These tracer studies clearly illustrate the presence of a defect in the integrity of the well seal and a hydraulic connection from the surface to the well water column. This connection may lead

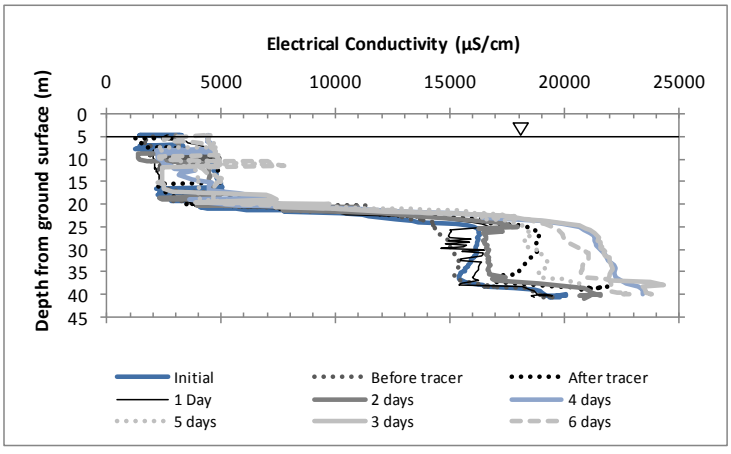
to contamination of the well if a potential source (e.g. bacteria, agricultural activities) is present in the vicinity and surface drainage is directed towards the well.

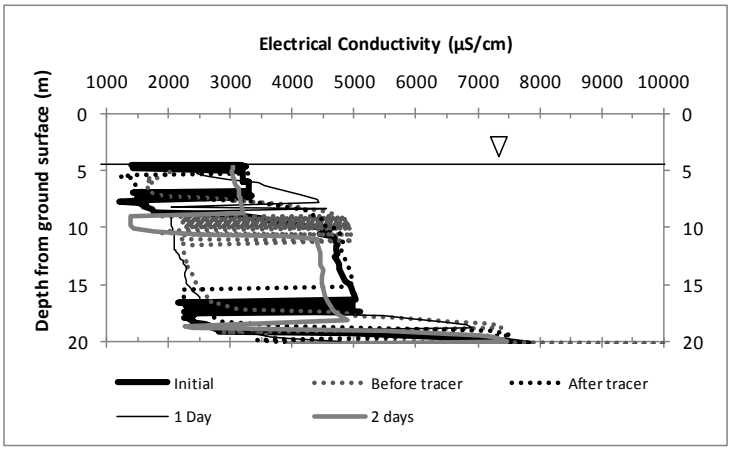
Well 6: Large ring infiltrometer (After grout injection)

Well upgrade

Grout was injected into the annular space (2 opposite locations) to test for the installation of a proper well seal. The grout injection follows this protocol:

- **West side:**
  - Rode depth: 17 feet (5.15 m)
  - From 5.15 to 1.5 meters deep, cement-bentonite mix (9 gal of slurry)
  - From 1.5 to surface Quick grout only (to resist frost effect) (25 L of bentonite)
- **East side:**
  - Rode depth: 16 feet (4.85 m)
  - From 4.85 to 1.8 meters deep, cement-bentonite mix (9 gal of slurry)
  - From 1.8 to surface Quick grout only (to resist frost effect) (20 L of bentonite)





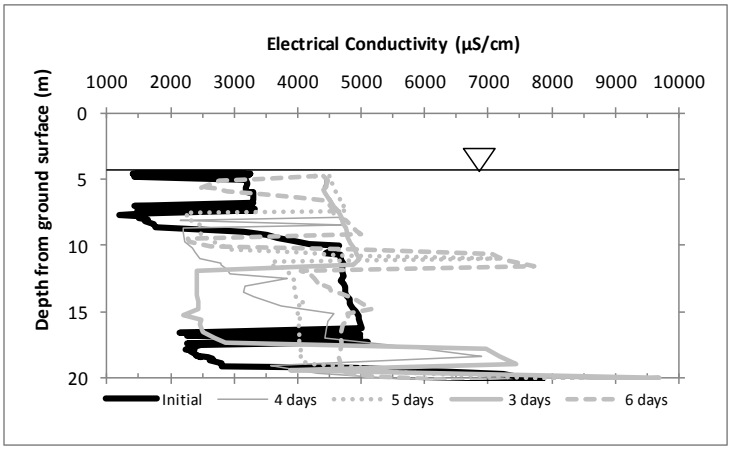
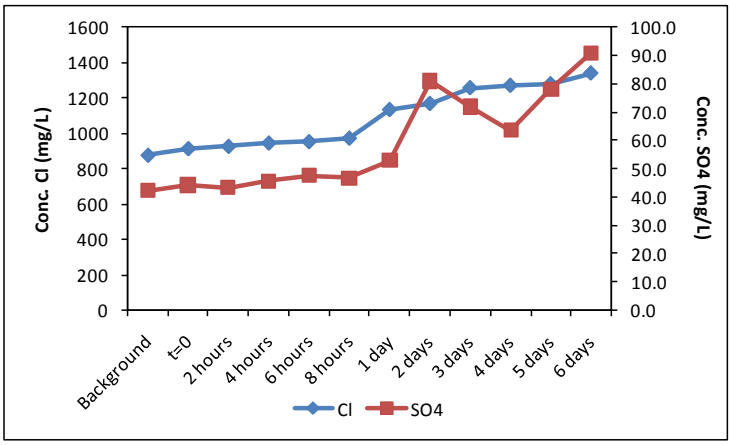


Figure B13: Electrical conductivity of the water column during tracer monitoring at W6, large ring infiltrometer after the well upgrade.



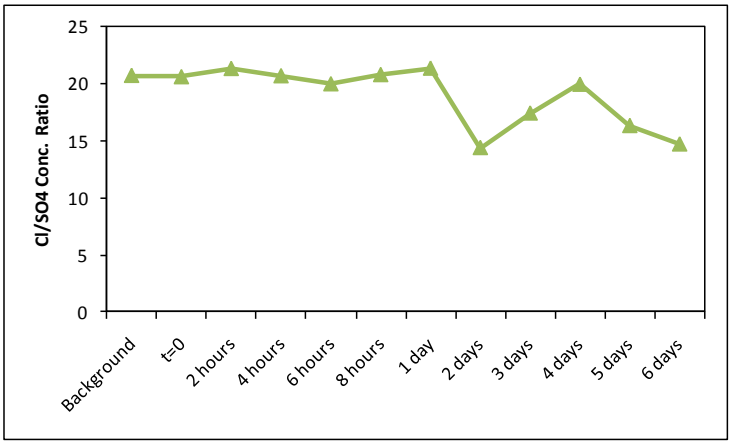


Figure B14: Cl/SO_4 ratio in water samples during tracer monitoring. Variation in the ratio results from an increase in Cl^- or variations in SO_4^{2-}.

W6 Conclusion/summary (after grout injection)

Hydraulic conductivity comparison (K):

- There is no significant difference between the K at the well and K in the vicinity (p-value 0.99)

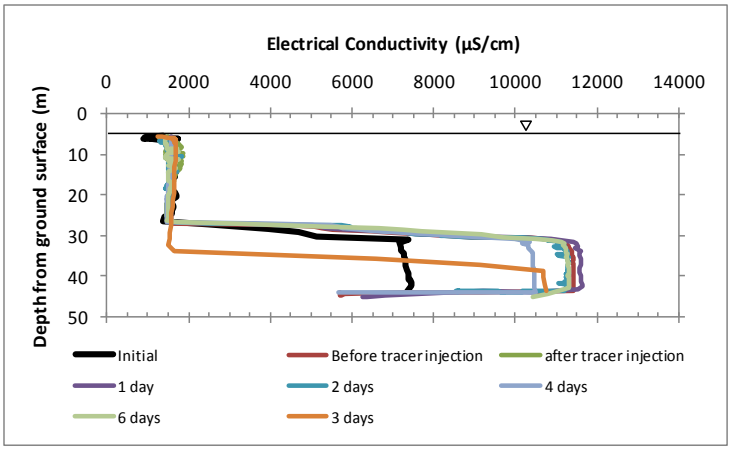
Electrical conductivity profile of the water column

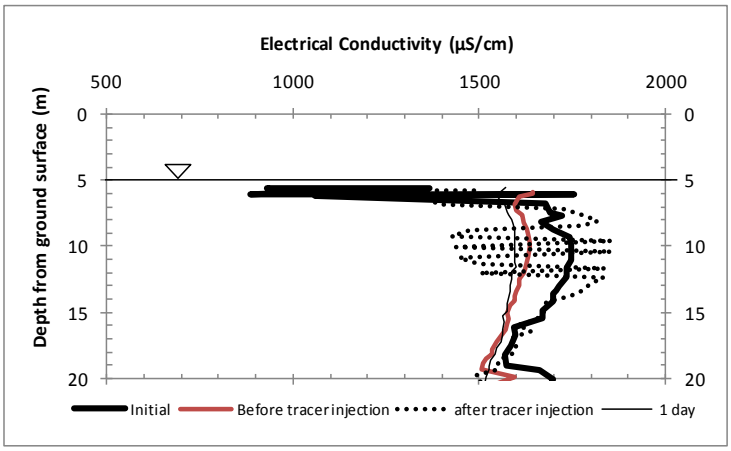
- There is evidence of the tracer in the water column before the injection had started which results from not flushing the system between the tracer tests. It is therefore difficult to interpret the tracer test results.

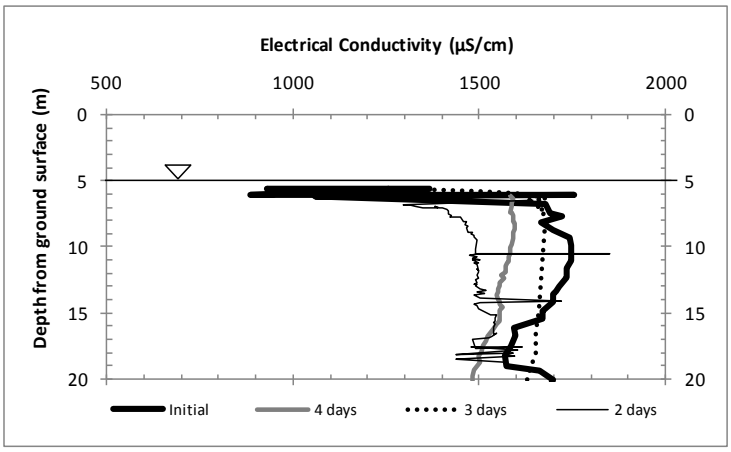
Verdict regarding the well seal

- Base on the K analysis only, there is no significant difference between the K at the well and the vicinity. However, there is a significant difference between before, and after the grout injection when using the pre-tracer K values (p-value=0.0001).

Well 7: Small ring infiltrometer







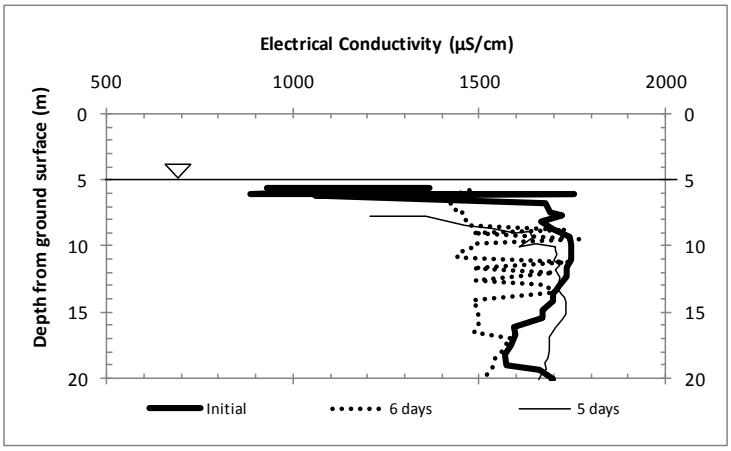


Figure B15: Electrical conductivity of the water column during tracer monitoring at W7, small-ring infiltrometer. Instabilities in the water column are observed shortly after the tracer injection.

Well 8: Small-ring infiltrometer

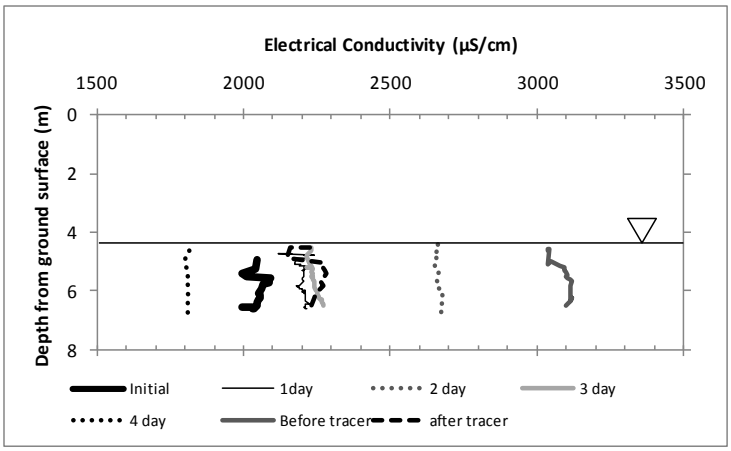
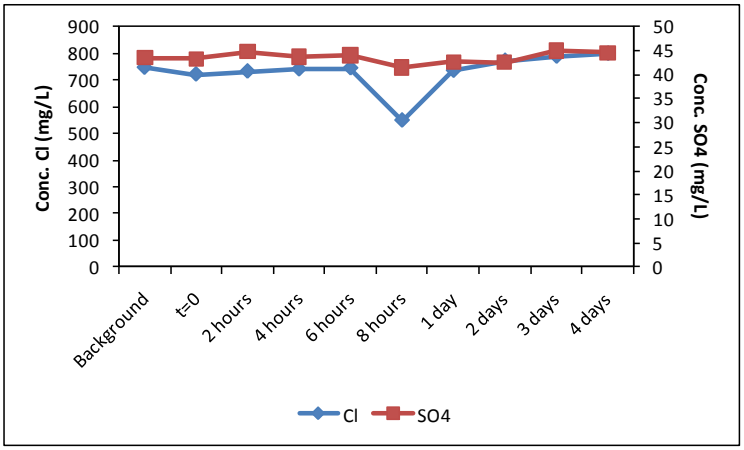


Figure B16: Electrical conductivity of the water column during tracer monitoring at W8, small-ring infiltrometer



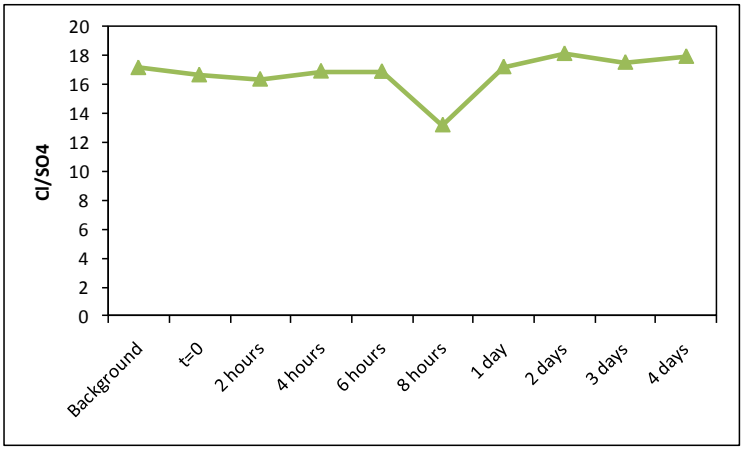


Figure B17: Cl/SO_4 ratio in water samples during tracer monitoring. Variation in the ratio 8 hours after the beginning of the test result from a decrease in Cl^-.

Well 8: Large ring infiltrometer (complete analysis)

Tracer Test

Tracer injection was done on July 15, 2007 with the tracer monitoring period extend until July 19. The soil was saturated prior to the tracer injection, with the 380 L of pre-tracer (Lindsay tap water EC of 500 µS/cm). Following the pre-tracer infiltration, 380L of a NaCl solution, with an EC of 12,349 µS/cm, was injected. The well was pumped, at a rate of 0.163L/min, for 8 hours. Water samples were taken at different intervals during that time period and EC was monitored. Finally, 560 L of tap water were infiltrated, acting as chaser water. The well was purged everyday, at a pumping rate of 3L/min for 10 minutes after the water column profiling to ensure flow to well. A total of 30 L were removed each time, which corresponded to half of the volume of water in the borehole. During the test period, rain events were monitored on the July 18 and 19.

Hydraulic conductivity

Hydraulic conductivity measurements at the well were done using a large-ring infiltrometer. Since fresh cuttings filled the annular space, the alpha value (soil texture parameter) was 0.04. During the pre-tracer and tracer infiltration, the soil in the annular space collapsed. The steady state infiltration rate was 12.3 cm^3/ sec, which lead to a K of 0.002 cm/sec. This K measurement at the well is four times faster than the average of the vicinity values. From this measurement, the estimated TOT was 55 hrs (2.3 days). The K measurement at the well is significantly more important than the vicinity measurements (p-value = 0.002), indicating that a faulty seal was detected. The faulty seal for this well is confirmed by the arrival of the tracer 2 days after tracer injection in the well (Fig. B18).

EC profiles of the water column

Tracer arrival was monitored for four days after the tracer injection. The EC profiles of the water column are shown in Figure B18 and it is observed that the EC values decrease (from 2000 to 1500 µS/cm) following the tracer injection. This decrease is most likely attributed to the dilution of the water column with the pre-tracer. Increases in EC values are observed from Day 2 to 4, indicating tracer arrival and the presence of a faulty

seal. A slight decrease on Day 3 is detected. This decrease occurs 5 days after a rain event (monitored the day before the injection). This 5 day "lag time" is interpreted as rapid meteoric water recharging into the well. This contributes to water column mixing and therefore, decreases our ability to detect the tracer. The tracer detection using the EC profiles demonstrates the hydraulic connection with surface water. This hydraulic connection is also illustrated using the geochemical analysis of the water samples taken during the monitoring period.

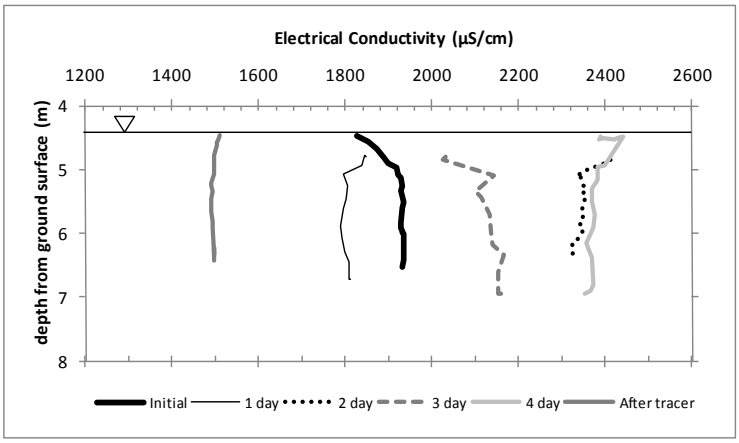
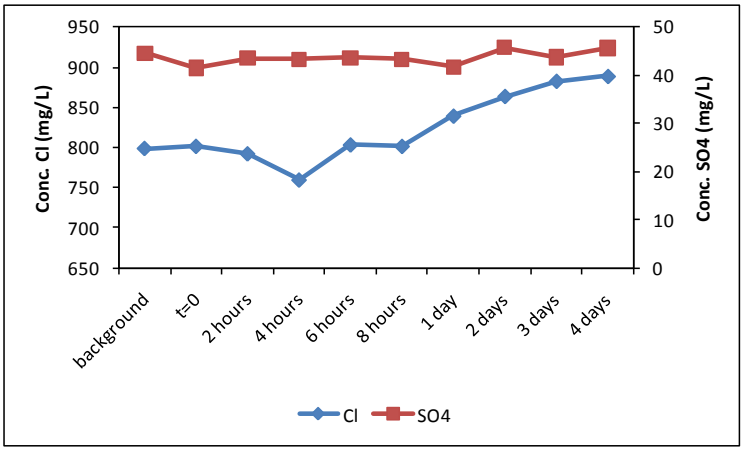


Figure B18: Electrical conductivity of the water column during tracer monitoring at W8, large-ring infiltrometer.



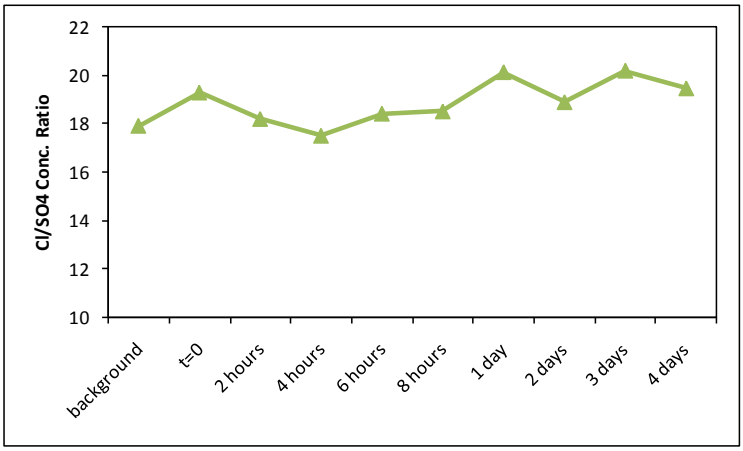


Figure B19: Cl/SO_4 ratio in water samples during tracer monitoring. Variation in the ratio 4 hours after the beginning of the test results from an increase in Cl^-.

A faulty seal is also inferred using the geochemical analytical results (Fig. B19). A decrease in the Cl^- concentration is observed four hours after the beginning of the tracer injection. This decrease may result from the pre-tracer reaching the well. In the following water samples, the chloride concentrations kept increasing indicating the tracer water in the well. This increase in Cl^- values has a minimal effect on the Cl/SO_4 ratio which is explained by the relatively high levels of chloride compared to sulphate.

W8 Conclusion/summary

This well is a good example where the investigative technique to detect faulty seal works on three different components: K measurement comparison; detection of the tracer in the water column using EC profiles; and increases of the chloride concentration from the water samples. This well also demonstrates how rapidly meteoric water reaches a well. The decrease caused by rain water into the well occurs 5 days after the rain event, suggesting a 5 day “lag time”. The rapid lag time after the rain event also gives an indication of a well vulnerability to contamination. The good correlation between the increases of EC and Cl^- concentrations also shows that in this case, geochemical analysis is not required and may be less reliable (Fig. B18, Day 3 and 6).

Well 8: Large ring infiltrometer (after grout injection)

Well upgrade

Grout was injected into the annular space (2 opposite locations) to test for installation of a proper well seal. The grout injection follows this protocol:

- **West side:**
  - Rod depth: 15 feet (4.5 m)
  - Only cement-bentonite mix (20% dry bentonite by weight and 5% bentonite in mixture) (12 gal of slurry)
  - For the last 5 feet the mix was coming up by the east side injection hole.

- **East side:**
  - Rod depth: 15 feet (4.5 m)
  - Only cement-bentonite mix (12 gal of slurry)

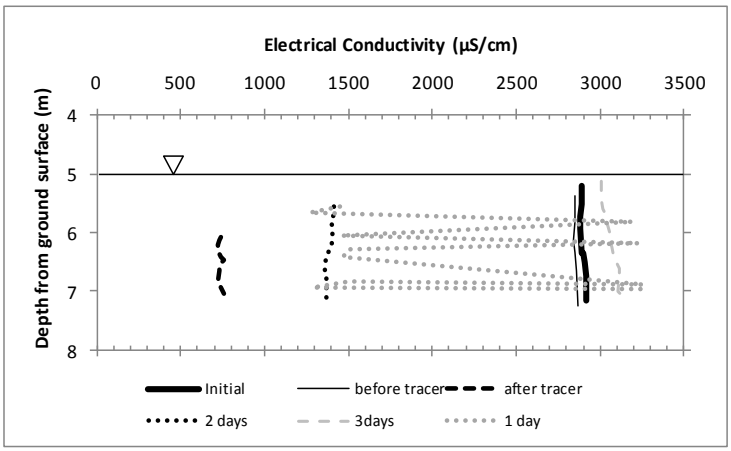


Figure B20: Electrical conductivity of the water column during tracer monitoring at W8, large-ring infiltrometer, after the well upgrade.

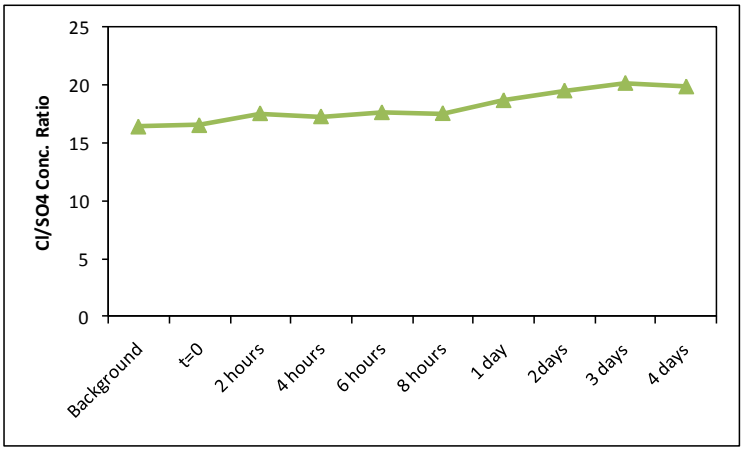


Figure B21: Cl/SO_4 ratio in water samples during tracer monitoring. The ratio starts increasing 1 day after the tracer injection.

W8 Conclusion/summary (after grout injection)

Hydraulic conductivity comparison (K):

- There is no significant difference between the K at the well and K in the vicinity (p-value 0.63)
- There is a significant difference between the K at the well before, and after the grout injection (p-value =0.05)

Electrical profile of the water column:

- The decrease of EC after the injection of the tracer is attributed to the pre-tracer reaching the well or the previous tracer test chaser water.
- There are instabilities in the water column 1 day following the injection and the EC values of the water column return to initial values 3 days following the injection. It is difficult to determine if the EC variations result from the current tracer test or the previous one.

Verdict regarding sealing method:

- Based on K values only, the injection of grout significantly reduced the infiltration of water at the well head. It is difficult to make firm conclusions from the tracer test.

Appendix C: Contamination of Private Well Study, Municipality of Chelsea, Québec

uOttawa

Université d'Ottawa • University of Ottawa
Faculté des sciences Faculty of Science
Sciences de la Terre Earth Sciences

Contamination of Private Well Study

Municipality of Chelsea, Québec



Report presented to:
W1
Chelsea, QC

Report prepared by:
Pascale St-Germain
PhD Candidate
University of Ottawa

May 2010

Acknowledgements

Thank you for your help with this study. Your assistance is valuable in our effort to better understand groundwater wells in fractured bedrock and potential contaminant pathways. We appreciate the access to your property, your hospitality and your collecting water samples for the purpose of this research.

Important note

The suggestions presented in this report are made to improve the quality of your well water. They may help reduce the number of coliforms in your well, but may not be the only solution to any problems. An attempt was made to find the most probable source of contamination; however, many factors can affect water quality. This report was prepared to give you a better understanding of your well and does not include all the conclusions found in the overall study. All suggestions should be treated with caution.

Before investing in your well (well upgrade or water treatment system) I would suggest seeking advice from professionals and getting your water tested independently by an accredited laboratory before future investment in a treatment system.

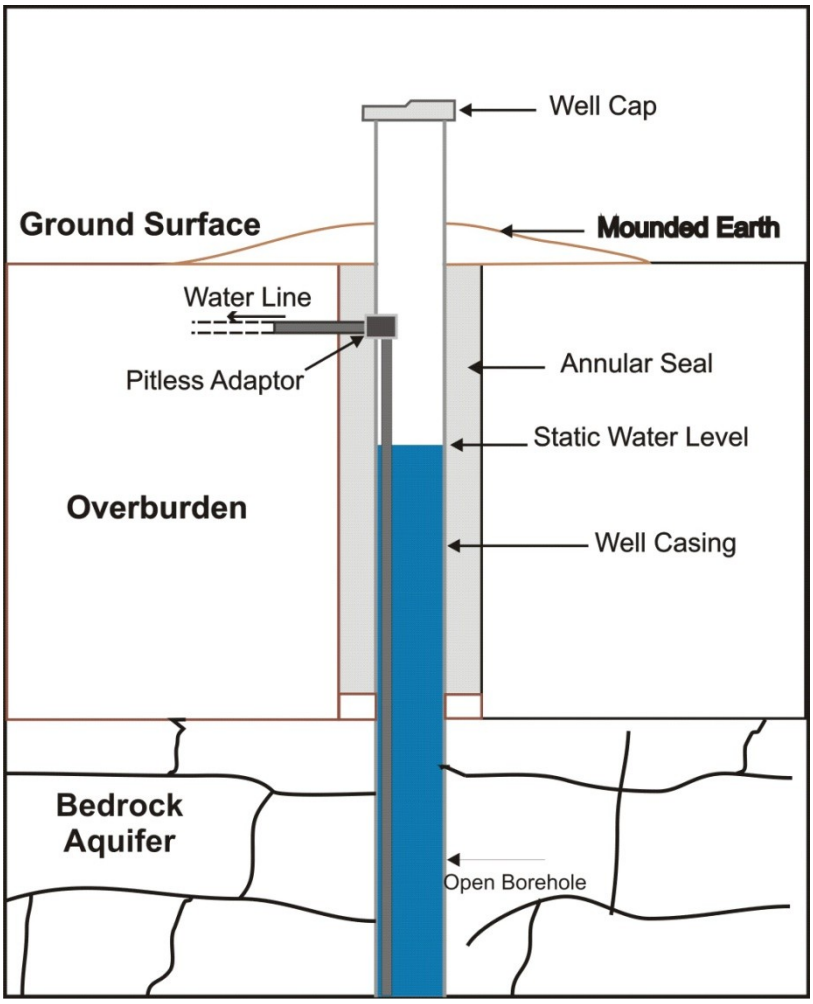
Thank you very much for your understanding

Pascale St-Germain
PhD candidate
University of Ottawa
Department of Earth Sciences

Glossary

Precambrian bedrock:	Fracture bedrock mainly composed of igneous and metamorphic rocks that are more than 542 million years old.
Overburden:	Unconsolidated sediments overlaying the bedrock and composed of grains of various sizes.
Champlain Sea:	Inland sea created about 10 000 year ago resulting from the melting of the *Inlandsis laurentidien* ice sheet. The sea principally covered the Montreal area but also some areas in south eastern Ontario.
Preferential pathways:	Direct movement of water through macro pores without the natural attenuation potential from the soil. This allows bacteria (or contaminant) to get carried faster and deeper.
Drilled well:	Well drilled into the fractured bedrock
Aquifer:	Geological unit capable of storing and transmitting water in sufficient quantity.
Confined aquifer:	Aquifer overlain by an impermeable layer. This layer protects the aquifer from surficial contaminant.
Unconfined aquifer:	Aquifer not overlain by an impermeable layer and exposed to atmospheric pressure.
Aquitard:	Geological unit capable of storing water but incapable of transmitting water in sufficient quantities.
Infiltration:	Movement of water from ground surface into the soil.
Hydraulic conductivity:	Ability of a porous media to transmit water.
Electrical conductivity (EC):	Ability of the water to conduct an electrical current. It is a general indication of the amount of total dissolved solids (TDS) in the water. EC is measure in Siemens per cm (S/cm) or microSiemens per cm (µS/cm = 10^{-6} S/cm). It ranges from several tens of µS/cm for rain water to several thousands of µS/cm for sea water. In the Chelsea area, the EC values range from approximately 90 to 1600 µS/cm.
Total coliforms:	Bacteria present in human and animal feces but also in the soil and vegetation
Faecal coliforms:	Bacteria originating from digestive tracts of humans and animals. Their presence indicates faecal pollution and the potential for pathogens to be present into the water
Macropore:	Pore of greater dimension resulting from biological activity in the soil, from roots and cracks in clay

Drilled well



Source: Modified from Best Management Practice – Water Well

Introduction

The objective of the project was to improve the understanding of private well contamination resulting from the infiltration of surface water. The risk of contamination in drilled wells was evaluated based on site characteristics and well construction.

Your well was tested every month for bacteria in order to assess the seasonality of contamination. Chemical analysis of the well water was carried out to understand the groundwater pathways and to establish possible links to potential contamination sources.

The objective of this report is to increase your awareness of possible water quality issues in your well and of the possible remedial actions that could taken preserve or improve the quality of your well water. It contains a summary of the work conducted, the data obtained, conclusions and some suggestions.

Site Description

Your well is drilled into the Precambrian bedrock, which is overlain by less than 2 metres of till. The till is composed primarily of sand and silt deposited during the last glaciation (about 10,000 years ago). The well casing is located in an open pit where it reaches the ground surface. Water was observed ponding in the pit around the casing. The well is 50 meters deep and the static water level is located at 29 meters below ground surface.

Your well draws water from an unconfined aquifer. An aquifer is defined as a geologic unit capable of storing and transmitting water. This aquifer is also considered unconfined because there is no impermeable protective layer overlaying it. Usually, these types of aquifer are more vulnerable to contamination since there is no confining layer. The confining layer provides an impermeable barrier, thereby naturally protecting the well against surface contamination.

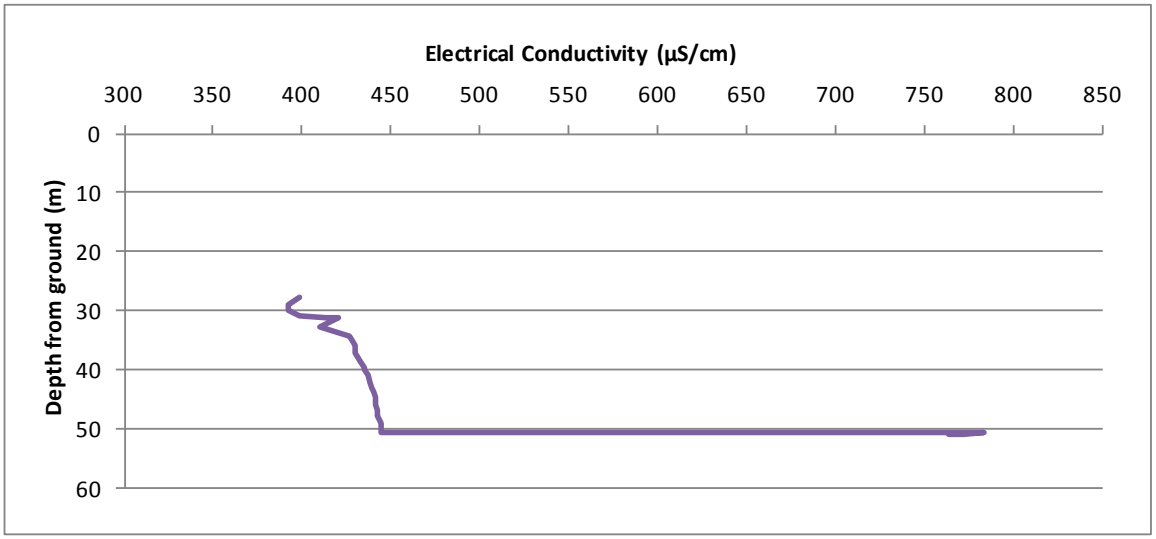


Figure 1: Electrical conductivity profile of the water column

The figure above displays the electrical conductivity (EC) profile of the well water column. The electrical conductivity is the ability of the water to conduct an electric current and it is a measure of the amount of dissolved solids in the well. For your well, the values range from 400 to 750 µS/cm.

Bacteria

Bacteria are naturally present in surface water and soil. They are carried to the groundwater system through the infiltration process. A number of factors may affect the movement of bacteria in soil. These are directly related to the bacteria (type, size and population dynamic) and the soil properties (chemical, biological and physical). Usually, most of the bacteria are filtered through the upper soil profile, but water can carry bacteria deeper using larger pore structures. These structures, called macropores, result from many things: earthworms, decayed roots and crack in clayey soil are some examples. Macropores reduce the efficiency of the soil to filter bacteria allowing them to travel deeper and faster.

Bacterial contamination in a well is a product of many factors. In a municipality like Chelsea, where agriculture is not a common practice, well construction (type, age, depth),

location, the presence of septic system and the geology (bedrock and surficial) would be the primary contributors to bacterial contamination.

Your well showed many contamination events during the April 2008 to May 2009 sampling period. This is illustrated in the figure below. A total of 14 samples were collected and analyzed for total and faecal coliforms. The presence of total coliforms was detected in nine samples and three samples exceeded the regulation limit of 10 cfu/100mL (colony forming units / 100 millilitres). During the same period, one sample exceeded the faecal coliforms regulation limit of 0 CFU/100mL.

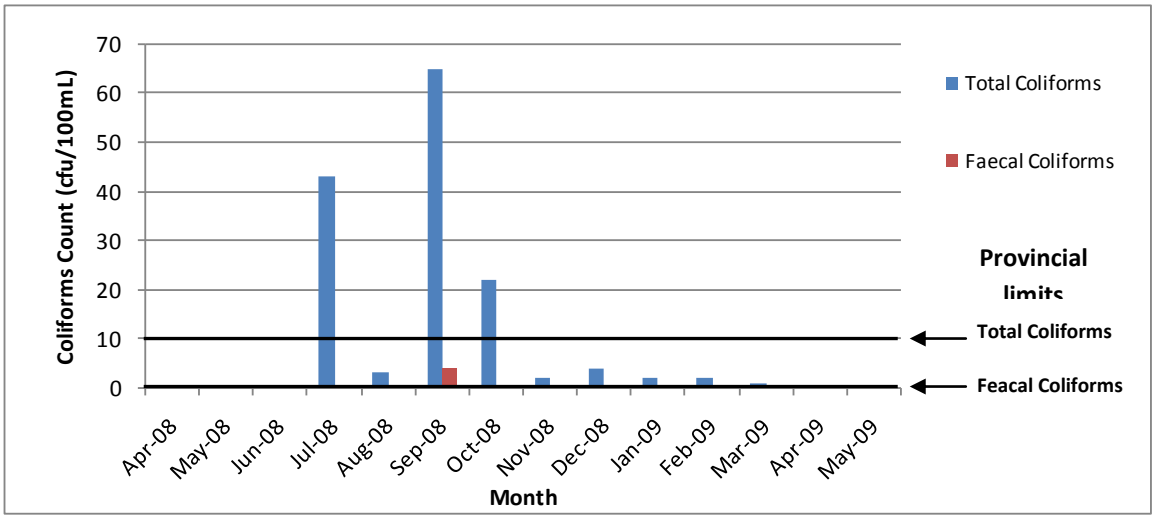


Figure 2: Results of the bacterial analysis (total and faecal coliforms) of the water samples, from April 2008 to May 2009.

Chemical analysis

As water naturally flows into the subsurface, it dissolves minerals along its pathway. The dissolution process is relatively slow in Precambrian bedrock compared to younger sedimentary rocks such as limestone or sandstone. However, other non natural sources may contribute to dissolved solids such as road salt application, septic systems or fertilizers.

Water samples were analyzed for various dissolved species at the University of Ottawa. The results of the analyses are given in the following table. This table also shows the yearly average and the provincial guideline, if applicable. The concentrations are measured in milligrams per litre (mg/L)

Sampling date	pH	Fluoride (mg/L)	Chloride (mg/L)	Nitrate-N (mg/L)	Sulphate (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Hardness (mg/L of $CaCO_3$)
Apr-08	7.0	0.5	34.4	0.9	36.5	80.0	30.3	19.8	324.7
May-08	7.1	bdl	NA	0.9	36.7	80.5	31.1	16.2	329.1
Jun-08	7.0	0.5	30.4	0.7	38.9	95.8	35.6	19.4	386.0
Jul-08	7.3	bdl	29.0	0.6	38.2	69.3	25.2	24.9	277.1
Aug-08	7.0	bdl	33.5	0.7	36.2	75.9	29.8	23.7	312.4
Sep-08	7.9	bdl	10.1	0.2	10.9	41.6	30.8	17.5	230.8
Oct-08	7.4	1.3	23.8	0.3	48.7	59.2	19.8	36.1	229.4
Nov-08	7.3	0.6	31.7	0.5	40.4	74.7	33.2	18.1	323.2
Dec-08	7.2	0.7	32.6	0.6	40.1	74.9	28.6	20.9	305.1
Jan-09	7.1	0.8	33.0	0.6	40.3	70.4	27.0	22.7	287.3
Feb-09	6.9	0.7	12.6	0.2	22.7	63.4	20.7	32.5	243.4
Mar-09	7.0	1.0	31.6	0.4	45.7	63.6	22.0	27.0	249.3
Apr-09	7.1	bdl	26.9	0.2	50.9	59.9	18.9	38.4	227.6
May-09	7.2	0.8	30.9	0.6	45.0	69.4	25.6	24.5	278.6
Average	7.2	0.8	27.7	0.5	37.9	69.9	27.0	24.4	286.0
Guideline		1.5 MAC	250.0 AO	10.0 MAC	500.0 AO			20.0 AO	100.0 AO

OG = Operational Guideline
MAC= Maximum Allowable Concentration
AO= Aesthetic Objective
Bdl= below detection limit

The dissolved solids measured during this study are water quality indicators. It is important to realize that their presence may not have an impact on health. The following table describes the parameters and their possible effects.

Parameters	Definition/sources	Possible effects/concerns
pH	Measure of the acidity of water	• An acid water (pH<6.5) can have a corrosive effect • Low pH increases metals in solution, which could yield health concerns
Fluoride	Natural occurrence	• Mottled teeth • Bone development (high concentrations)
Chloride	Natural occurrence or human related activities	• Corrosive effect on plumbing • Salty taste
Nitrates	Human related activities	• Health Concerns
Sulphates	Natural occurrence or human related activities	• Water has laxative effect
Sodium	Natural occurrence or human related activities	• Health concerns • Salty taste
Hardness	Caused by the presence of calcium and magnesium and occasionally iron in the water	• No health effect • Soap scum • Scale buildup on plumbing fixture and pipes • Stained and mottled laundry

Sources: Best Management Practices –Water Well

Guidelines for Hardness

Category	Concentration of calcium carbonate (mg/L)
Soft	0 to <60
Medium Hard	60 to <120
Hard	120 to <180
Very Hard	180 and more

Source : Health Canada

Summary and Suggestions

Possible sources of contamination

The well shows three distinct contamination events which exceeded regulation limits, however, the presence of total coliforms were detected consistently. The consistent presence of total coliforms may be an indication of surface water reaching the well. The bacterial contamination could result from the shallow soil depth, the drainage toward the well, but is most likely the result of the well pit, which allows surface water to accumulate around the well casing. The presence of total coliforms during winter months, when infiltration is minimal, suggests that total coliforms are present in the aquifer.

Chemical analysis

The amount of dissolved constituents in your water is relatively low, which is an indication of good quality water. Most constituent concentrations are below guidelines/regulations with the exception of sodium (Na) which is slightly above the guideline of 20 mg/L.

Concentrations of nitrate were detected in the well, but the levels are below the maximum allowed concentration. It would be important to monitor this parameter. It is recommended by the MDDEP to have this parameter analyzed every few years. If the level gets above 5 mg-N/L, then yearly monitoring is recommended.

Suggestions

- The open well pit around your well can pose a significant risk to the water quality, as it was experienced in September 2008 when a dead squirrel was found in the open pit. A possible solution to prevent further direct infiltration at the well head would be to get the well pit sealed with impermeable materials, such as bentonite (type of swelling clay). A licence well driller should be able to provide suggestions on how to properly fill the well pit.

- In your situation, the presence of bacteria is recurrent and extra care should be taken for any use of water related to human consumption. The installation of a filtration system that kills microorganisms should be considered.
- Every year, examine into the inside of the well with a flash light. You can look for cracks in the casing caused by corrosion. Also check for holes around the pitless adaptor (area where pipes are connected). A record should be kept and comparisons made year to year. Corrective action can be suggested a licensed well contractor if something wrong is detected.
- It is recommended to get your water tested for bacteria at least 1 time a year, especially after important rainfall events and snowmelt.

The information presented in this report comes from the following sources:

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Ministère du développement durable, environnement et parcs (MDDEP) -*La qualité de l'eau de mon puits* (French only)
http://www.mddep.gouv.qc.ca/eau/potable/depliant/index.htm

Ontario Ministry of Agriculture Food and Rural Affairs/Agriculture and Agri-food Canada. 2003 *Best Management Practices –Water Well*
http://www.omafra.gov.on.ca/english/environment/water/publications.htm

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Faculté des sciences Faculty of Science
Sciences de la Terre Earth Sciences

Contamination of Private Well Study
Municipality of Chelsea, Québec



Report presented to:
W2
Chelsea, QC

Report prepared by:
Pascale St-Germain
PhD Candidate
University of Ottawa

May 2010

Acknowledgements

Thank you for your help with this study. Your assistance is valuable in our effort to better understand groundwater wells in fractured bedrock and potential contaminant pathways. We appreciate the access to your property, your hospitality and your collecting water samples for the purpose of this research.

Important note

The suggestions presented in this report are made to improve the quality of your well water. They may help reduce the number of coliforms in your well, but may not be the only solution to any problems. An attempt was made to find the most probable source of contamination; however, many factors can affect water quality. This report was prepared to give you a better understanding of your well and does not include all the conclusions found in the overall study. All suggestions should be treated with caution.

Before investing in your well (well upgrade or water treatment system) I would suggest seeking advice from professionals and getting your water tested independently by an accredited laboratory before future investment in a treatment system.

Thank you very much for your understanding

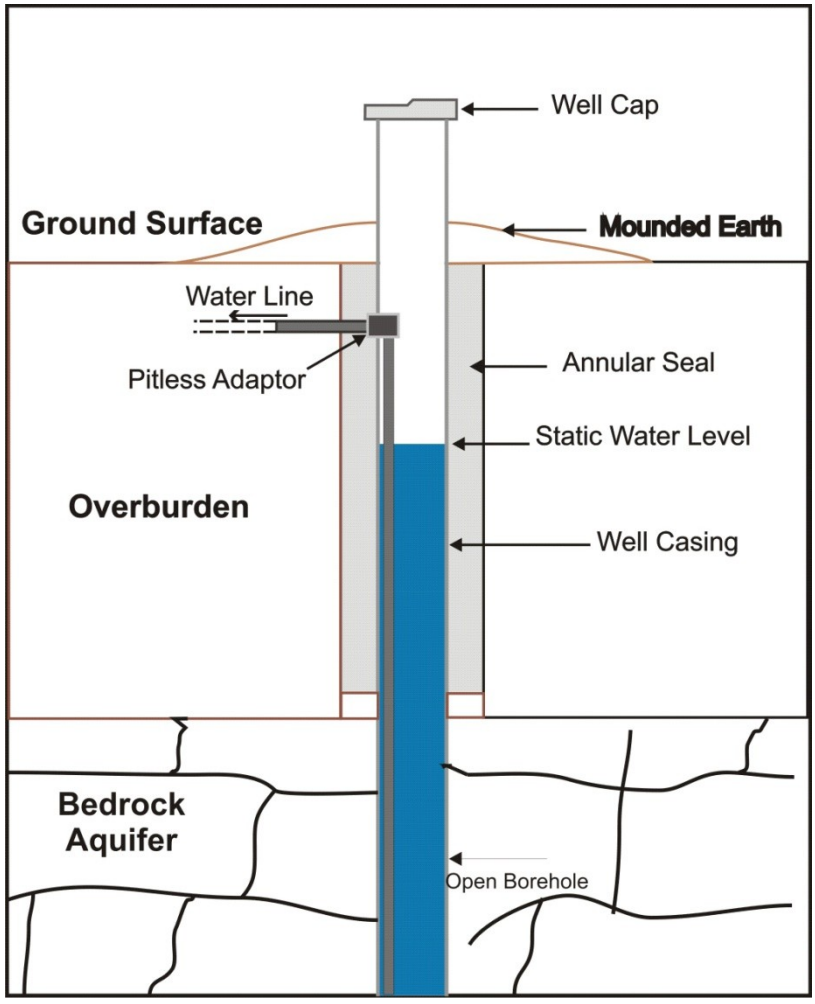
Pascale St-Germain
PhD candidate
University of Ottawa
Department of Earth Sciences

Glossary

Precambrian bedrock:	Fracture bedrock mainly composed of igneous and metamorphic rocks that are more than 542 million years old.
Overburden:	Unconsolidated sediments overlaying the bedrock and composed of grains of various sizes.
Champlain Sea:	Inland sea created about 10 000 year ago resulting from the melting of the *Inlandsis laurentidien* ice sheet. The sea principally covered the Montreal area but also some areas in south eastern Ontario.
Preferential pathways:	Direct movement of water through macro pores without the natural attenuation potential from the soil. This allows bacteria (or contaminant) to get carried faster and deeper.
Drilled well:	Well drilled into the fractured bedrock
Aquifer:	Geological unit capable of storing and transmitting water in sufficient quantity.
Confined aquifer:	Aquifer overlain by an impermeable layer. This layer protects the aquifer from surficial contaminant.
Unconfined aquifer:	Aquifer not overlain by an impermeable layer and exposed to atmospheric pressure.
Aquitard:	Geological unit capable of storing water but incapable of transmitting water in sufficient quantities.
Infiltration:	Movement of water from ground surface into the soil.
Hydraulic conductivity:	Ability of a porous media to transmit water.
Electrical conductivity (EC):	Ability of the water to conduct an electrical current. It is a general indication of the amount of total dissolved solids (TDS) in the water. EC is measure in Siemens per cm (S/cm) or microSiemens per cm (µS/cm = 10^{-6} S/cm). It ranges from several tens of µS/cm for rain water to several thousands of µS/cm for sea water. In the Chelsea area, the EC values range from approximately 90 to 1600 µS/cm.
Total coliforms:	Bacteria present in human and animal feces but also in the soil and vegetation

Faecal coliforms:	Bacteria originating from digestive tracts of humans and animals. Their presence indicates faecal pollution and the potential for pathogens to be present into the water
Macropore:	Pore of greater dimension resulting from biological activity in the soil, from roots and cracks in clay

Drilled well



Source: Modified from Best Management Practice – Water Well

Introduction

The objective of the project was to improve the understanding of private well contamination resulting from the infiltration of surface water. The risk of contamination in drilled wells was evaluated based on site characteristics and well construction.

Your well was tested every month for bacteria in order to assess the seasonality of contamination. Chemical analysis of the well water was carried out to understand the groundwater pathways and to establish possible links to potential contamination sources.

The objective of this report is to increase your awareness of possible water quality issues in your well and of the possible remedial actions that could taken preserve or improve the quality of your well water. It contains a summary of the work conducted, the data obtained, conclusions and some suggestions.

Site Description

Your well is drilled into the Precambrian bedrock, which is overlain by a layer of clay. This clay layer is a minimum of 5 metres thick and resulted from deposition in the Champlain Sea during the last glaciation (about 10,000 years ago). The well is approximately 70 metres deep and the static water level is located at 25 metres below ground surface.

Your well draws water from a confined aquifer. An aquifer is defined as a geologic unit capable of storing and transmitting water. This aquifer is also considered confined because there is an impermeable protective layer overlaying it. Usually, these types of aquifer are less vulnerable to contamination because of the presence of a confining layer. The confining layer provides an impermeable barrier, thereby naturally protecting the well against surface contamination.

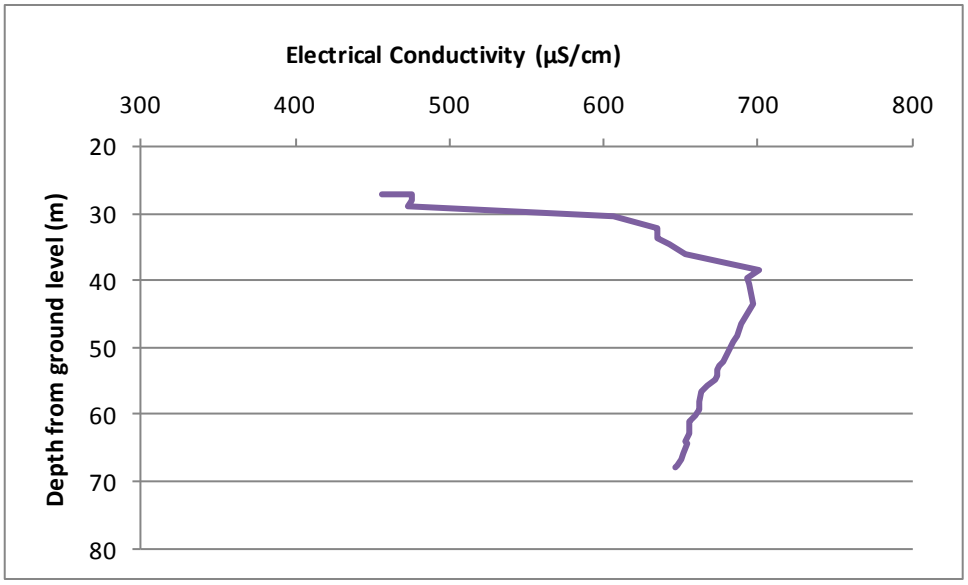


Figure 1: Electrical conductivity profile of the water column

The figure above displays the electrical conductivity (EC) profile of the well water column. The electrical conductivity is the ability of the water to conduct an electric current and it is a measure of the amount of dissolved solids in the well. For your well, the values range from 450 to 700 µS/cm with an important change at a depth of 30 to 35 metres from ground level. It is interpreted that at this depth, a fracture with a higher EC water connects with the water column.

Analytical Techniques

To evaluate the status of the well seal, two techniques were employed:

1. Hydraulic Conductivity

   The first technique measures the hydraulic conductivity (K) around the well to see if water infiltrates into the ground more easily than in the surrounding area. A statistical test was done to compare the K values resulting from the infiltration tests. If the K value at the well was found to be relatively greater than the K values of the surrounding, then there is a potential for a faulty seal.

2. Tracer Test

   The second technique involves injecting a tracer (a solution of NaCl or commonly, table salt) around the well casing and then measuring the electrical conductivity of the well water over time. If the tracer is detected in the well water, then surface water is likely capable of seeping down the sides of the well, indicating a hydraulic connection with the surface.

Results

1. Hydraulic conductivity comparison

The infiltration tests were done on August 12th and 13th 2008. The hydraulic conductivity value measured at the well was significantly higher than the hydraulic conductivity measurements in the vicinity of the well.

2. Tracer test

The tracer was injected on August 12th and monitored until August 23rd. During that period, a rainfall event (more than 15 mm of rain) was recorded on the 18th, corresponding to Day 6 following the injection of the tracer.

A total of 380L of the tracer solution, with an EC of 10,500 µS/cm, was injected following the infiltration of 380L of well water (EC around 500 µS/cm), which acted as the pre-tracer in this case. After the injection of the tracer, more well water was infiltrated as a "chaser" in order to help the infiltration of the tracer.

The tracer in the well water column was detected within an hour after its injection. For comparison purposes, the EC profiles are plotted in the figure above. The tracer arrival is detected in the profile *after tracer injection*. The EC values return to typical values the following day and stay relatively constant until the end of the monitoring period.

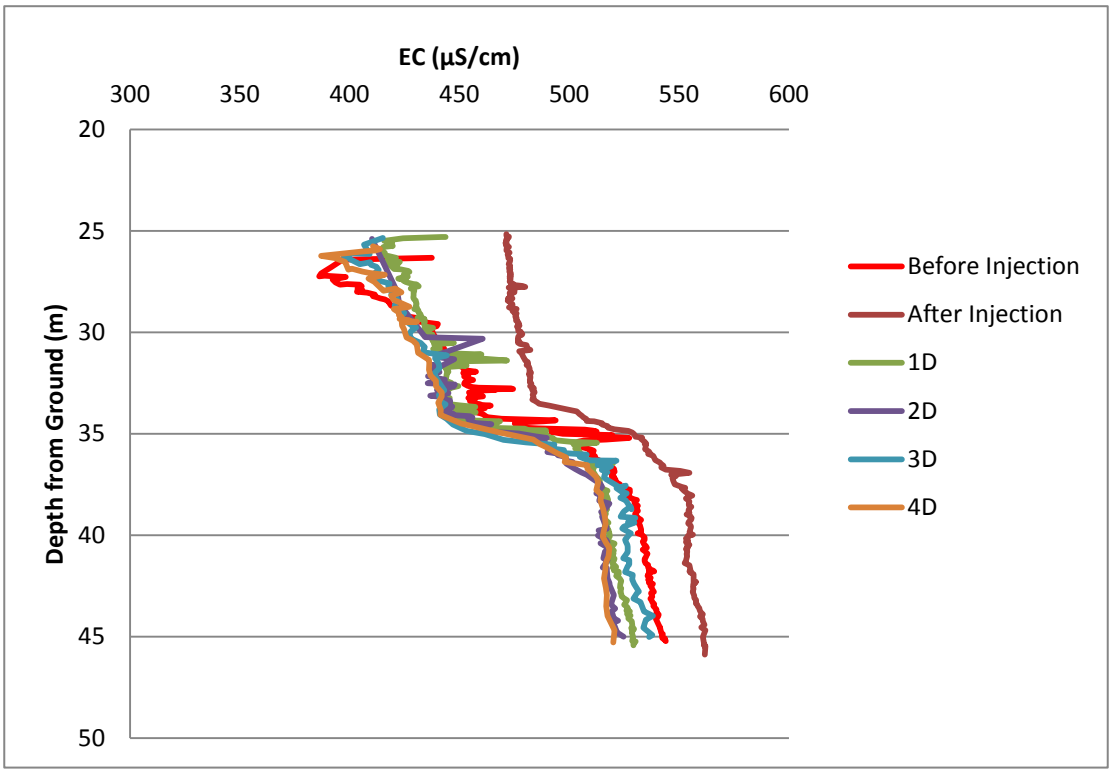


Figure 2: Electrical conductivity profiles of the water columns, before the tracer injection up to 4 days following the injection. The tracer can be noticed in the *after tracer injection* profile

Bacteria

Bacteria are naturally present in surface water and soil. They are carried to the groundwater system through the infiltration process. A number of factors may affect the movement of bacteria in soil. These are directly related to the bacteria (type, size and population dynamic) and the soil properties (chemical, biological and physical). Usually, most of the bacteria are filtered through the upper soil profile, but water can carry bacteria deeper using larger pore structures. These structures, called macropores, result from many things: earthworms, decayed roots and crack in clayey soil are some examples. Macropores reduce the efficiency of the soil to filter bacteria allowing them to travel deeper and faster.

Bacterial contamination in a well is a product of many factors. In a municipality like Chelsea, where agriculture is not a common practice, well construction (type, age, depth), location, the presence of septic system and the geology (bedrock and surficial) would be the primary contributors to bacterial contamination.

The well showed many contamination events during the April 2008 to May 2009 sampling period. This is illustrated in the figure below. A total of 11 samples were collected and analysed for total and faecal coliforms. The presence of total coliforms was detected in eight samples and five samples exceeded the regulation limit, of 10 cfu/100mL. During the same period, four samples exceeded the faecal coliforms regulation limit of 0 cfu/100mL.

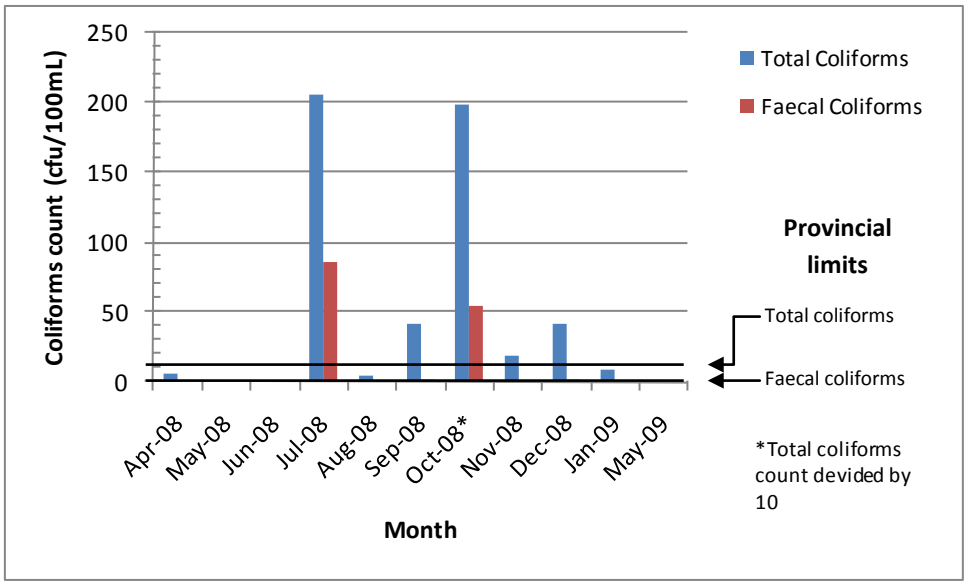


Figure 3: Results of the bacterial analysis (total and faecal coliforms) of the water samples, from April 2008 to May 2009.

Chemical analysis

As water naturally flows into the subsurface, it dissolves minerals along its pathway. The dissolution process is relatively slow in Precambrian bedrock compared to younger sedimentary rocks such as limestone or sandstone. However, other non natural sources may contribute to dissolved solids such as road salt application, septic systems or fertilizers.

Water samples were analysed for various dissolved species at the University of Ottawa. The results of the analyses are given in the following table. This table also shows the yearly average and the provincial guideline, if applicable. The concentrations are measured in milligrams per litre (mg/L)

Sampling date	pH	Fluoride (mg/L)	Chloride (mg/L)	Nitrate as N (mg/L)	Sulphate (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Hardness (mg/L de $CaCO_3$)
Apr-08	8.0	3.7	145.1	bdrl	59.9	27.2	28.0	72.0	183.2
May-08	7.5	0.9	58.9	bdrl	47.5	88.7	37.5	82.9	376.3
Jun-08	8.0	1.4	43.9	bdrl	19.4	16.2	25.3	69.7	144.7
Jul-08	7.4	0.7	58.4	bdl	42.4	74.8	34.0	84.5	326.9
Aug-08	7.6	bdl	47.2	bdl	19.5	26.1	27.7	76.5	179.4
Sep-08	8.4	0.8	20.5	bdl	6.9	16.8	22.4	66.0	134.3
Oct-08	9.1	1.0	62.3	bdl	36.3	5.6	28.3	84.4	130.4
Nov-08	7.6	1.5	48.4	0.7	22.8	30.5	26.8	73.1	186.4
Dec-08	7.9	1.4	48.1	2.1	21.1	26.0	25.4	73.0	169.3
Jan-09	7.5	1.3	57.7	1.2	36.5	59.2	32.7	79.7	282.6
May-09	7.4	1.2	63.8	bdl	40.0	67.3	33.0	77.5	303.9
Average	7.8	1.4	59.5	1.3	32.0	39.9	29.2	76.3	219.8
Guidelines		1.5 MAC	250.0 AO	10.0 MAC	500.0 AO			20.0 AO	100.0 AO

OG = Operational Guideline
MAC= Maximum Allowable Concentration
AO= Aesthetic Objective
Bdl= below detection limit

The dissolved solids measured during this study are water quality indicators. It is important to realize that their presence may not have an impact on health. The following table describes the parameters and their possible effects.

Parameters	Definition/sources	Possible effects/concerns
pH	Measure of the acidity of water	• An acid water (pH<6.5) can have a corrosive effect • Low pH increases metals in solution, which could yield health concerns
Fluoride	Natural occurrence	• Mottled teeth • Bone development (high concentrations)
Chloride	Natural occurrence or human related activities	• Corrosive effect on plumbing • Salty taste
Nitrates	Human related activities	• Health Concerns
Sulphates	Natural occurrence or human related activities	• Water has laxative effect
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Hardness	Caused by the presence of calcium and magnesium and occasionally iron in the water	• No health effect • Soap scum • Scale buildup on plumbing fixture and pipes • Stained and mottled laundry

Sources: Best Management Practices –Water Well

Guidelines for Hardness

Category	Concentration of calcium carbonate (mg/L)
Soft	0 to <60
Medium Hard	60 to <120
Hard	120 to <180
Very Hard	180 and more

Source : Health Canada

Summary and Suggestions

Seal testing

The infiltration tests demonstrated that surface water is infiltrating easier at the wellhead compared to the area surrounding the well. The detection of the tracer in the well suggests the presence of a hydraulic connection between the wellhead and the water column. Although a faulty seal is a potential pathway to contamination, other factors such as the proximity to the Gatineau River or cracks in clayey soil may lead to such contamination.

Possible sources of contamination

Your well is characterized by recurrent contamination suggesting that the aquifer itself is contaminated during a period of the year, especially during the summer months. This could result from septic contamination along the pathway from the recharge area to your well or cracks in clayey soil leading to rapid infiltration of water.

It was observed that the well cap is not insect-proof and spider webs were present in the well cap. The presence of bugs most likely contributes to a small concentration of bacteria into the well.

Another possible explanation for the high bacteria concentration is proximity to the Gatineau River or the little creek north of your well. The water level in the well is similar to the river/creek elevation. During pumping, it is possible that the well draws part of its water from this source of surface water, thereby contaminating it. In fact, it was observed that during pumping, the water level dropped below the river/creek elevation. Depending on the fracture network and flow direction, flow can be induced from the river/creek toward the well. If the water does not undergo natural filtration processes, bacteria present in the surface water may reach the well.

Chemical analysis

The amount of dissolved constituents in your water is relatively low, which is an indication of good quality water. Most constituent concentrations are below

guidelines/regulations with the exception of sodium (Na) which is slightly above the guideline of 20 mg/L.

Suggestions

- In your situation, the presence of bacteria is recurrent and extra care should be taken for any use of water related to human consumption. The installation of a filtration system that kills microorganisms should be considered.
- It is recommended to get your water tested for bacteria at least 1 time a year, especially after important rainfall events and snowmelt.
- A potential preferential pathway to surface water infiltration is the well annular space. To diminish the infiltration at the wellhead, it is recommended that the soil be mounded around the casing, which will deviate the runoff away from the wellhead, allowing the natural soil process to attenuate the bacteria present in the water.
- A good well cap should keep bugs out of the well. Proper insect-proof cap are available and will easily fit on your well. This will not stop the contamination but will prevent insects entering the well, which can increase the concentration of total coliforms.
- Every year, examine into the inside of the well with a flash light. You can look for cracks in the casing caused by corrosion. Also check for holes around the pitless adaptor (area where pipes are connected). A record should be kept and comparisons made year to year. Corrective action can be suggested a licensed well contractor if something wrong is detected.
- It is important to consider activities around the wellhead, especially uphill from the well. For example: if the driveway is located uphill from the well and runoff water flow towards the well. Extra care should be taken to make sure there are no leaks from cars and salt should not be used as de-icing agent. To prevent nitrate contamination, no fertilizers should be used uphill or near the well recharge area.
- It is not recommended to plant flowers, shrubs or trees near the wellhead since their roots can affect the integrity of the annular seal protecting the well. The roots also increase the infiltration rate in the area.

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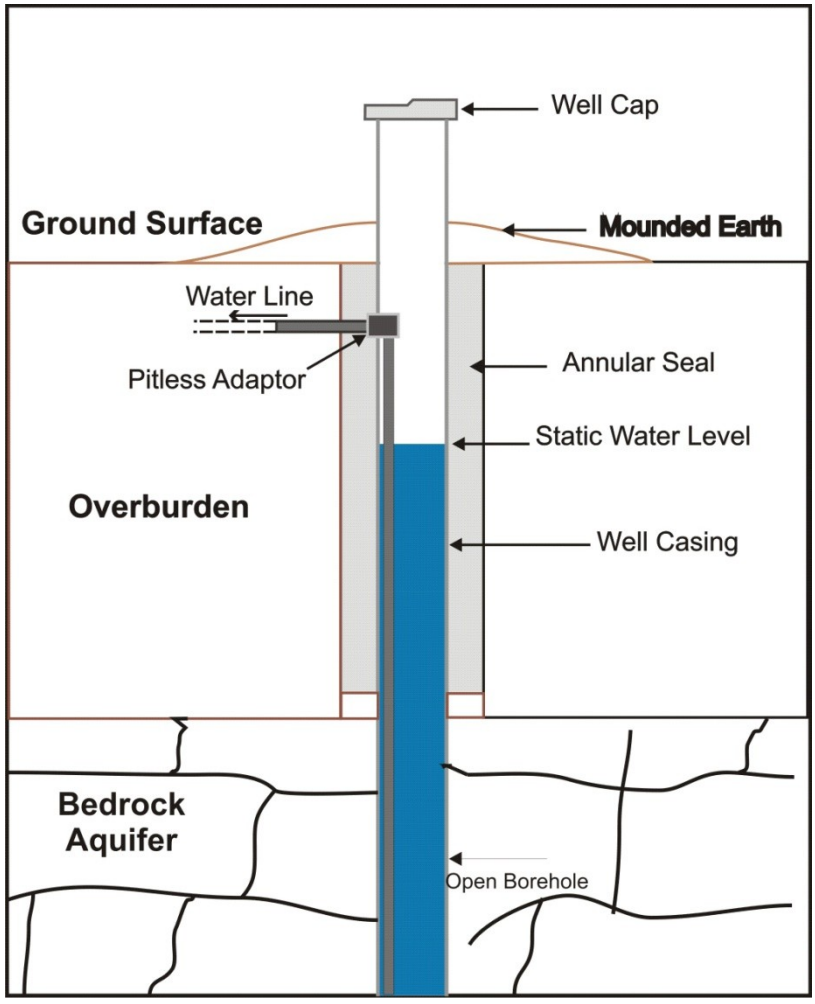
Pascale St-Germain
PhD candidate
University of Ottawa
Department of Earth Sciences

Glossary

Precambrian bedrock:	Fracture bedrock mainly composed of igneous and metamorphic rocks that are more than 542 million years old.
Overburden:	Unconsolidated sediments overlaying the bedrock and composed of grains of various sizes.
Champlain Sea:	Inland sea created about 10 000 year ago resulting from the melting of the *Inlandsis laurentidien* ice sheet. The sea principally covered the Montreal area but also some areas in south eastern Ontario.
Preferential pathways:	Direct movement of water through macro pores without the natural attenuation potential from the soil. This allows bacteria (or contaminant) to get carried faster and deeper.
Drilled well:	Well drilled into the fractured bedrock
Aquifer:	Geological unit capable of storing and transmitting water in sufficient quantity.
Confined aquifer:	Aquifer overlain by an impermeable layer. This layer protects the aquifer from surficial contaminant.
Unconfined aquifer:	Aquifer not overlain by an impermeable layer and exposed to atmospheric pressure.
Aquitard:	Geological unit capable of storing water but incapable of transmitting water in sufficient quantities.
Infiltration:	Movement of water from ground surface into the soil.
Hydraulic conductivity:	Ability of a porous media to transmit water.
Electrical conductivity (EC):	Ability of the water to conduct an electrical current. It is a general indication of the amount of total dissolved solids (TDS) in the water. EC is measure in Siemens per cm (S/cm) or microSiemens per cm (µS/cm = 10^{-6} S/cm). It ranges from several tens of µS/cm for rain water to several thousands of µS/cm for sea water. In the Chelsea area, the EC values range from approximately 90 to 1600 µS/cm.
Total coliforms:	Bacteria present in human and animal feces but also in the soil and vegetation

Faecal coliforms:	Bacteria originating from digestive tracts of humans and animals. Their presence indicates faecal pollution and the potential for pathogens to be present into the water
Macropore:	Pore of greater dimension resulting from biological activity in the soil, from roots and cracks in clay

Drilled well



Source: Modified from Best Management Practice – Water Well

Introduction

The objective of the project was to improve the understanding of private well contamination resulting from the infiltration of surface water. The risk of contamination in drilled wells was evaluated based on site characteristics and well construction.

Your well was tested every month for bacteria in order to assess the seasonality of contamination. Chemical analysis of the well water was carried out to understand the groundwater pathways and to establish possible links to potential contamination sources.

The objective of this report is to increase your awareness of possible water quality issues in your well and of the possible remedial actions that could taken preserve or improve the quality of your well water. It contains a summary of the work conducted, the data obtained, conclusions and some suggestions.

Site Description

Your well is drilled into the Precambrian bedrock, which is overlain by less than 2 metres of till. The till is composed primarily of sand and silt deposited during the last glaciation (about 10,000 years ago). The well is approximately 77 metres deep and the static water level is located 3 metres below ground surface.

Your well draws water from an unconfined aquifer. An aquifer is defined as a geologic unit capable of storing and transmitting water. This aquifer is also considered unconfined because there is no impermeable protective layer overlaying it. Usually, these types of aquifer are more vulnerable to contamination since there is no confining layer. The confining layer provides an impermeable barrier, thereby naturally protecting the well against surface contamination.

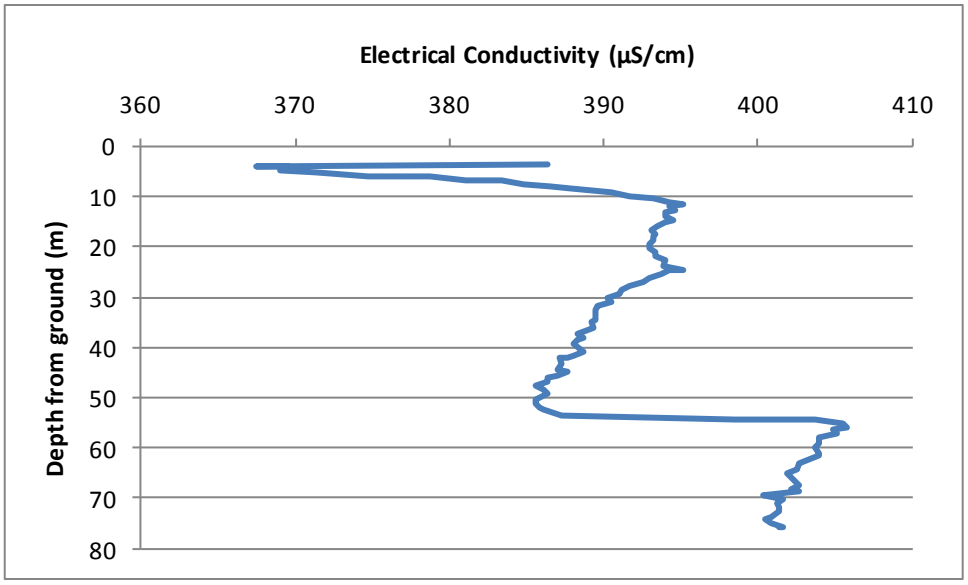


Figure 1: Electrical conductivity profile of the water column

The figure above displays the electrical conductivity (EC) profile of the well water column. The electrical conductivity is the ability of the water to conduct an electric current and it is a measure of the amount of dissolved solids in the well. For your well, the values range from 370 to 410 µS/cm with an important change at a depth of 55 metres from ground level. It is interpreted that at this depth, a fracture with higher EC water connects with the water column. However, the magnitude of the variations falls within the uncertainty range of the instrument.

Analytical Techniques

To evaluate the status of the well seal, two techniques were employed:

1. Hydraulic Conductivity

   The first technique measures the hydraulic conductivity (K) around the well to see if water infiltrates into the ground more easily than in the surrounding area. A statistical test was done to compare the K values resulting from the infiltration tests. If the K value at the well was found to be relatively greater than the K values of the surrounding, then there is a potential for a faulty seal.

2. Tracer Test

   The second technique involves injecting a tracer (a solution of NaCl or commonly, table salt) around the well casing and then measuring the electrical conductivity of the well water over time. If the tracer is detected in the well water, then surface water is likely capable of seeping down the sides of the well, indicating a hydraulic connection with the surface.

Results

1. Hydraulic conductivity comparison

The infiltration tests were done on June 9th and 10th 2008. There were no statistically significant differences between the hydraulic conductivity value measured at the well and the hydraulic conductivity measurements in the vicinity of the well. This indicates that the infiltration rates are similar on the site.

2. Tracer test

The tracer was injected on June 9th and monitored until June 19th. During the monitoring period, rain events were recorded from June 15th to the 19th. These rain events could have contributed to the tracer dilution and prevent its detection.

A total of 400L of the tracer solution, with an EC of 13,000 µS/cm, was injected following the infiltration of 200L of well water (EC around 400 µS/cm), which acted as the pre-tracer in this case. After the injection of the tracer, more well water was infiltrated as a "chaser" in order to help the infiltration of the tracer.

For comparison purposes, the EC profiles are plotted in the figure below. The tracer was possibly detected in the water column 6 days following its injection. A higher peak in the EC values can be observed at 10 metres depth. The variations in the EC profiles show a good correlation to rainfall. For example, it rained the day of the tracer injection and the well responded 1 day after (EC values decreases). This observation can also be used to explain the decreases observed in the EC profiles 7 days after the tracer injection.

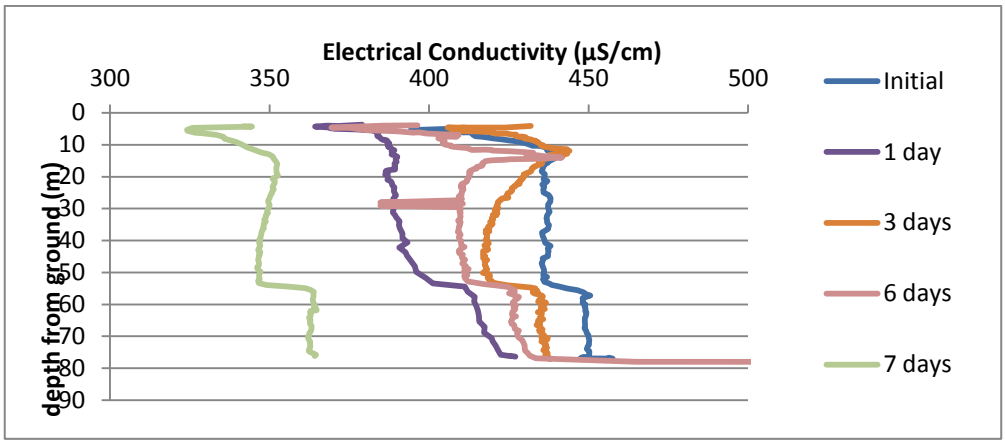


Figure 2: Electrical conductivity profiles of the water columns, before the tracer injection (*initial* profile) up to 7 days following the injection. The tracer can be noticed in the *6 days* profile

Bacteria

Bacteria are naturally present in surface water and soil. They are carried to the groundwater system through the infiltration process. Different factors affect movement of bacteria in soil. These are directly related to the bacteria (type, size and population dynamic) or the soil properties (chemical, biological and physical). Usually, most of the bacteria are filtered through the upper soil profile, but water can carry bacteria deeper using larger pore structures. These structures, called macropores, result from many things: earthworms, decayed roots and crack in clayey soil are some examples. Macropores affect the efficiency of the soil to filter bacteria allowing them to travel deeper and faster.

Bacterial contamination in a well is a product of many factors. In a municipality like Chelsea, where agriculture is not a common practice, well construction (type, age, depth), location, the presence of septic system and the geology (bedrock and surficial) would be the primary contributors to bacterial contamination.

The well showed many contamination events during the April 2008 to May 2009 sampling period. This is illustrated in the figure below. A total of 14 samples were collected and analysed for total and faecal coliforms. The presence of total coliforms was detected 4 times and one sample exceeded the regulation limit of 10 cfu/100mL (colony forming units / 100 millilitres). During the same period, three samples exceeded the faecal coliforms regulation limit of 0 cfu/100mL.

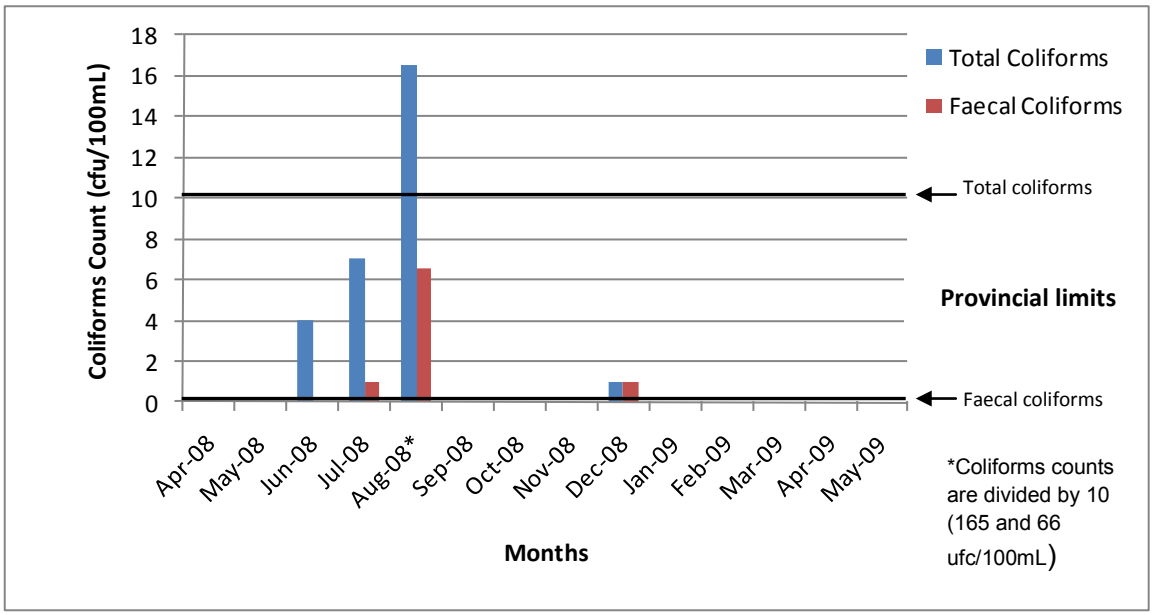


Figure 3: Results of the bacterial analysis (total and faecal coliforms) of the water samples, from April 2008 to May 2009.

Chemical analysis

As water naturally flows into the subsurface, it dissolves minerals along its pathway. The dissolution process is relatively slow in Precambrian bedrock compared to younger sedimentary rocks such as limestone or sandstone. However, other non natural sources may contribute to dissolved solids such as road salt application, septic systems or fertilizers.

Water samples were analysed for various dissolved species at the University of Ottawa. The results of the analyses are given in the following table. This table also shows the yearly average and the provincial guideline, if applicable. The concentrations are measured in milligrams per litre (mg/L).

Sampling date	pH	Fluoride (mg/L)	Chloride (mg/L)	Nitrate as Nitrogene (mg/L)	Sulphate (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Hardness (mg/L of $CaCO_3$)
Apr-08	7.4	1.5	7.9	bdl	33.5	58.3	11.1	41.0	191.6
May-08	7.6	1.0	8.2	bdl	34.6	55.9	10.7	40.8	183.5
Jun-08	7.5	1.6	8.3	bdl	36.2	80.6	15.7	47.4	266.1
Jul-08	7.4	1.2	10.3	bdl	31.9	54.5	10.5	37.6	179.3
Aug-08	7.0	1.4	7.7	bdl	33.4	57.9	11.6	40.1	192.3
Sep-08	7.5	0.7	4.5	bdl	13.8	31.5	10.5	40.2	122.1
Oct-08	7.2	1.8	8.7	bdl	37.5	56.4	10.8	40.3	185.7
Nov-08	7.2	1.4	5.7	bdl	21.8	55.6	10.8	38.3	183.6
Dec-08	7.1	1.7	9.4	bdl	37.1	54.0	10.7	37.9	179.0
Jan-09	6.9	1.8	9.7	bdl	38.0	54.1	10.8	38.9	179.7
Feb-09	7.1	1.3	3.4	bdl	13.3	53.8	10.7	39.5	178.7
Mar-09	7.2	1.8	9.5	bdl	39.5	49.4	9.9	36.2	164.0
Apr-09	7.1	1.8	9.1	bdl	39.0	53.8	10.7	40.8	178.8
May-09	7.2	1.9	8.7	bdl	41.1	52.1	10.5	41.1	173.7
average	7.2	1.5	7.9		32.2	54.9	11.1	40.0	182.7
Guideline		1.5 MAC	250.0 AO	10.0 MAC	500.0 AO			20.0 AO	100.0 AO

OG = Operational Guideline
MAC= Maximum Allowable Concentration
AO= Aesthetic Objective
Bdl= below detection limit

The dissolved solids measured during this study are water quality indicators. It is important to realize that their presence may not have an impact on health. The following table describes the parameters and their possible effects.

Parameters	Definition/sources	Possible effects/concerns
pH	Measure of the acidity of water	• An acid water (pH<6.5) can have a corrosive effect • Low pH increases metals in solution, which could yield health concerns
Fluoride	Natural occurrence	• Mottled teeth • Bone development (high concentrations)
Chloride	Natural occurrence or human related activities	• Corrosive effect on plumbing • Salty taste
Nitrates	Human related activities	• Health Concerns
Sulphates	Natural occurrence or human related activities	• Water has laxative effect
Sodium	Natural occurrence or human related activities	• Health concerns • Salty taste
Hardness	Caused by the presence of calcium and magnesium and occasionally iron in the water	• No health effect • Soap scum • Scale buildup on plumbing fixture and pipes • Stained and mottled laundry

Sources: Best Management Practices –Water Well

Guidelines for Hardness

Category	Concentration of calcium carbonate (mg/L)
Soft	0 to <60
Medium Hard	60 to <120
Hard	120 to <180
Very Hard	180 and more

Source : Health Canada

Summary and Suggestions

Seal testing

The hydraulic conductivity (K) at the well and the K in the vicinity are similar and no differences could be detected using statistical analysis. The tracer was possibly detected in the water column 6 days following its injection. This indicates the presence of a potential hydraulic connection between the surface and the water column. However, it is not clear if the tracer traveled through the annular space of the well or in the fractures surrounding it. The geology may have an impact as important as the well construction in the bacterial contamination of the water column.

Possible sources of contamination

Your well is characterized by sporadic contamination events. While monitoring the tracer arrival in the well, we observed a short response time to rainfall events. This could result from the characteristics of the site, which may allow rapid infiltration of surface water. When rapid infiltration occurs, the soil may not have sufficient time to filter the bacteria and they can reach the water column. During the major contamination events, the total coliforms were associated with faecal coliforms. This could be resulting from natural causes near the well or in the recharge area.

It was observed that the well cap is not insect-proof and spider webs were present in the well cap. The presence of bugs most likely contributes to a small concentration of bacteria into the well.

Chemical analysis

Most constituent concentrations are below guidelines/regulations with the exception of sodium (Na) which is slightly above the guideline of 20 mg/L. The hardness is also above the aesthetic objective. The yearly average for this parameter is 183 mg/L as $CaCO_3$, while the aesthetic objective is 100 mg/L as $CaCO_3$. Your well water is therefore considered very hard.

Suggestions

- In your situation, the presence of bacteria is recurrent and extra care should be taken for any use of water related to human consumption. The installation of a filtration system that kills microorganisms should be considered.
- It is recommended to get your water tested for bacteria at least 1 time a year, especially after important rainfall events and snowmelt.
- A potential preferential pathway to surface water infiltration is the well annular space. To diminish the infiltration at the wellhead, it is recommended that the soil be mounded around the casing, which will deviate the runoff away from the wellhead, allowing the natural soil process to attenuate the bacteria present in the water.
- A good well cap should keep bugs out of the well. Proper insect-proof cap are available and will easily fit on your well. This will not stop the contamination but will prevent insects entering the well, which can increase the concentration of total coliforms.
- Keeping the animals and wildlife away from the well head; for example, by installing a fence around the well will also help prevent contamination.
- Every year, examine into the inside of the well with a flash light. You can look for cracks in the casing caused by corrosion. Also check for holes around the pitless adaptor (area where pipes are connected). A record should be kept and comparisons made year to year. Corrective action can be suggested a licensed well contractor if something wrong is detected.
- It is important to consider activities around the wellhead, especially uphill from the well. For example: if the driveway is located uphill from the well and runoff water flow towards the well. Extra care should be taken to make sure there are no leaks from cars and salt should not be used as de-icing agent. To prevent nitrate contamination, no fertilizers should be used uphill or near the well recharge area.

The information presented in this report comes from the following sources:

*****These are also excellent sources for more information on water wells**

Conboy M.J, Smith S., 2005. A comprehensive consumer's guide for private water wells ISBN 0-9780387-0-3
www.wellwise.ca

Guidelines for Canadian Water Quality-Hardness
http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/hardness-durete/index-eng.php

Ministère du développement durable, environnement et parcs (MDDEP) -*La qualité de l'eau de mon puits* (French only)
http://www.mddep.gouv.qc.ca/eau/potable/depliant/index.htm

Ontario Ministry of Agriculture Food and Rural Affairs/Agriculture and Agri-food Canada. 2003 *Best Management Practices –Water Well*
http://www.omafra.gov.on.ca/english/environment/water/publications.htm

uOttawa

Université d'Ottawa • University of Ottawa

Faculté des sciences Faculty of Science
Sciences de la Terre Earth Sciences

Contamination of Private Well Study
Municipality of Chelsea, Québec



Report presented to:
W4
Chelsea, Québec

Report prepared by:
Pascale St-Germain
PhD Candidate
University of Ottawa

May 2010

Acknowledgements

Thank you for your help with this study. Your assistance is valuable in our effort to better understand groundwater wells in fractured bedrock and potential contaminant pathways. We appreciate the access to your property, your hospitality and your collecting water samples for the purpose of this research.

Important note

The suggestions presented in this report are made to improve the quality of your well water. They may help reduce the number of coliforms in your well, but may not be the only solution to any problems. An attempt was made to find the most probable source of contamination; however, many factors can affect water quality. This report was prepared to give you a better understanding of your well and does not include all the conclusions found in the overall study. All suggestions should be treated with caution.

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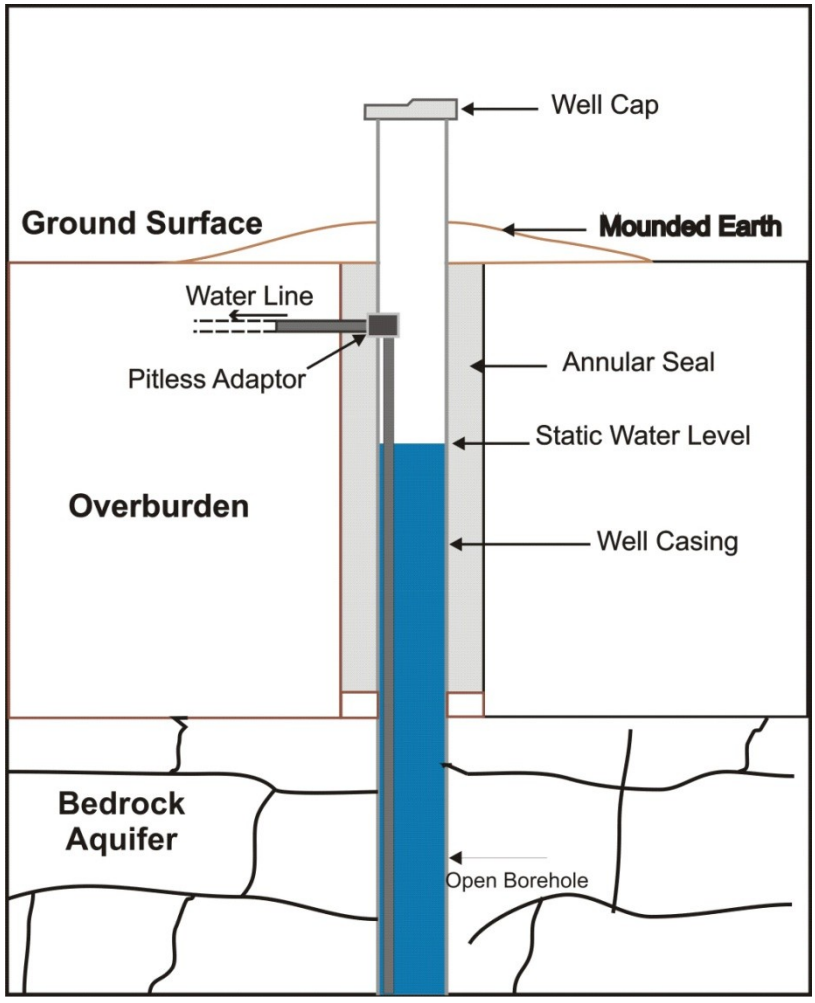
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Drilled well



Source: Modified from Best Management Practice – Water Well

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Site Description

Your well is drilled into the Precambrian bedrock, which is overlain by less than 2 metres of till. The till is composed primarily of sand and silt deposited during the last glaciation (about 10,000 years ago). The well is approximately 50 metres deep and the static water level is located 11 metres below ground surface.

Your well draws water from an unconfined aquifer. An aquifer is defined as a geologic unit capable of storing and transmitting water. This aquifer is also considered unconfined because there is no impermeable protective layer overlaying it. Usually, these types of aquifer are more vulnerable to contamination since there is no confining layer. The confining layer provides an impermeable barrier, thereby naturally protecting the well against surface contamination.

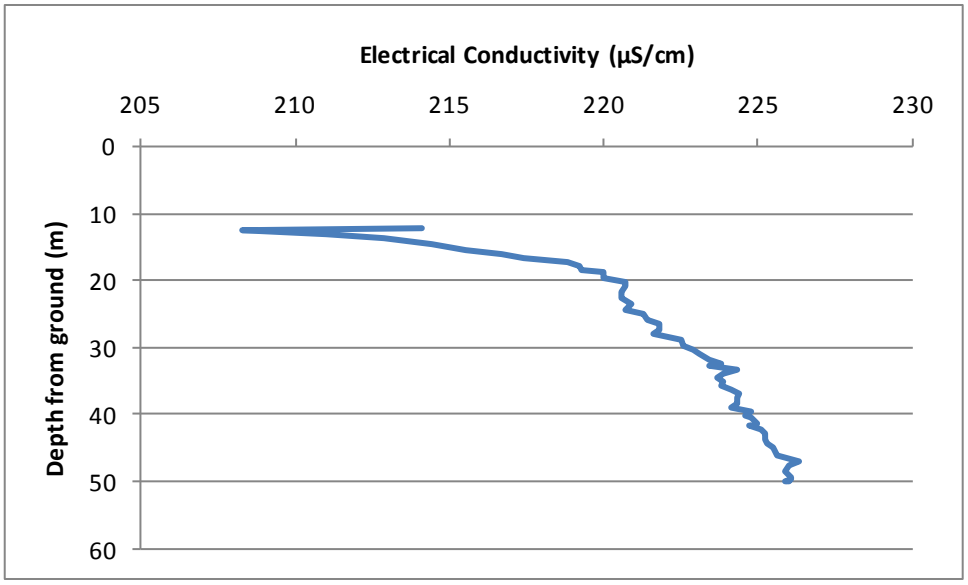


Figure 1: Electrical conductivity profile of the water column

The figure above displays the electrical conductivity (EC) profile of the well water column. The electrical conductivity is the ability of the water to conduct an electric current and it is a measure of the amount of dissolved solids in the well. For this well, the values range from 205 to 225 µS/cm with an gradational increase towards the bottom of the well. The small variations represent multiple fractures in the well. These EC values are relatively low which is indicator of water of good quality. The variations in EC values are all within measurement uncertainty.

Bacteria

Bacteria are naturally present in surface water and soil. They are carried to the groundwater system through the infiltration process. A number of factors may affect the movement of bacteria in soil. These are directly related to the bacteria (type, size and population dynamic) and the soil properties (chemical, biological and physical). Usually, most of the bacteria are filtered through the upper soil profile, but water can carry bacteria deeper using larger pore structures. These structures, called macropores, result from many things: earthworms, decayed roots and crack in clayey soil are some examples.

Macropores reduce the efficiency of the soil to filter bacteria allowing them to travel deeper and faster.

Bacterial contamination in a well is a product of many factors. In a municipality like Chelsea, where agriculture is not a common practice, well construction (type, age, depth), location, the presence of septic system and the geology (bedrock and surficial) would be the primary contributors to bacterial contamination.

The well showed two contamination events during the April 2008 to May 2009 sampling period. This is illustrated in the figure below. A total of 14 samples were collected and analysed for total and faecal coliforms. The presence of total coliforms was detected in eight samples and two samples exceeded the regulation limit, of 10 cfu/100mL (colony forming units / 100 millilitres). Faecal coliforms were not detected during the sampling period.

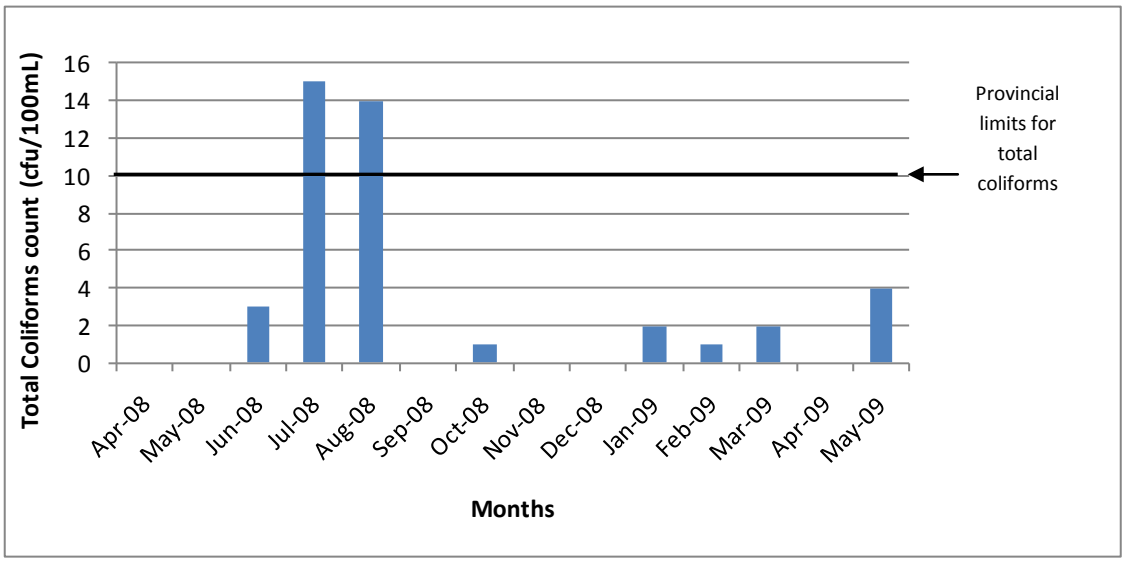


Figure 2: Results of the bacterial analysis (total and faecal coliforms) of the water samples, from April 2008 to May 2009.

Chemical analysis

As water naturally flows into the subsurface, it dissolves minerals along its pathway. The dissolution process is relatively slow in Precambrian bedrock compared to younger sedimentary rocks such as limestone or sandstone. However, other non natural sources may contribute to dissolved solids such as road salt application, septic systems or fertilizers.

Water samples were analysed for various dissolved species at the University of Ottawa. The results of the analyses are given in the following table. This table also shows the yearly average and the provincial guideline, if applicable. The concentrations are measured in milligrams per litre (mg/L)

Sampling date	pH	Fluoride (mg/L)	Chloride (mg/L)	Nitrate as N (mg/L)	Sulphate (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Hardness (mg/L as $CaCO_3$)
Apr-08	7.5	bdrl	4.6	0.4	10.9	62.1	5.9	2.1	179.4
May-08	7.3	bdrl	4.2	0.5	9.8	57.2	5.8	2.3	166.9
Jun-08	7.2	bdrl	4.1	0.4	11.3	54.9	5.6	1.9	160.2
Jul-08	7.3	bdl	3.6	0.4	10.4	54.3	6.0	2.5	160.7
Aug-08	7.3	bdl	3.6	0.5	9.2	58.1	6.4	2.3	171.7
Sep-08	7.2	bdl	3.7	0.4	11.4	55.1	6.0	2.1	162.7
Oct-08	7.4	bdl	3.3	0.5	11.6	59.0	6.4	2.2	173.8
Nov-08	7.2	bdl	2.7	0.6	5.9	59.8	5.9	2.1	173.7
Dec-08	7.2	bdl	4.4	0.5	10.4	58.7	5.7	2.3	170.4
Jan-09	7.1	bdl	4.3	0.4	11.1	56.8	5.7	2.0	165.7
Feb-09	7.2	bdl	4.2	0.4	10.9	56.6	5.4	1.9	164.0
Mar-09	7.0	bdl	4.2	0.4	11.0	54.3	5.5	2.1	158.3
Apr-09	7.1	bdl	4.8	0.6	10.5	58.0	5.5	2.1	167.4
May-09	7.0	bdl	3.9	0.3	11.5	52.3	5.8	2.0	154.4
Average	7.2		4.0	0.4	10.4	56.9	5.8	2.1	166.4
Guideline		1.5 MAC	250.0 AO	10.0 MAC	500.0 AO			20.0 AO	100.0 AO

OG = Operational Guideline
MAC= Maximum Allowable Concentration
AO= Aesthetic Objective
bdl= below detection limit

The dissolved solids measured during this study are water quality indicators. It is important to realize that their presence may not have an impact on health. The following table describes the parameters and their possible effects.

Parameters	Definition/sources	Possible effects/concerns
pH	Measure of the acidity of water	• An acid water (pH<6.5) can have a corrosive effect • Low pH increases metals in solution, which could yield health concerns
Fluoride	Natural occurrence	• Mottled teeth • Bone development (high concentrations)
Chloride	Natural occurrence or human related activities	• Corrosive effect on plumbing • Salty taste
Nitrates	Human related activities	• Health Concerns
Sulphates	Natural occurrence or human related activities	• Water has laxative effect
Sodium	Natural occurrence or human related activities	• Health concerns • Salty taste
Hardness	Caused by the presence of calcium and magnesium and occasionally iron in the water	• No health effect • Soap scum • Scale buildup on plumbing fixture and pipes • Stained and mottled laundry

Sources: Best Management Practices –Water Well

Guidelines for Hardness

Category	Concentration of calcium carbonate (mg/L)
Soft	0 to <60
Medium Hard	60 to <120
Hard	120 to <180
Very Hard	180 and more

Source : Health Canada

Summary and Suggestions

Possible sources of contamination

The well shows two distinct contamination events which exceeded regulation limits, however, the presence of total coliforms were detected consistently. The consistent presence of total coliforms may be an indicator of surface water reaching the well. The bacterial contamination could result from the low soil depth, the drainage toward the well or the presence of trees at the wellhead. The presence of total coliforms during winter months, when infiltration is minimal, suggests that coliforms are present in the aquifer.

It was observed that the well cap is not insect-proof and spider webs were present in the well cap. The presence of bugs most likely contributes to a small concentration of bacteria into the well.

Chemical analysis

Most constituent concentrations are below guidelines/regulations with the exception of the hardness. The yearly average for this parameter is 166 mg/L as $CaCO_3$, while the aesthetic objective is 100 mg/L as $CaCO_3$. Your well water is therefore considered as hard.

Concentrations of nitrate were detected in the well, but the levels are below the maximum allowed concentration. It would be important to monitor this parameter. It is recommended by the MDDEP to have this parameter analysed every few years. If the level gets above 5 mg-N/L, then yearly monitoring is recommended.

Suggestions:

- In your situation, the presence of bacteria is recurrent and extra care should be taken for any use of water related to human consumption. The installation of a filtration system that kills microorganisms should be considered.
- It is recommended to get your water tested for bacteria at least 1 time a year, especially after important rainfall events and snowmelt.

- A good well cap should keep bugs out of the well. Proper insect-proof cap are available and will easily fit on your well. This will not stop the contamination but will prevent insects entering the well, which can increase the concentration of total coliforms.
- Every year, examine into the inside of the well with a flash light. You can look for cracks in the casing caused by corrosion. Also check for holes around the pitless adaptor (area where pipes are connected). A record should be kept and comparisons made year to year. Corrective action can be suggested a licensed well contractor if something wrong is detected.

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Université d'Ottawa • University of Ottawa
Faculté des sciences Faculty of Science
Sciences de la Terre Earth Sciences

Contamination of Private Well Study
Municipality of Chelsea, Québec



Report presented to:
W5
Chelsea, Qc

Report prepared by:
Pascale St-Germain
PhD Candidate
University of Ottawa

May 2010

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Important note

The suggestions presented in this report are made to improve the quality of your well water. They may help reduce the number of coliforms in your well, but may not be the only solution to any problems. An attempt was made to find the most probable source of contamination; however, many factors can affect water quality. This report was prepared to give you a better understanding of your well and does not include all the conclusions found in the overall study. All suggestions should be treated with caution.

Before investing in your well (well upgrade or water treatment system) I would suggest seeking advice from professionals and getting your water tested independently by an accredited laboratory before future investment in a treatment system.

Thank you very much for your understanding

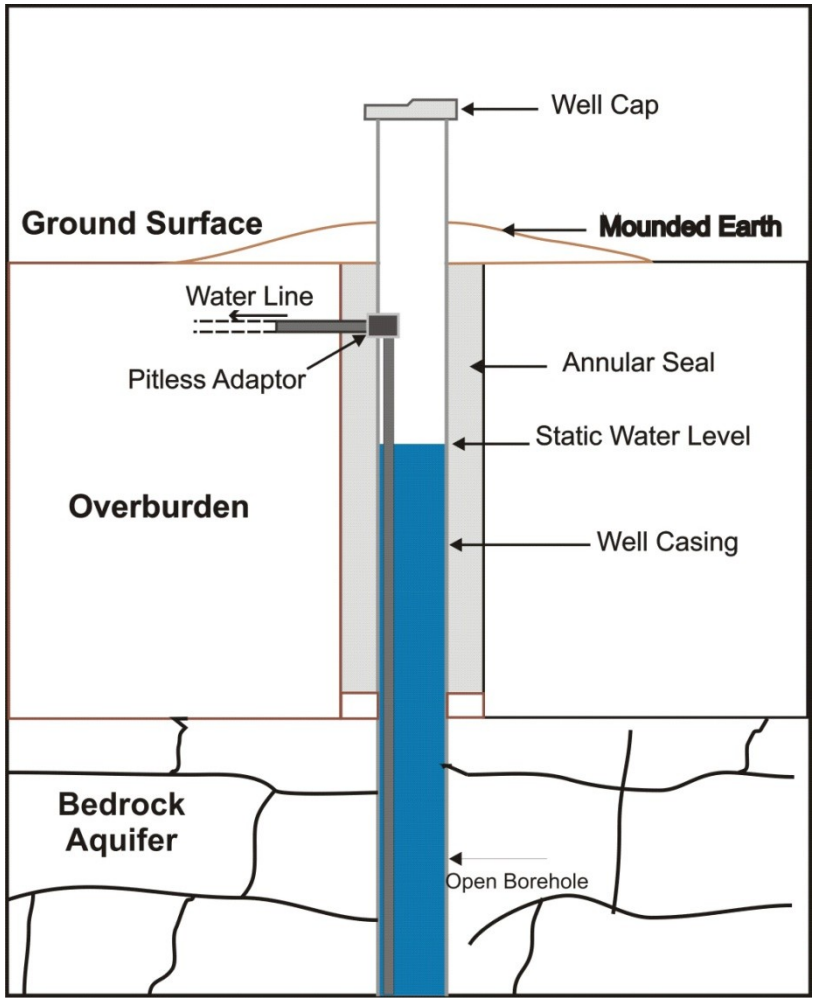
Pascale St-Germain
PhD candidate
University of Ottawa
Department of Earth Sciences

Glossary

Precambrian bedrock:	Fracture bedrock mainly composed of igneous and metamorphic rocks that are more than 542 million years old.
Overburden:	Unconsolidated sediments overlaying the bedrock and composed of grains of various sizes.
Champlain Sea:	Inland sea created about 10 000 year ago resulting from the melting of the *Inlandsis laurentidien* ice sheet. The sea principally covered the Montreal area but also some areas in south eastern Ontario.
Preferential pathways:	Direct movement of water through macro pores without the natural attenuation potential from the soil. This allows bacteria (or contaminant) to get carried faster and deeper.
Drilled well:	Well drilled into the fractured bedrock
Aquifer:	Geological unit capable of storing and transmitting water in sufficient quantity.
Confined aquifer:	Aquifer overlain by an impermeable layer. This layer protects the aquifer from surficial contaminant.
Unconfined aquifer:	Aquifer not overlain by an impermeable layer and exposed to atmospheric pressure.
Aquitard:	Geological unit capable of storing water but incapable of transmitting water in sufficient quantities.
Infiltration:	Movement of water from ground surface into the soil.
Hydraulic conductivity:	Ability of a porous media to transmit water.
Electrical conductivity (EC):	Ability of the water to conduct an electrical current. It is a general indication of the amount of total dissolved solids (TDS) in the water. EC is measure in Siemens per cm (S/cm) or microSiemens per cm (µS/cm = 10^{-6} S/cm). It ranges from several tens of µS/cm for rain water to several thousands of µS/cm for sea water. In the Chelsea area, the EC values range from approximately 90 to 1600 µS/cm.
Total coliforms:	Bacteria present in human and animal feces but also in the soil and vegetation

Faecal coliforms:	Bacteria originating from digestive tracts of humans and animals. Their presence indicates faecal pollution and the potential for pathogens to be present into the water
Macropore:	Pore of greater dimension resulting from biological activity in the soil, from roots and cracks in clay

Drilled well



Source: Modified from Best Management Practice – Water Well

Introduction

The objective of the project was to improve the understanding of private well contamination resulting from the infiltration of surface water. The risk of contamination in drilled wells was evaluated based on site characteristics and well construction.

Your well was tested every month for bacteria in order to assess the seasonality of contamination. Chemical analysis of the well water was carried out to understand the groundwater pathways and to establish possible links to potential contamination sources.

The objective of this report is to increase your awareness of possible water quality issues in your well and of the possible remedial actions that could taken preserve or improve the quality of your well water. It contains a summary of the work conducted, the data obtained, conclusions and some suggestions.

Site Description

Your well is drilled into the Precambrian bedrock, which is overlain by less than 2 metres of till. The till is composed primarily of sand and silt deposited during the last glaciation (about 10,000 years ago). The well is approximately 90 metres deep and the static water level is located 24 metres below ground surface.

Your well draws water from an unconfined aquifer. An aquifer is defined as a geologic unit capable of storing and transmitting water. This aquifer is also considered unconfined because there is no impermeable protective layer overlaying it. Usually, these types of aquifer are more vulnerable to contamination since there is no confining layer. The confining layer provides an impermeable barrier, thereby naturally protecting the well against surface contamination.

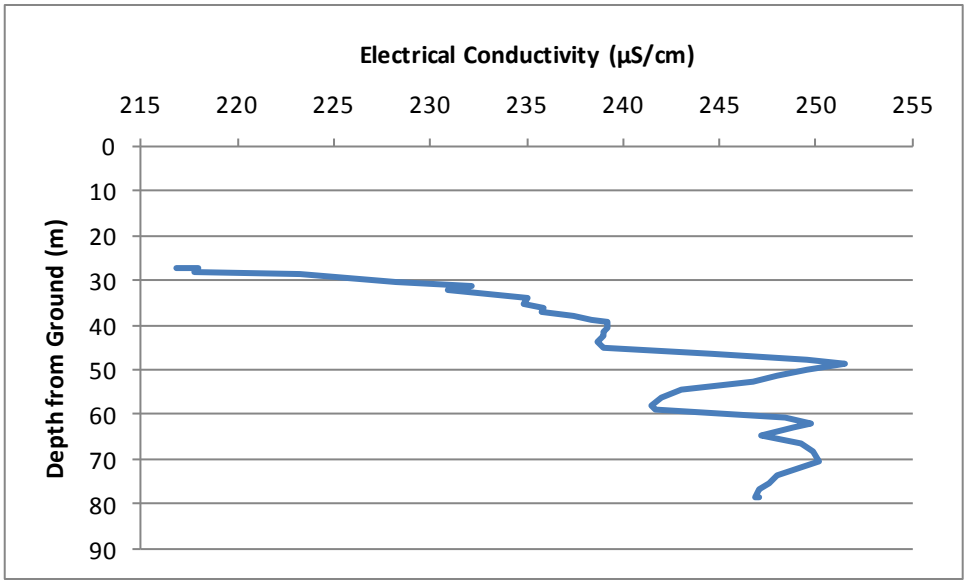


Figure 1: Electrical conductivity profile of the water column

The figure above displays the electrical conductivity (EC) profile of the well water column. The electrical conductivity is the ability of the water to conduct an electric current and it is a measure of the amount of dissolved solids in the well. For your well, the values range from 215 to 255 µS/cm with a at a depth of 50 metres from ground level. It is interpreted that at this depth, a fracture with a higher EC water connects with the water column. However, the magnitude of the variations falls within the measurement error range of the instrument.

Bacteria

Bacteria are naturally present in surface water and soil. They are carried to the groundwater system through the infiltration process. A number of factors may affect the movement of bacteria in soil. These are directly related to the bacteria (type, size and population dynamic) and the soil properties (chemical, biological and physical). Usually, most of the bacteria are filtered through the upper soil profile, but water can carry bacteria deeper using larger pore structures. These structures, called macropores, result from many things: earthworms, decayed roots and crack in clayey soil are some examples.

Macropores reduce the efficiency of the soil to filter bacteria allowing them to travel deeper and faster.

Bacterial contamination in a well is a product of many factors. In a municipality like Chelsea, where agriculture is not a common practice, well construction (type, age, depth), location, the presence of septic system and the geology (bedrock and surficial) would be the primary contributors to bacterial contamination.

The well showed three contamination events during the April 2008 to May 2009 sampling period. This is illustrated in the figure below. A total of 14 samples were collected and analysed for total and faecal coliforms. The presence of total coliforms was detected in eight samples and two samples exceeded the regulation limit of 10 cfu/100mL (colony forming units / 100 millilitres). During the same period, one sample exceeded the faecal coliforms regulation limit of 0 cfu/100mL.

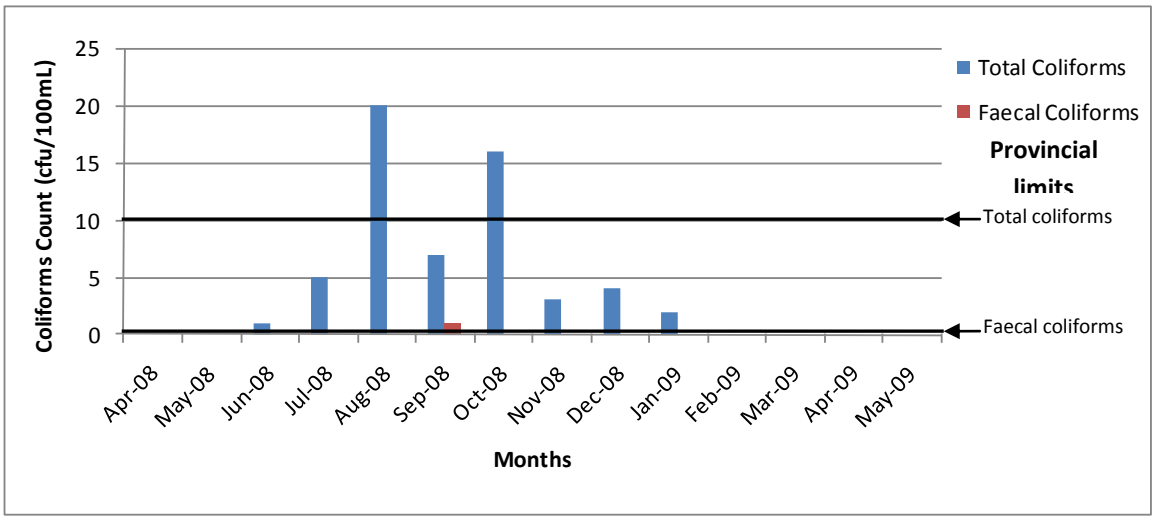


Figure 2: Results of the bacterial analysis (total and faecal coliforms) of the water samples, from April 2008 to May 2009.

Chemical analysis

As water naturally flows into the subsurface, it dissolves minerals along its pathway. The dissolution process is relatively slow in Precambrian bedrock compared to younger sedimentary rocks such as limestone or sandstone. However, other non natural sources may contribute to dissolved solids such as road salt application, septic systems or fertilizers.

Water samples were analysed for various dissolved species at the University of Ottawa. The results of the analyses are given in the following table. This table also shows the yearly average and the provincial guideline, if applicable. The concentrations are measured in milligrams per litre (mg/L).

Sampling date	pH	Fluoride (mg/L)	Chloride (mg/L)	Nitrate - N (mg/L)	Sulphate (mg/L)	Calcium (mg/L)	Potassium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Hardness (mg/L as $CaCO_3$)
Apr-08	6.7	NA	**NA**	NA	NA	48.4	1.9	8.9	12.3	157.6
May-08	6.8	bdl	22.5	0.8	18.7	44.6	1.9	7.8	11.6	143.5
Jun-08	6.7	bdl	21.9	0.8	20.8	45.4	1.7	7.9	10.8	146.0
Jul-08	6.7	bdl	19.7	0.9	19.9	48.4	1.9	8.7	13.0	157.0
Aug-08	7.0	bdl	18.8	1.2	22.3	49.9	2.0	9.4	12.9	163.5
Sep-08	7.1	bdl	20.4	1.2	23.9	47.4	2.0	9.4	13.3	157.3
Oct-08	6.8	bdl	21.7	1.9	25.3	61.5	2.2	10.5	14.9	197.0
Nov-08	6.6	bdl	8.7	0.6	11.5	54.9	2.1	9.9	14.0	178.1
Dec-08	6.7	bdl	14.4	1.4	22.5	50.9	2.1	9.3	13.2	165.4
Jan-09	6.6	bdl	14.6	1.3	21.0	47.4	2.3	8.5	11.9	153.3
Feb-09	6.8	bdl	16.5	1.6	24.5	50.0	2.4	8.8	12.4	161.3
Mar-09	6.6	NA	NA	NA	NA	12.0	0.7	2.6	3.4	40.7
Apr-09	6.7	bdl	15.5	0.6	16.2	37.4	1.6	6.7	9.4	120.9
May-09	6.6	bdl	17.4	0.7	18.7	40.1	1.6	7.3	9.8	130.2
Average	6.7		17.7	1.1	20.4	45.6	1.9	8.3	11.6	148.0
Guideline		1.5 MAC	250.0 AO	10.0 MAC	500.0 AO				20.0 AO	100.0 AO

OG = Operational Guideline
MAC= Maximum Allowable Concentration
AO= Aesthetic Objective
Bdl= below detection limit

The dissolved solids measured during this study are water quality indicators. It is important to realize that their presence may not have an impact on health. The following table describes the parameters and their possible effects.

Parameters	Definition/sources	Possible effects/concerns
pH	Measure of the acidity of water	• An acid water (pH<6.5) can have a corrosive effect • Low pH increases metals in solution, which could yield health concerns
Fluoride	Natural occurrence	• Mottled teeth • Bone development (high concentrations)
Chloride	Natural occurrence or human related activities	• Corrosive effect on plumbing • Salty taste
Nitrates	Human related activities	• Health Concerns
Sulphates	Natural occurrence or human related activities	• Water has laxative effect
Sodium	Natural occurrence or human related activities	• Health concerns • Salty taste
Hardness	Caused by the presence of calcium and magnesium and occasionally iron in the water	• No health effect • Soap scum • Scale buildup on plumbing fixture and pipes • Stained and mottled laundry

Sources: Best Management Practices –Water Well

Guidelines for Hardness

Category	Concentration of calcium carbonate (mg/L)
Soft	0 to <60
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Hard	120 to <180
Very Hard	180 and more

Source : Health Canada

Summary and Suggestions

Possible sources of contamination

The well shows two distinct contamination events which exceeded regulation limits, however, the total coliforms were detected consistently. This may be an indicator of surface water reaching the well. The bacterial contamination could result from the shallow soil, the drainage toward the well or the presence of trees at the wellhead. The presence of total coliforms during winter months, when infiltration is minimal, may suggest that coliforms are present in the aquifer.

It was observed that the well cap is not insect-proof and spider webs were present in the well cap. The presence of bugs most likely contributes to a small concentration of bacteria into the well.

Chemical analysis

Most constituent concentrations are below guidelines/regulations with the exception of the hardness. The yearly average for this parameter is 148 mg/L as $CaCO_3$, while the aesthetic objective is 100 mg/L as $CaCO_3$. Your well water is therefore considered as hard.

Concentrations of nitrate were detected in the well, but the levels are below the maximum allowed concentration. It would be important to monitor this parameter. It is recommended by the MDDEP to have this parameter analysed every few years. If the level gets above 5 mg-N/L, then yearly monitoring is recommended.

Suggestions:

- In your situation, the presence of bacteria is recurrent and extra care should be taken for any use of water related to human consumption. The installation of a filtration system that kills microorganisms should be considered.
- It is recommended to get your water tested for bacteria at least 1 time a year, especially after important rainfall events and snowmelt.
- A good well cap should keep bugs out of the well. Proper insect-proof cap are available and will easily fit on your well. This will not stop the contamination but will

prevent insects entering the well, which can increase the concentration of total coliforms.

- Every year, examine into the inside of the well with a flash light. You can look for cracks in the casing caused by corrosion. Also check for holes around the pitless adaptor (area where pipes are connected). A record should be kept and comparisons made year to year. Corrective action can be suggested a licensed well contractor if something wrong is detected.
- It is important to consider activities around the wellhead, especially uphill from the well. For example: if the driveway is located uphill from the well and runoff water flow towards the well. Extra care should be taken to make sure there are no leaks from cars and salt should not be used as de-icing agent. To prevent nitrate contamination, no fertilizers should be used uphill or near the well recharge area.
- It is not recommended to plant flowers, shrubs or trees near the wellhead since their roots can affect the integrity of the annular seal protecting the well. The roots also increase the infiltration rate in the area.

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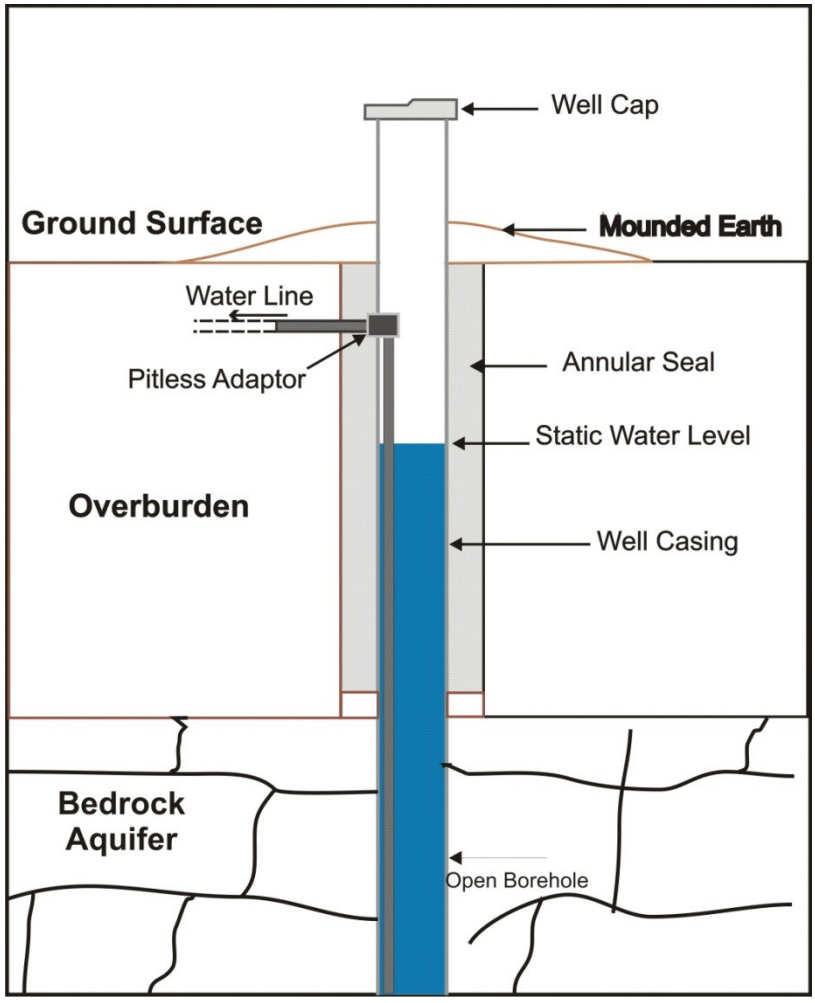
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Drilled well



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Site Description

Your well is drilled into the Precambrian bedrock, which is overlain by less than 2 metres of till. The till is composed primarily of sand and silt deposited during the last glaciation (about 10,000 years ago). The well is approximately 50 metres deep and the static water level is located 7 metres below ground surface.

Your well draws water from an unconfined aquifer. An aquifer is defined as a geologic unit capable of storing and transmitting water. This aquifer is also considered unconfined because there is no impermeable protective layer overlaying it. Usually, these types of aquifer are more vulnerable to contamination since there is no confining layer. The confining layer provides an impermeable barrier, thereby naturally protecting the well against surface contamination.

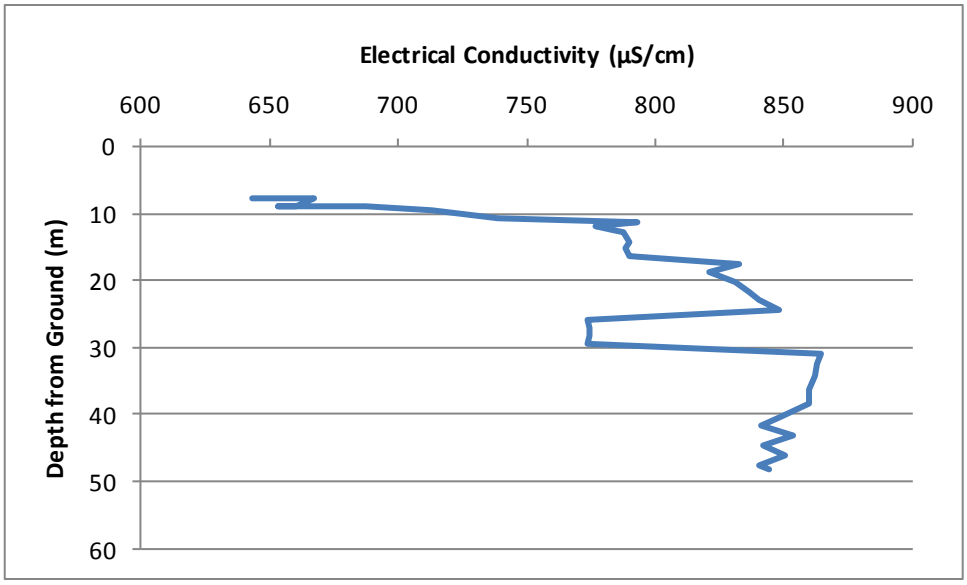


Figure 1: Electrical conductivity profile of the water column

The figure above displays the electrical conductivity (EC) profile of the well water column. The electrical conductivity is the ability of the water to conduct an electric current and it is a measure of the amount of dissolved solids in the well. For your well, the values range from 650 to 850 µS/cm with an important change at a depth of 20 to 30 metres from ground level. It is interpreted that at this depth, a fracture with a higher EC water connects with the water column.

Bacteria

Bacteria are naturally present in surface water and soil. They are carried to the groundwater system through the infiltration process. A number of factors may affect the movement of bacteria in soil. These are directly related to the bacteria (type, size and population dynamic) and the soil properties (chemical, biological and physical). Usually, most of the bacteria are filtered through the upper soil profile, but water can carry bacteria deeper using larger pore structures. These structures, called macropores, result from many things: earthworms, decayed roots and crack in clayey soil are some examples. Macropores reduce the efficiency of the soil to filter bacteria allowing them to travel deeper and faster.

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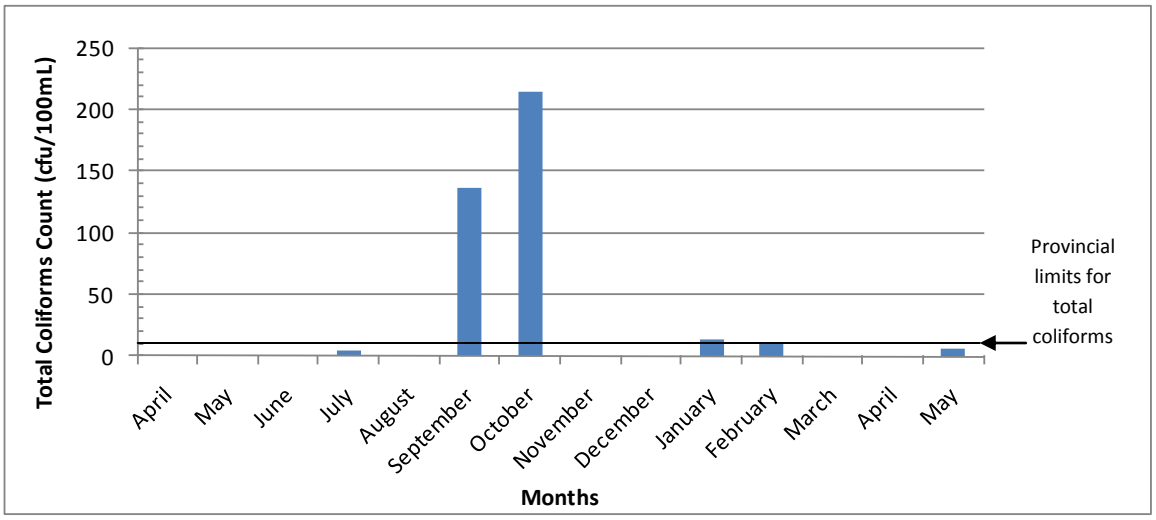


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Water samples were analysed for various dissolved species at the University of Ottawa. The results of the analyses are given in the following table. This table also shows the yearly average and the provincial guideline, if applicable. The concentrations are measured in milligrams per litre (mg/L)

Sampling date	pH	Fluoride (mg/L)	Chloride (mg/L)	Nitrate as N (mg/L)	Sulphate (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Hardness (mg/L as $CaCO_3$)
Apr-08	6.9	bdl	139.7	1.0	39.6	79.9	57.2	60.0	435.0
May-08	7.1	bdl	120.4	1.0	37.5	74.1	52.1	55.1	399.9
Jun-08	7.1	bdl	119.3	0.7	39.1	71.6	50.1	47.1	385.0
Jul-08	6.9	bdl	162.6	0.6	33.9	77.0	59.0	48.0	435.4
Aug-08	6.7	bdl	199.2	0.7	37.5	91.4	71.8	58.4	524.2
Sep-08	6.4	bdl	47.4	0.2	11.9	40.2	23.2	22.5	195.9
Oct-08	7.2	bdl	226.8	0.7	41.5	95.2	69.6	62.5	524.6
Nov-08	6.9	bdl	263.4	0.7	40.9	98.4	74.8	59.6	553.6
Dec-08	7.0	bdl	251.4	0.7	39.6	95.7	72.7	62.0	538.1
Jan-09	6.7	bdl	170.3	0.7	39.3	97.6	72.8	66.1	543.8
Feb-09	6.9	bdl	253.3	0.6	40.1	93.4	69.0	63.7	517.4
Mar-09	7.0	bdl	248.0	0.8	37.2	82.3	62.8	55.9	464.1
Apr-09	6.8	bdl	245.0	0.9	38.8	87.7	67.7	66.2	497.6
May-09	6.8	bdl	213.6	0.7	37.6	80.1	62.8	53.1	458.6
Average	6.9	NA	190.0	0.7	36.7	83.2	61.8	55.7	462.4
Guideline		1.5 MAC	250.0 AO	10.0 MAC	500.0 AO			20.0 AO	100.0 AO

OG = Operational Guideline
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AO= Aesthetic Objective
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The dissolved solids measured during this study are water quality indicators. It is important to realize that their presence may not have an impact on health. The following table describes the parameters and their possible effects.

Parameters	Definition/sources	Possible effects/concerns
pH	Measure of the acidity of water	• An acid water (pH<6.5) can have a corrosive effect • Low pH increases metals in solution, which could yield health concerns
Fluoride	Natural occurrence	• Mottled teeth • Bone development (high concentrations)
Chloride	Natural occurrence or human related activities	• Corrosive effect on plumbing • Salty taste
Nitrates	Human related activities	• Health Concerns
Sulphates	Natural occurrence or human related activities	• Water has laxative effect
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Category	Concentration of calcium carbonate (mg/L)
Soft	0 to <60
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Very Hard	180 and more

Source : Health Canada

Summary and Suggestions

Possible sources of contamination

The well shows four distinct contamination events which exceeded regulation limits, however, the total coliforms were detected consistently. This may be an indicator of surface water reaching the well. The bacterial contamination could result from the shallow soil, the drainage toward the well or the presence of trees at the wellhead. The presence of total coliforms during winter months, when infiltration is minimal, may suggest that coliforms are present in the aquifer.

It was observed that the well cap is not insect-proof and spider webs were present in the well cap. The presence of bugs most likely contributes to a small concentration of bacteria into the well.

Chemical analysis

Most constituent concentrations are below guidelines/regulations with the exception of sodium (Na) which is slightly above the guideline of 20 mg/L, and the hardness. The yearly average for this parameter is 462 mg/L as $CaCO_3$, while the aesthetic objective is 100 mg/L as $CaCO_3$. Your well water is therefore considered as very hard.

Concentrations of nitrate were detected in the well, but the levels are below the maximum allowed concentration. It would be important to monitor this parameter. It is recommended by the MDDEP to have this parameter analysed every few years. If the level gets above 5 mg-N/L, then yearly monitoring is recommended.

There is also a high concentration of chloride. Since the sodium is also high, this could be an indicator of de-icing road salt leaching into the well or contamination from a septic system nearby.

Suggestions

- In your situation, the presence of bacteria is recurrent and extra care should be taken for any use of water related to human consumption. The installation of a filtration system that kills microorganisms should be considered.
- It is recommended to get your water tested for bacteria at least 1 time a year, especially after important rainfall events and snowmelt.
- A good well cap should keep bugs out of the well. Proper insect-proof cap are available and will easily fit on your well. This will not stop the contamination but will prevent insects entering the well, which can increase the concentration of total coliforms.
- Every year, examine into the inside of the well with a flash light. You can look for cracks in the casing caused by corrosion. Also check for holes around the pitless adaptor (area where pipes are connected). A record should be kept and comparisons made year to year. Corrective action can be suggested a licensed well contractor if something wrong is detected.
- It is important to consider activities around the wellhead, especially uphill from the well. For example: if the driveway is located uphill from the well and runoff water flow towards the well. Extra care should be taken to make sure there are no leaks from cars and salt should not be used as de-icing agent. To prevent nitrate contamination, no fertilizers should be used uphill or near the well recharge area.
- It is not recommended to plant flowers, shrubs or trees near the wellhead since their roots can affect the integrity of the annular seal protecting the well. The roots also increase the infiltration rate in the area.

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*****These are also excellent sources for more information on water wells**

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Ontario Ministry of Agriculture Food and Rural Affairs/Agriculture and Agri-food Canada. 2003 *Best Management Practices –Water Well*
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Sciences de la Terre Earth Sciences

Contamination of Private Well Study
Municipality of Chelsea, Québec



Report presented to:
W7
Chelsea, QC

Report prepared by:
Pascale St-Germain
PhD Candidate
University of Ottawa

May 2010

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Important note

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Before investing in your well (well upgrade or water treatment system) I would suggest seeking advice from professionals and getting your water tested independently by an accredited laboratory before future investment in a treatment system.

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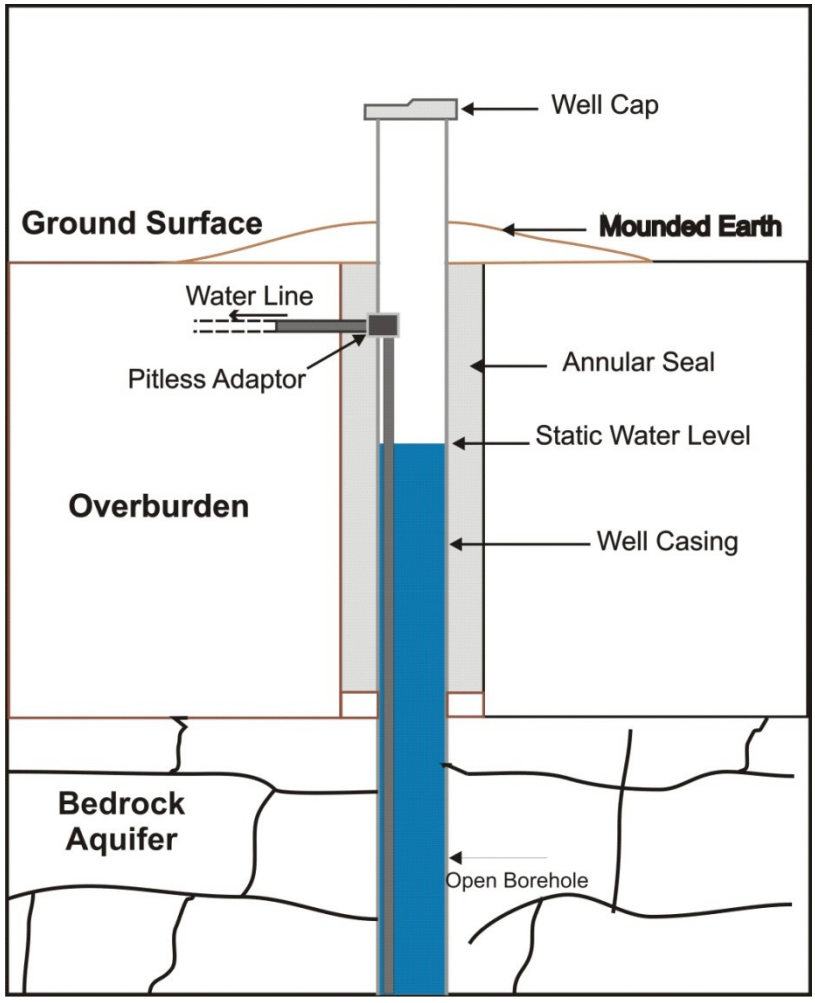
Pascale St-Germain
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Glossary

Precambrian bedrock:	Fracture bedrock mainly composed of igneous and metamorphic rocks that are more than 542 million years old.
Overburden:	Unconsolidated sediments overlaying the bedrock and composed of grains of various sizes.
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Drilled well:	Well drilled into the fractured bedrock
Aquifer:	Geological unit capable of storing and transmitting water in sufficient quantity.
Confined aquifer:	Aquifer overlain by an impermeable layer. This layer protects the aquifer from surficial contaminant.
Unconfined aquifer:	Aquifer not overlain by an impermeable layer and exposed to atmospheric pressure.
Aquitard:	Geological unit capable of storing water but incapable of transmitting water in sufficient quantities.
Infiltration:	Movement of water from ground surface into the soil.
Hydraulic conductivity:	Ability of a porous media to transmit water.
Electrical conductivity (EC):	Ability of the water to conduct an electrical current. It is a general indication of the amount of total dissolved solids (TDS) in the water. EC is measure in Siemens per cm (S/cm) or microSiemens per cm (µS/cm = 10^{-6} S/cm). It ranges from several tens of µS/cm for rain water to several thousands of µS/cm for sea water. In the Chelsea area, the EC values range from approximately 90 to 1600 µS/cm.
Total coliforms:	Bacteria present in human and animal feces but also in the soil and vegetation

Faecal coliforms:	Bacteria originating from digestive tracts of humans and animals. Their presence indicates faecal pollution and the potential for pathogens to be present into the water
Macropore:	Pore of greater dimension resulting from biological activity in the soil, from roots and cracks in clay

Drilled well



Source: Modified from Best Management Practice – Water Well

Introduction

The objective of the project was to improve the understanding of private well contamination resulting from the infiltration of surface water. The risk of contamination in drilled wells was evaluated based on site characteristics and well construction.

Your well was tested every month for bacteria in order to assess the seasonality of contamination. Chemical analysis of the well water was carried out to understand the groundwater pathways and to establish possible links to potential contamination sources.

The objective of this report is to increase your awareness of possible water quality issues in your well and of the possible remedial actions that could taken preserve or improve the quality of your well water. It contains a summary of the work conducted, the data obtained, conclusions and some suggestions.

Site Description

Your well is drilled into the Precambrian bedrock, which is overlain by a layer of clay. This clay layer is a minimum of 5 metres thick and resulted from deposition in the Champlain Sea during the last glaciation (about 10,000 years ago). The well depth is approximately 75 metres deep and the static water level is located at 10 metres below ground surface.

Your well draws water from a confined aquifer. An aquifer is defined as a geologic unit capable of storing and transmitting water. This aquifer is also considered confined because there is an impermeable protective layer overlaying it. Usually, these types of aquifer are less vulnerable to contamination because of the presence of a confining layer. The confining layer provides an impermeable barrier, thereby naturally protecting the well against surface contamination.

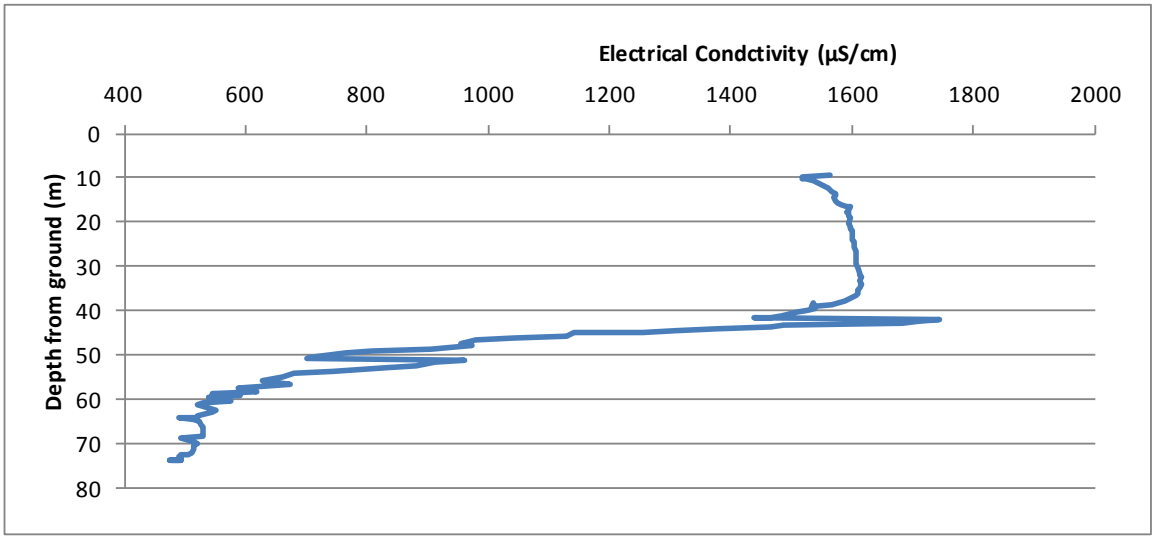


Figure 1: Electrical conductivity profile of the water column

The figure above displays the electrical conductivity (EC) profile of the well water column. The electrical conductivity is the ability of the water to conduct an electric current and it is a measure of the amount of dissolved solids in the well.For your well, the values range from 500 to 1600 µS/cm with an important change at a depth of 45 metres from ground level. It is interpreted that at this depth, fractures with lower EC values connect with the water column. The fact that the higher EC values are located above the lower EC values, in cojunction with the large contrast indicates that there is sufficient groundwater flow across the borehole to maintain the contrast. These high values suggest that the well may be affected by a contamination plume from road salt or a septic field. However, this plume does not impact the water quality of the well.

Analytical Techniques

To evaluate the status of the well seal, two techniques were employed:

1. Hydraulic Conductivity

   The first technique measures the hydraulic conductivity (K) around the well to see if water infiltrates into the ground more easily than in the surrounding area. A statistical test was done to compare the K values resulting from the infiltration

tests. If the K value at the well was found to be relatively greater than the K values of the surrounding, then there is a potential for a faulty seal.

2. Tracer Test

   The second technique involves injecting a tracer (a solution of NaCl or commonly, table salt) around the well casing and then measuring the electrical conductivity of the well water over time. If the tracer is detected in the well water, then surface water is likely capable of seeping down the sides of the well, indicating a hydraulic connection with the surface.

Results

1. Hydraulic conductivity comparison

The infiltration tests were done on August 14th and 15th 2008. The hydraulic conductivity value measured at the well was significantly higher than the hydraulic conductivity measurements in the vicinity of the well.

2. Tracer test

The tracer was injected on August 14th and water samples were collect until August 25th. During the monitoring period, a rainfall event (more than 15 mm of rain) was recorded on the 18th, which corresponds to 3 days following the injection of the tracer.

A total of 380L of the tracer solution, with an EC of 10,500µS/cm, was injected following the infiltration of 540L of well water (EC around 500µS/cm), which acted as the pre-tracer in this case. After the injection of the tracer, more well water was infiltrated as a "chaser" in order to help the infiltration of the tracer.

For comparison purposes, the EC profiles are plotted in the figure below. It is observed that the EC values in the well decrease towards the bottom. The decrease observed in the *before tracer injection* profile can therefore be interpreted as resulting from the pre-tracer injection (because the EC value of the pre-tracer is similar to the EC value of the bottom of the well). The tracer was detected in the well shortly after the end of the

injection. This is more noticeable in the *1 day* profile. The EC values return to typical on the *2 days* profiles. Again, the contrast in the EC values is observed in the profiles.

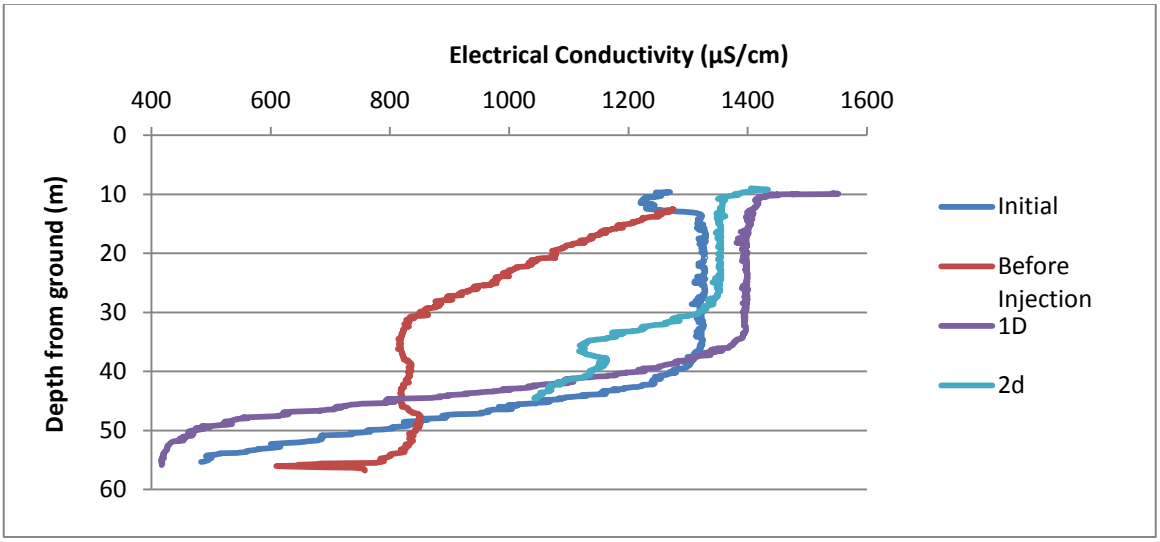


Figure 2: Electrical conductivity profiles of the water columns representing the initial profile, the before tracer injection profile and up to 2 days following the injection. The tracer can be noticed in the *1 day* profile. The contrast in the EC values is interpreted as a contaminant plume flowing across the borehole at a significant velocity.

Bacteria

Bacteria are naturally present in surface water and soil. They are carried to the groundwater system through the infiltration process. A number of factors may affect the movement of bacteria in soil. These are directly related to the bacteria (type, size and population dynamic) and the soil properties (chemical, biological and physical). Usually, most of the bacteria are filtered through the upper soil profile, but water can carry bacteria deeper using larger pore structures. These structures, called macropores, result from many things: earthworms, decayed roots and crack in clayey soil are some examples. Macropores reduce the efficiency of the soil to filter bacteria allowing them to travel deeper and faster.

Bacterial contamination in a well is a product of many factors. In a municipality like Chelsea, where agriculture is not a common practice, well construction (type, age, depth), location, the presence of septic system and the geology (bedrock and surficial) would be the primary contributors to bacterial contamination.

The well did not show contamination events during the April 2008 to May 2009 sampling period. This is illustrated in the figure below. A total of 13 samples were collected and analysed for total and faecal coliforms. The presence of total coliforms was detected in one sample, but did not exceed the regulation limit of 10 cfu/100mL (colony forming units / 100 millilitres). Faecal coliforms were not detected in the samples during the sampling period.

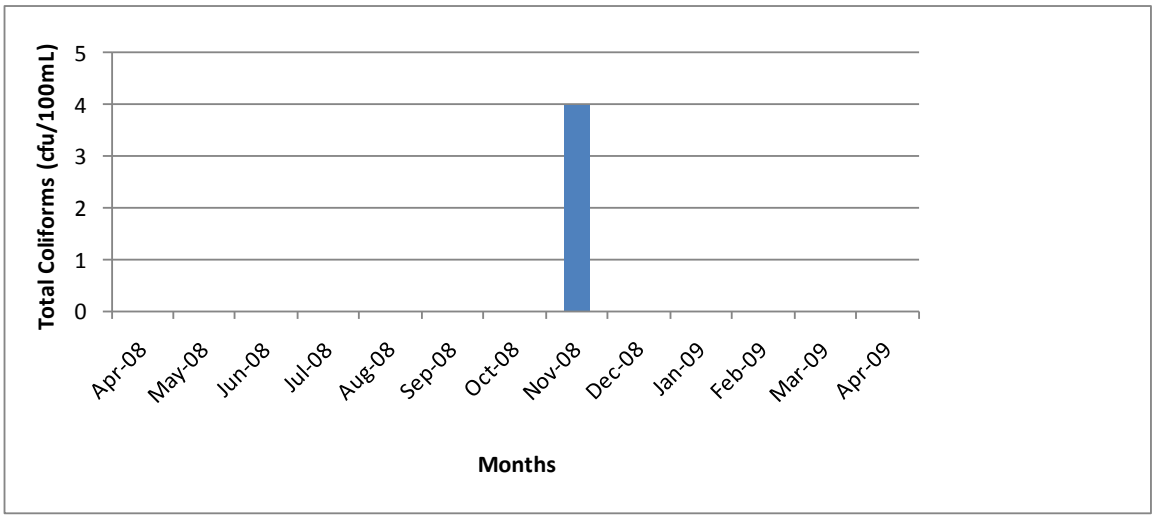


Figure 3: Results of the bacterial analysis (total and faecal coliforms) of the water samples, from April 2008 to May 2009.

Chemical analysis

As water naturally flows into the subsurface, it dissolves minerals along its pathway. The dissolution process is relatively slow in Precambrian bedrock compared to younger sedimentary rocks such as limestone or sandstone. However, other non natural sources may contribute to dissolved solids such as road salt application, septic systems or fertilizers.

Water samples were analysed for various dissolved species at the University of Ottawa. The results of the analyses are given in the following table. This table also shows the yearly average and the provincial guideline, if applicable. The concentrations are measured in milligrams per litre (mg/L).

Sampling date	pH	Fluoride (mg/L)	Chloride (mg/L)	Nitrate as N (mg/L)	Sulphate (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Hardness (mg/L as $CaCO_3$)
Apr-08	7.2	0.7	51.1	0.6	29.7	38.4	10.1	15.9	137.4
May-08	7.5	0.6	68.0	0.6	29.4	0.3	0.0	144.7	0.8
Jun-08	7.5	bdl	61.3	0.7	29.4	82.7	11.9	19.9	255.8
Jul-08	7.1	bdl	56.5	0.6	27.8	80.0	11.6	17.9	247.8
Aug-08	7.1	bdl	58.1	0.6	27.2	84.2	13.2	19.1	264.7
Sep-08	7.0	bdl	53.2	0.7	29.5	52.7	10.9	14.4	176.4
Oct-08	7.3	0.6	53.2	0.7	30.2	84.7	11.2	15.0	257.9
Nov-08	7.2	0.5	59.4	0.9	30.9	87.0	10.8	15.6	262.0
Dec-08	7.3	0.7	49.8	0.7	30.2	79.5	11.1	14.7	244.6
Jan-09	7.1	0.7	50.2	0.8	30.3	80.3	11.4	15.2	247.6
Feb-09	7.0	0.7	59.4	0.8	30.9	78.7	10.6	14.5	240.6
Mar-09	6.6	bdl	61.0	0.8	29.0	42.2	10.6	15.9	149.0
May-09	7.1	0.8	52.6	0.7	30.9	78.2	11.4	14.1	242.2
Average	7.1	0.7	56.4	0.7	29.7	66.8	10.4	25.9	209.8
Guideline		1.5 MAC	250.0 AO	10.0 MAC	500.0 AO			20.0 AO	100.0 AO

OG = Operational Guideline
MAC= Maximum Allowable Concentration
AO= Aesthetic Objective
Bdl= below detection limit

The dissolved solids measured during this study are water quality indicators. It is important to realize that their presence may not have an impact on health. The following table describes the parameters and their possible effects.

Parameters	Definition/sources	Possible effects/concerns
pH	Measure of the acidity of water	• An acid water (pH<6.5) can have a corrosive effect • Low pH increases metals in solution, which could yield health concerns
Fluoride	Natural occurrence	• Mottled teeth • Bone development (high concentrations)
Chloride	Natural occurrence or human related activities	• Corrosive effect on plumbing • Salty taste
Nitrates	Human related activities	• Health Concerns
Sulphates	Natural occurrence or human related activities	• Water has laxative effect
Sodium	Natural occurrence or human related activities	• Health concerns • Salty taste
Hardness	Caused by the presence of calcium and magnesium and occasionally iron in the water	• No health effect • Soap scum • Scale buildup on plumbing fixture and pipes • Stained and mottled laundry

Sources: Best Management Practices –Water Well

Guidelines for Hardness

Category	Concentration of calcium carbonate (mg/L)
Soft	0 to <60
Medium Hard	60 to <120
Hard	120 to <180
Very Hard	180 and more

Source : Health Canada

Summary and Suggestions

Seal testing

The infiltration tests demonstrated that surface water is infiltrating easier at the wellhead compared to the area surrounding the well. The detection of the tracer in the well suggests the presence of a hydraulic connection between the wellhead and the water column. Although a faulty seal is a potential pathway to contamination, other factors such as cracks in clayey soil may lead to such contamination.

Possible sources of contamination

It was observed that the well cap is not insect-proof and spider webs were present in the well cap. The presence of bugs most likely contributes to a small concentration of bacteria into the well.

Chemical analysis

Most constituent concentrations are below guidelines/regulations with the exception of the hardness. The yearly average for this parameter is 210 mg/L as $CaCO_3$, while the aesthetic objective is 100 mg/L as $CaCO_3$. Your well water is therefore considered as very hard.

Suggestions

- A potential preferential pathway to surface water infiltration is the well annular space. To diminish the infiltration at the wellhead, it is recommended that the soil be mounded around the casing, which will deviate the runoff away from the wellhead, allowing the natural soil process to attenuate the bacteria present in the water.
- A good well cap should keep bugs out of the well. Proper insect-proof cap are available and will easily fit on your well. This will not stop the contamination but will prevent insects entering the well, which can increase the concentration of total coliforms.

- Every year, examine into the inside of the well with a flash light. You can look for cracks in the casing caused by corrosion. Also check for holes around the pitless adaptor (area where pipes are connected). A record should be kept and comparisons made year to year. Corrective action can be suggested a licensed well contractor if something wrong is detected.
- It is important to consider activities around the wellhead, especially uphill from the well. For example: if the driveway is located uphill from the well and runoff water flow towards the well. Extra care should be taken to make sure there are no leaks from cars and salt should not be used as de-icing agent. To prevent nitrate contamination, no fertilizers should be used uphill or near the well recharge area.
- Even if total and faecal coliforms are not problematic, it is recommended to get your water tested for bacteria at least 1 time a year, especially after important rainfall events and snowmelt.

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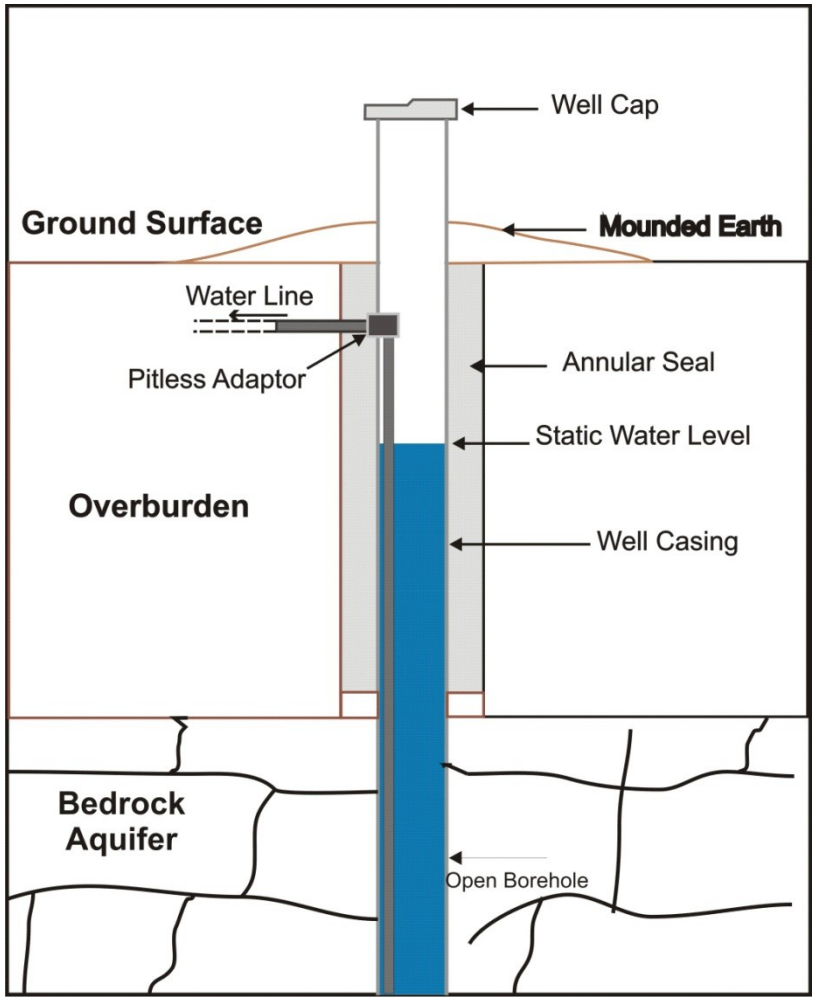
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Site Description

Your well is drilled into the Precambrian bedrock, which is overlain by less than 2 metres of till. The till is composed primarily of sand and silt deposited during the last glaciation (about 10,000 years ago). The well is approximately 37 metres deep and the static water level is located 7 metres below ground surface.

Your well draws water from an unconfined aquifer. An aquifer is defined as a geologic unit capable of storing and transmitting water. This aquifer is also considered unconfined because there is no impermeable protective layer overlaying it. Usually, these types of aquifer are more vulnerable to contamination since there is no confining layer. The confining layer provides an impermeable barrier, thereby naturally protecting the well against surface contamination.

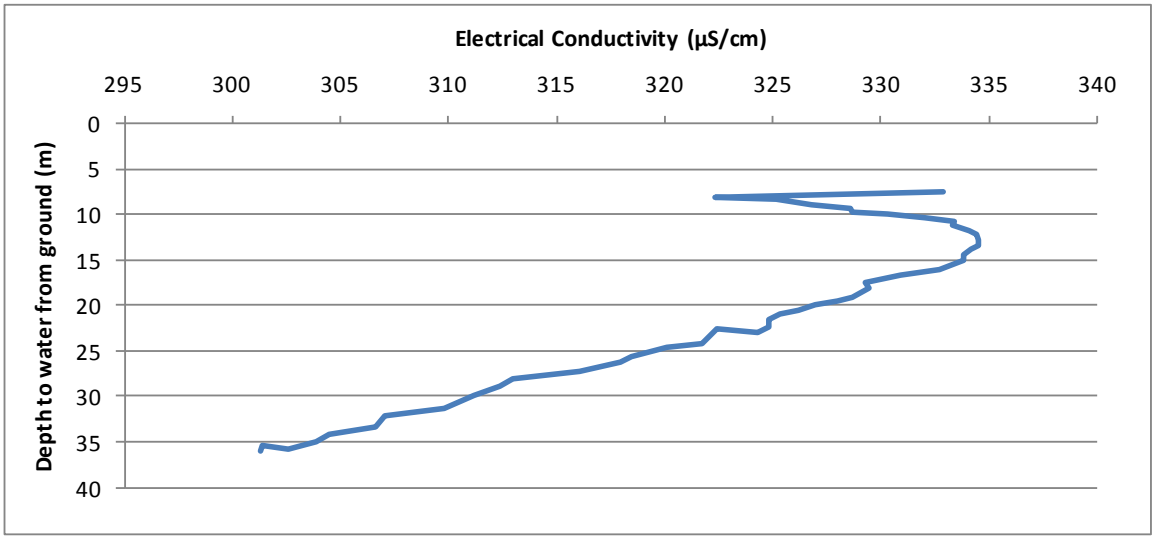


Figure 1: Electrical conductivity profile of the water column

The figure above displays the electrical conductivity (EC) profile of the well water column. The electrical conductivity is the ability of the water to conduct an electric current and it is a measure of the amount of dissolved solids in the well. For your well, the values range from 300 to 335 µS/cm with an important change at a depth of 12 metres from ground level. It is interpreted that at this depth, a fracture with a higher EC water connects with the water column. However, the magnitude of the variations falls within the error range of the instrument.

Bacteria

Bacteria are naturally present in surface water and soil. They are carried to the groundwater system through the infiltration process. A number of factors may affect the movement of bacteria in soil. These are directly related to the bacteria (type, size and population dynamic) and the soil properties (chemical, biological and physical). Usually, most of the bacteria are filtered through the upper soil profile, but water can carry bacteria deeper using larger pore structures. These structures, called macropores, result from many things: earthworms, decayed roots and crack in clayey soil are some examples. Macropores reduce the efficiency of the soil to filter bacteria allowing them to travel deeper and faster.

Bacterial contamination in a well is a product of many factors. In a municipality like Chelsea, where agriculture is not a common practice, well construction (type, age, depth), location, the presence of septic system and the geology (bedrock and surficial) would be the primary contributors to bacterial contamination.

The well did not show contamination events during the sampling period. This is illustrated in the figure below. A total of 6 samples were collected and analysed for total and faecal coliforms. Total coliforms were detected in four samples, but did not exceed the regulation limit of 10 cfu/100mL (colony forming units / 100 millilitres). Faecal coliforms were not detected during the sampling period.

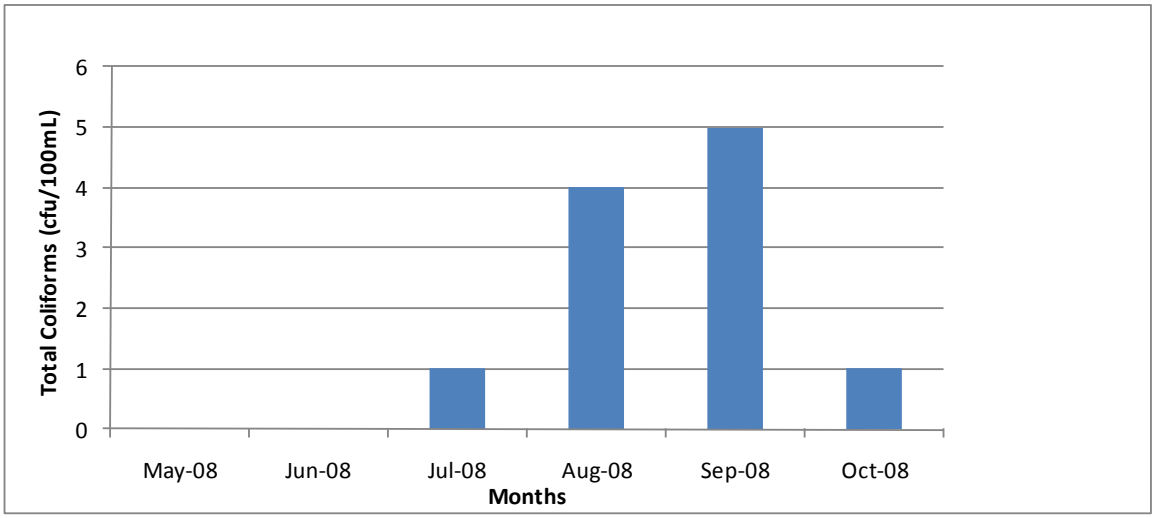


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Jun-08	7.4	bdl	15.1	1.0	29.9	76.3	36.3	24.8	340.1
Jul-08	7.1	bdl	13.4	bdl	32.4	49.6	15.8	19.4	188.9
Aug-08	6.9	bdl	16.2	1.2	30.5	62.0	32.8	29.3	289.9
Sep-08	7.0	bdl	11.3	bdl	12.8	63.2	22.6	25.9	251.1
Oct-08	7.4	0.7	14.7	1.0	40.5	76.4	38.0	31.1	347.2
Average	7.2	0.7	16.0	1.1	30.4	60.7	25.3	24.0	256.1
Guideline		1.5 MAC	250.0 AO	10.0 MAC	500.0 AO			20.0 AO	100.0 AO

OG = Operational Guideline
MAC= Maximum Allowable Concentration
AO= Aesthetic Objective
Bdl= below detection limit

The dissolved solids measured during this study are water quality indicators. It is important to realize that their presence may not have an impact on health. The following table describes the parameters and their possible effects.

Parameters	Definition/sources	Possible effects/concerns
pH	Measure of the acidity of water	• An acid water (pH<6.5) can have a corrosive effect • Low pH increases metals in solution, which could yield health concerns
Fluoride	Natural occurrence	• Mottled teeth • Bone development (high concentrations)
Chloride	Natural occurrence or human related activities	• Corrosive effect on plumbing • Salty taste
Nitrates	Human related activities	• Health Concerns
Sulphates	Natural occurrence or human related activities	• Water has laxative effect
Sodium	Natural occurrence or human related activities	• Health concerns • Salty taste
Hardness	Caused by the presence of calcium and magnesium and occasionally iron in the water	• No health effect • Soap scum • Scale buildup on plumbing fixture and pipes • Stained and mottled laundry

Sources: Best Management Practices –Water Well

Guidelines for Hardness

Category	Concentration of calcium carbonate (mg/L)
Soft	0 to <60
Medium Hard	60 to <120
Hard	120 to <180
Very Hard	180 and more

Source : Health Canada

Summary and Suggestions

Possible sources of contamination

Even if the well did not shown contamination events that exceeded regulation limits, the total coliforms were detected consistently. This may be an indicator of surface water reaching the well. The bacterial contamination could result from the shallow soil, the drainage toward the well or the presence of trees at the wellhead. The presence of total coliforms during winter months, when infiltration is minimal, may suggest that coliforms are present in the aquifer.

Chemical analysis

Most constituent concentrations are below guidelines/regulations with the exception of sodium (Na) which is slightly above the guideline of 20 mg/L, and the hardness. The yearly average for the hardness is 256 mg/L as $CaCO_3$, while the aesthetic objective is 100 mg/L as $CaCO_3$. Your well water is therefore considered as very hard.

Suggestions

- Every year, examine into the inside of the well with a flash light. You can look for cracks in the casing caused by corrosion. Also check for holes around the pitless adaptor (area where pipes are connected). A record should be kept and comparisons made year to year. Corrective action can be suggested a licensed well contractor if something wrong is detected.
- It is not recommended to plant flowers, shrubs or trees near the wellhead since their roots can affect the integrity of the annular seal protecting the well. The roots also increase the infiltration rate in the area.

The information presented in this report comes from the following sources:

*****These are also excellent sources for more information on water wells**

Conboy M.J, Smith S., 2005. A comprehensive consumer's guide for private water wells ISBN 0-9780387-0-3
www.wellwise.ca

Guidelines for Canadian Water Quality-Hardness
http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/hardness-durete/index-eng.php

Ministère du développement durable, environnement et parcs (MDDEP) -*La qualité de l'eau de mon puits* (French only)
http://www.mddep.gouv.qc.ca/eau/potable/depliant/index.htm

Ontario Ministry of Agriculture Food and Rural Affairs/Agriculture and Agri-food Canada. 2003 *Best Management Practices –Water Well*
http://www.omafra.gov.on.ca/english/environment/water/publications.htm

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Université d'Ottawa • University of Ottawa
Faculté des sciences Faculty of Science
Sciences de la Terre Earth Sciences

Étude sur la contamination des puits domestiques Municipalité de Chelsea, Québec



Rapport présenté à :
W9
Chelsea, QC

Rapport préparé par :
Pascale St-Germain
Doctorante
Université d'Ottawa

Mai 2010

Remerciements

Merci d'avoir participé à cette étude. Vos efforts furent importants dans l'avancement de notre compréhension sur les voies préférentielles de contamination des puits. Nous sommes très reconnaissants pour nous avoir donné l'accès à votre propriété, pour votre hospitalité ainsi que votre aide dans le prélèvement mensuel des échantillons.

Notes importantes

Les idées présentées dans ce rapport sont des suggestions qui pourraient améliorer la qualité de l'eau de votre puits. Elles pourraient possiblement être utiles dans la réduction du nombre de coliformes mais ne résoudront pas nécessairement le problème général. Nous avons fait notre possible pour évaluer la source probable de contamination, mais plusieurs facteurs peuvent affecter la qualité de l'eau d'un puits. Ce rapport a pour but de vous aider à comprendre votre puits et n'inclut pas toutes les conclusions de l'étude. Ces suggestions doivent être considérées avec prudence.

Avant d'investir dans votre puits (amélioration du puits ou système de traitement de l'eau) il serait important de demander l'avis d'un professionnel certifié et de faire analyser votre eau par un laboratoire indépendant.

Merci beaucoup pour votre compréhension.

Pascale St-Germain
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Glossaire

Roc Précambrien :	Socle rocheux composé de roches ignées et métamorphiques datant de plus de 542 Millions d'années
Dépôts meubles :	Sédiments non consolidés recouvrant le socle rocheux
Mer de Champlain :	Mer créée lors de la fonte du Glacier *Inlandsis laurentidien*, il y a environ 10 000 ans, submergeant principalement la région de Montréal et une partie du sud-est ontarien.
Voies préférentielles :	Présence de macro pores favorisant l'écoulement de l'eau sans le potentiel atténuant du sol, permettant aux contaminants de se faire transporter plus rapidement et plus profondément
Puits foré :	Puits creusé dans le socle rocheux à l'aide d'une foreuse
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Aquitard :	Unité géologique imperméable capable de contenir de l'eau mais incapable de la transmettre en quantité suffisante
Infiltration :	Mouvement de l'eau de la surface jusque dans le sol
Conductivité hydraulique :	Capacité d'un milieu poreux à transmettre l'eau
Conductivité électrique (EC) :	Capacité de l'eau à transmettre un courant électrique; donne une mesure du montant total des composantes dissoutes dans l'eau. L'unité de mesure de la conductivitéélectrique est le Siemens par cm (S/cm) ou microsiemens par cm (µS/cm = 10^{-6} S/cm). A titre comparatif, la EC varie de quelques dizaines de µS/cm dans le cas des eaux de pluie à quelques centaines de millier de µS/cm dans le cas des eaux salées. Dans la région de Chelsea, elle varie entre environ 80 et 1600 µS/cm.
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Représentation schématique d'un puits domestique

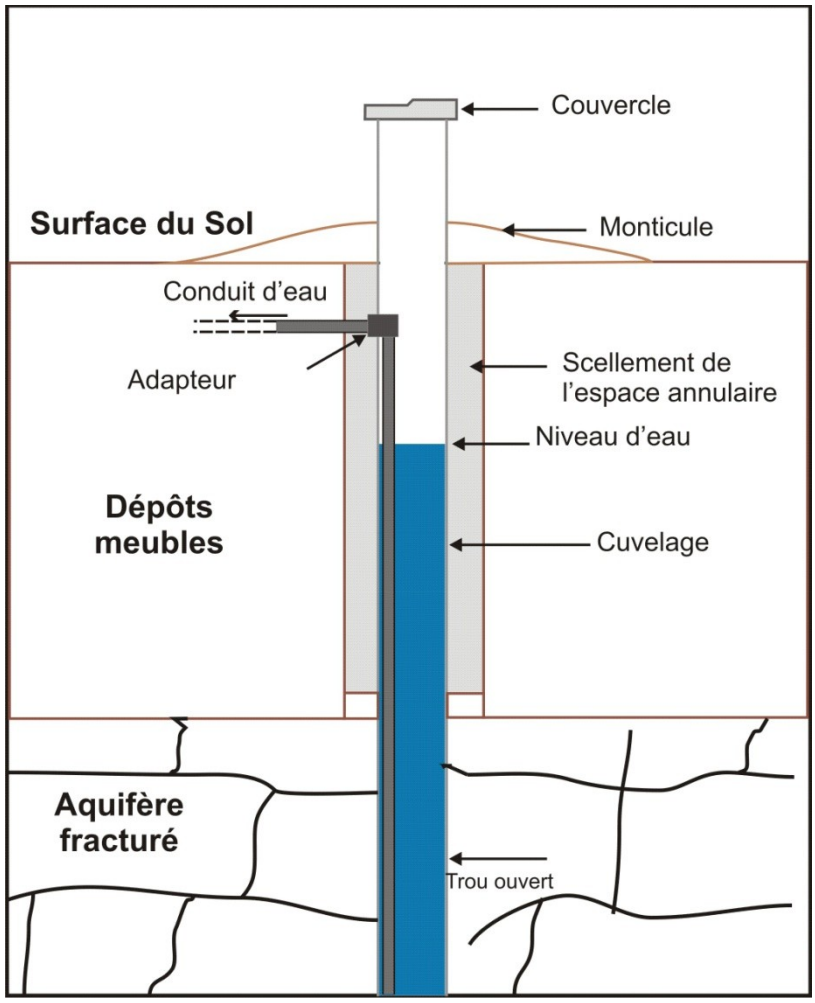


Image modifiée de : *Pratiques de gestion optimale-Les puits*

Introduction

L'objectif de ce projet est d'améliorer nos connaissances en ce qui a trait à la contamination des puits d'eau potable résultant de l'infiltration des eaux de surfaces. Notre but est d'évaluer le risque de contamination des puits forés en se basant sur les caractéristiques du site et sur la construction du puits.

En effectuant une analyse bactériologique mensuelle, il fut possible d'avoir une meilleure idée sur la saisonnalité de la contamination. L'analyse chimique de l'eau fût utilisée pour comprendre l'évolution des eaux souterraines et pour effectuer un lien avec une source possible de contamination.

L'objectif de ce rapport est de vous sensibiliser à la qualité de l'eau de votre puits et aux mesures existantes pour préserver ou améliorer sa qualité. Ce rapport présente un sommaire des travaux effectués, les principaux résultats ainsi que quelques suggestions, si nécessaire.

Description du site

Votre puits est foré dans le roc précambrien sur lequel repose une épaisse couche d'argile. Cette couche que l'on nomme couche de confinement, d'une dizaine de mètre d'épaisseur ou plus, s'est déposée lors de la dernière glaciation (environ 10 000 ans), lorsque la Mer de Champlain recouvrait partiellement la région. Le niveau de l'eau est situé à 6 mètres de la surface du sol.

L'eau de votre puits provient d'un aquifère. Un aquifère peut être défini comme une unité géologique capable de contenir et de transmettre de l'eau. Cet aquifère est également considéré comme étant « captif » car il est recouvert d'une couche imperméable. Ce type d'aquifère est généralement moins vulnérable à la contamination car la couche de confinement (l'argile) est imperméable et protège naturellement l'aquifère des contaminants de surface.

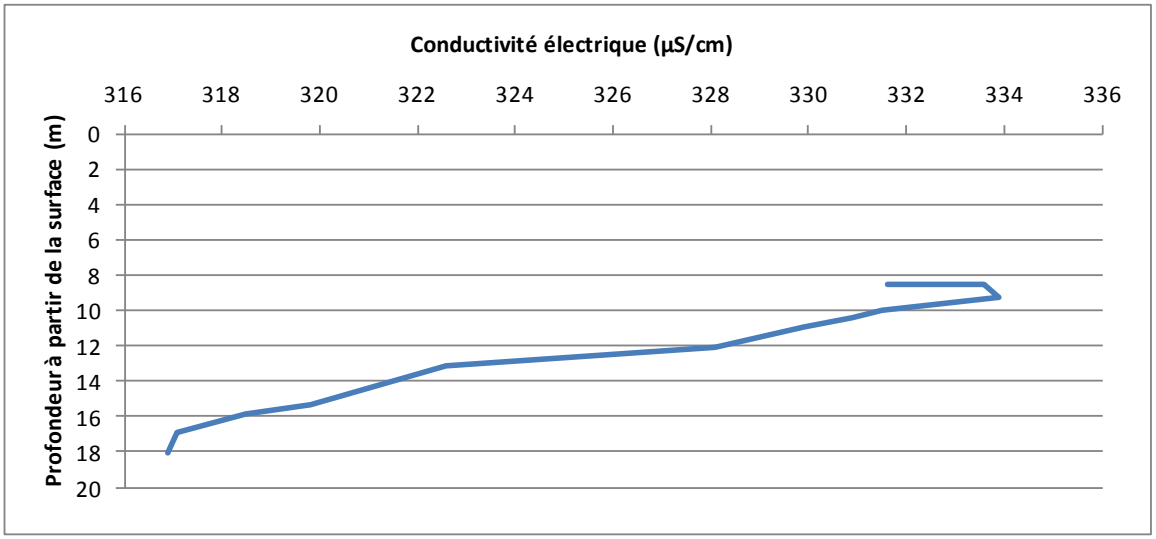


Figure 1: Profil de conductivité électrique de la colonne d'eau dans le puits

La figure ci-dessus représente un profil de conductivité électrique de la colonne d'eau de votre puits. La conductivité électrique est une mesure des composantes dissoutes dans l'eau. Dans le cas de votre puits, il fut impossible de descendre notre sonde au-delà de 18 mètres de profondeur. Le niveau d'eau est situé à environ 8 mètres sous la surface. La conductivité électrique varie entre 317 et 334 µS/cm, ce qui indique une qualité de l'eau excellente. Il semble que la conductivité électrique décroît en profondeur, mais en fait l'écart de conductivité électrique de l'eau entre la surface et la profondeur est du même ordre de grandeur que l'incertitude sur la mesure. Comme nous n'avons qu'une partie du profil, il est impossible d'avoir une meilleur conprehension du réseau de fractures alimentant votre puits.

Analyse bactériologique

Les bactéries sont naturellement présentes dans les eaux de surface et dans les sols. Elles sont transportées dans les eaux souterraines par le processus d'infiltration. Plusieurs facteurs affectent le mouvement des bactéries. Ces facteurs peuvent être reliés aux bactéries (type, taille, dynamique de la population) ou aux caractéristiques du sol (physique, chimique ou biologique). La plupart des bactéries sont filtrées dans le premier

horizon du sol mais la présence de « macro-pores » peut contribuer au mouvement des bactéries en profondeur. Les macro-pores sont en fait des pores de grandes dimensions formées par l'activité biologique, les racines ou bien des fissures dans un milieu argileux. Ces macro-pores affectent la capacité du sol à filtrer les bactéries, ce qui leur permet de pénétrer plus profondément et rapidement.

La contamination bactérienne dans un puits peut provenir de plusieurs sources. Dans une municipalité comme Chelsea, où l'agriculture n'est que localisée et quasi-inexistante, la construction d'un puits (type, âge et profondeur), son emplacement, la distance au système septique ainsi que des facteurs reliés à la géologie sont les principales sources contribuant à la présence de bactéries dans un puits.

La figure ci-dessous présente les résultats de l'analyse bactériologique sous forme de graphique. On remarque une présence constante de bactéries de juin à décembre. Par contre, le nombre de coliformes totaux respecte la limite provinciale de 10 ufc/100mL. Il n'y a qu'au mois d'août 2008 que ce nombre a été légèrement plus élevé que la limite. Il est alors possible que la présence de l'aérateur au robinet ait contribué à l'augmentation du nombre de coliformes totaux pour ce mois. La présence de coliformes fécaux n'a jamais été détectée dans les échantillons prélevés.

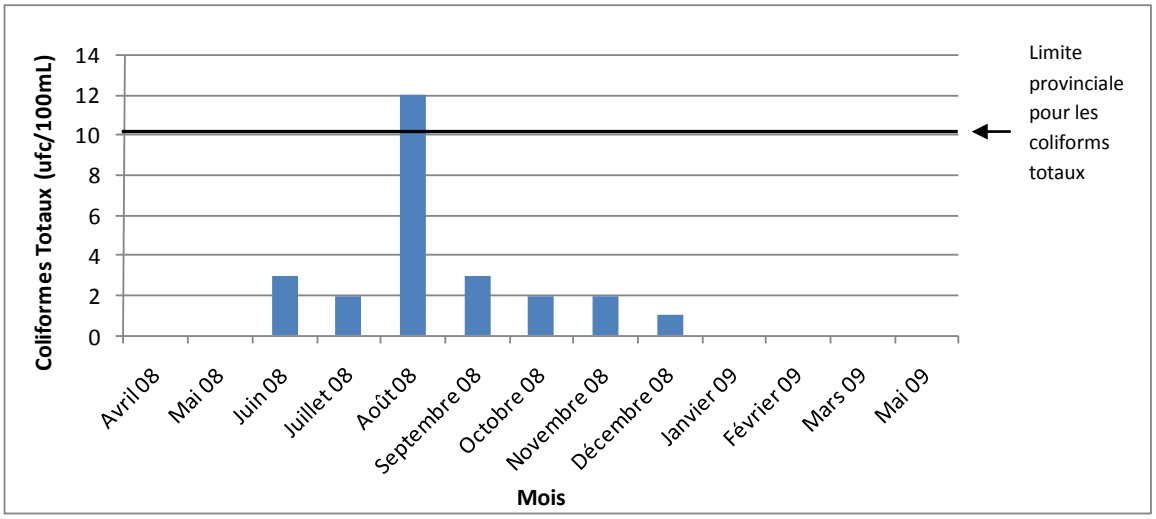


Figure 2: Résultats des analyses bactériennes (coliformes totaux) des échantillons d'avril 2008 à mai 2009.

Analyse Chimique

Naturellement, l'eau dissout les minéraux lorsqu'elle s'écoule dans le sol. Le processus de dissolution est habituellement lent dans la roche Précambrienne comparativement aux jeunes roches sédimentaires telles le grès ou la calcite. Des sources anthropogéniques, telles l'épandage de sels routiers, les fertilisants et les systèmes septiques peuvent également contribuer à la teneur en minéraux dissouts dans les eaux souterraines.

Les échantillons d'eau furent analysés à l'université d'Ottawa pour identifier diverses composantes dissoutes. Les résultats sont présentés dans le tableau suivant. Ce tableau donne également la moyenne annuelle ainsi que les lignes directrices relatives à certains paramètres. Les concentrations sont mesurées en milligrammes par litre (mg/L).

Mois	pH	Fluorure (mg/L)	Chlorure (mg/L)	Nitrate -N (mg/L)	Sulphate (mg/L)	Calcium (mg/L)	Magnésium (mg/L)	Sodium (mg/L)	Dureté (mg/L de $CaCO_3$)
Avril 08	8.2	1.5	16.0	bdl	38.5	8.0	4.0	92.9	36.3
Mai 08	8.5	1.5	15.0	bdl	39.8	7.5	3.8	91.1	34.4
Juin 08	8.5	1.5	15.9	bdl	40.0	8.1	4.0	83.9	36.4
Juillet 08	8.4	1.6	20.1	bdl	41.1	8.5	4.3	95.6	38.8
Août 08	7.9	1.7	14.9	bdl	39.4	8.4	4.3	92.8	38.5
Septembre 08	8.7	1.6	13.5	bdl	36.5	4.9	3.1	70.4	25.1
Octobre 08	8.0	1.7	13.6	bdl	40.4	7.3	3.6	85.5	33.2
Novembre 08	8.2	1.7	10.1	bdl	25.9	7.8	3.8	87.6	35.1
Décembre 08	8.2	1.7	18.6	bdl	42.5	8.4	4.0	89.7	37.6
Janvier 09	7.9	1.7	19.5	bdl	42.6	8.5	4.1	89.1	38.3
Février 09	8.2	1.7	20.4	bdl	44.5	8.2	4.2	87.8	37.7
Mars 09	7.4	1.7	19.8	bdl	43.3	8.4	4.0	81.4	37.4
Avril 09	7.9	1.7	20.2	bdl	44.7	9.0	4.6	91.6	41.3
Mai09	8.3	1.7	19.1	bdl	45.3	8.3	4.3	86.5	38.3
Moyenne	8.2	1.7	16.9		40.3	7.9	4.0	87.6	36.3
Ligne directrice		1.5 CMP	250 OE	10.0 CMP	500 OE			20 OE	100.0 OE

LDP = Ligne directrice opérationnelle
CMP= Concentration Maximale Permise
OE= Objectif Esthétique
bdl= Sous limite de détection

Les paramètres mesurés lors de notre étude sont des indicateurs de la qualité de l'eau. Il est important de considérer que dans certain cas, leur présence n'a pas nécessairement un impact sur la santé. Le tableau décrit certain de ces paramètre ainsi que ce que les effets possible de leur présence.

Paramètres mesurés	Définitions/Sources	Effets possibles
pH	Mesure de l'acidité de l'eau	• Une eau acide (pH<6.5) peut avoir un effet corrosif
Fluorure	Présence naturelle	• Affecte la dentition des enfants • Des concentrations très élevées peuvent affecter le développement des os
Chlorure	Présence naturelle ou causée par l'activité humaine	• Effet corrosif sur la plomberie • Goût salé
Nitrates	Fertilisants, système septique	• Effets sur la santé
Sulfates	Présence naturelle ou causée par l'activité humaine	• L'eau à un effet laxatif
Sodium	Présence naturelle ou causée par l'activité humaine	• Hypertension (personne à risque)
Dureté	Causée par la présence de Calcium et Magnésium dans l'eau	• Aucun effet sur la santé • Réduit l'efficacité des savons • Effets sur la tuyauterie (dépôts et blocage) • Tache et salie le linge

Sources : Pratiques de gestion optimale-Les puits

Recommandations pour la qualité de l'eau potable au Canada

Catégorie	Concentration de carbonate de Calcium (mg/L)
Eau Douce	0 à <60
Eau modérément dure	60 à <120
Eau dure	120 à <180
Eau très dure	180 et plus

Source : Santé Canada

Sommaire et suggestions

Source possible de contamination

L'analyse bactériologique de l'eau de votre puits est relativement bonne. Dans la majorité des analyses, le nombre de coliformes totaux est sous la norme provinciale et dans tous les cas, les coliformes fécaux ne sont pas détectés. Quoique qu'en faible nombre, les coliformes totaux sont constamment présents de juin à décembre. Leur présence pourrait être expliquée par le couvercle du puits qui n'est pas étanche aux insectes ou bien tout simplement par une faible contamination de l'aquifère. Le seul dépassement pour les coliformes totaux fut possiblement expliqué par la présence de l'aérateur lors de la prise d'échantillon.

Analyse chimique

Tous les paramètres respectent les lignes directrices à l'exception du sodium qui est beaucoup plus élevé que l'objectif esthétique.

Suggestions

- Un bon couvercle devrait garder les insectes hors du puits. Lors de notre dernière visite, il nous fut impossible de vérifier la présence d'insectes dans le couvercle. Il est donc recommandé de vérifier l'intérieur et de s'assurer que le couvercle soit étanche aux insectes (il doit cependant laisser passer l'air). Ceci pourrait prévenir un nombre élevé de coliformes totaux dans le puits.
- Il est important de faire un suivi continu sur l'état de votre puits. Une fois l'an, vous devriez regarder dans le puits avec une lampe de poche. Recherchez la présence de fissures et de trous dans le cuvelage et près de l'embranchement des tuyaux vers la maison. Prenez des notes et comparez au fil des ans. Des mesures correctives peuvent être entreprises, par un puisatier, si un problème est détecté.
- Il n'est pas recommandé d'avoir des arbustes et des plantes près du puits puisque leurs racines peuvent affecter l'intégrité du scellement dans l'espace annulaire. Le taux d'infiltration est également augmenté à cet endroit, ce qui accroît les chances d'infiltration d'eaux de surface dans le puits.

- Finalement, votre puits étant susceptible à la contamination bactériologique, il est recommandé de faire une analyse bactériologique au moins 1 fois par année, et à l'occasion, notamment après une pluie importante et la fonte des neiges.

L'information présentée dans ce rapport provient des sources suivantes :

*****Ces sources sont également excellentes pour en savoir plus sur les puits, les sources de contamination ainsi que sur la qualité de l'eau**

Conboy M.J, Smith S., 2005. A comprehensive consumer's guide for private water wells ISBN 0-9780387-0-3
www.wellwise.ca

Recommandations pour la qualité de l'eau potable au Canada -La dureté
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http://www.health.gov.on.ca/english/public/pub/watersafe/watersafe_wellknow.html

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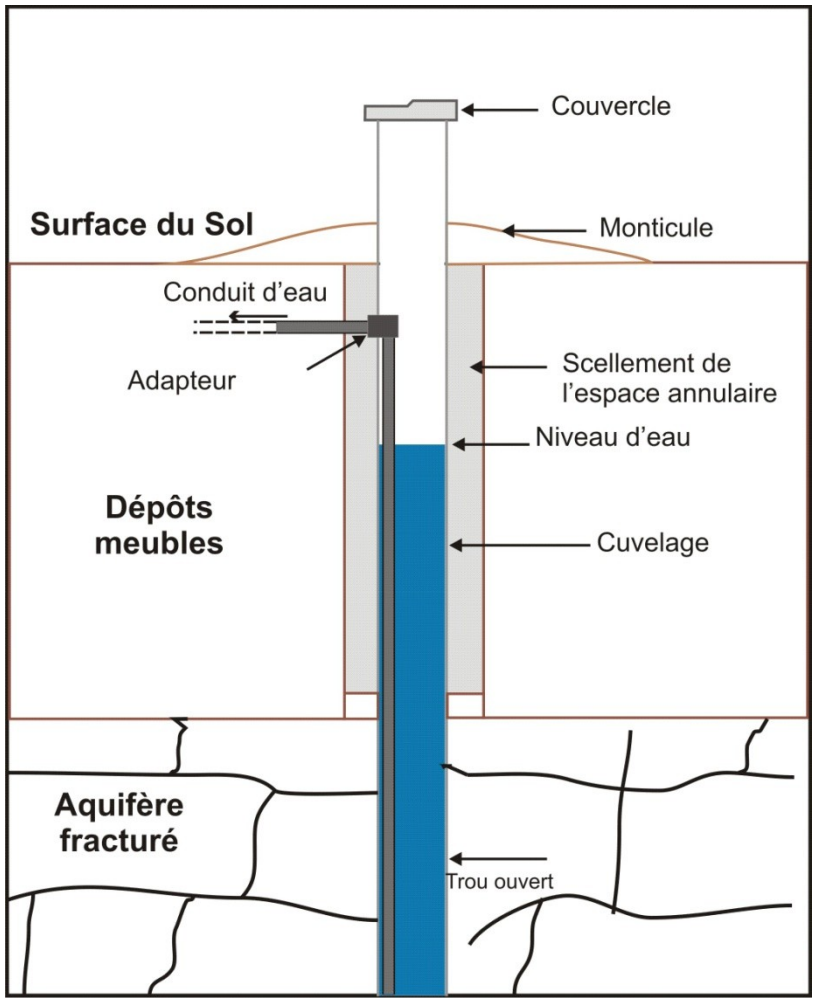


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En effectuant une analyse bactériologique mensuelle, il fut possible d'avoir une meilleure idée sur la saisonnalité de la contamination. L'analyse chimique de l'eau fût utilisée pour comprendre l'évolution des eaux souterraines et pour effectuer un lien avec une source possible de contamination.

L'objectif de ce rapport est de vous sensibiliser à la qualité de l'eau de votre puits et aux mesures existantes pour préserver ou améliorer sa qualité. Ce rapport présente un sommaire des travaux effectués, les principaux résultats ainsi que quelques suggestions, si nécessaire.

Description du site

Votre puits est foré dans le roc précambrien sur lequel repose une épaisse couche d'argile. Cette couche que l'on nomme couche de confinement, d'une dizaine de mètre d'épaisseur ou plus, s'est déposée lors de la dernière glaciation (environ 10 000 ans), lorsque la Mer de Champlain recouvrait partiellement la région. La profondeur du puits est d'environ 30 mètres et le niveau de l'eau est situé à 6 mètres de la surface du sol.

L'eau de votre puits provient d'un aquifère. Un aquifère peut être défini comme une unité géologique capable de contenir et de transmettre de l'eau. Cet aquifère est également considéré comme étant « captif » car il est recouvert d'une couche imperméable. Ce type d'aquifère est généralement moins vulnérable à la contamination car la couche de confinement (l'argile) est imperméable et protège naturellement l'aquifère des contaminants de surface.

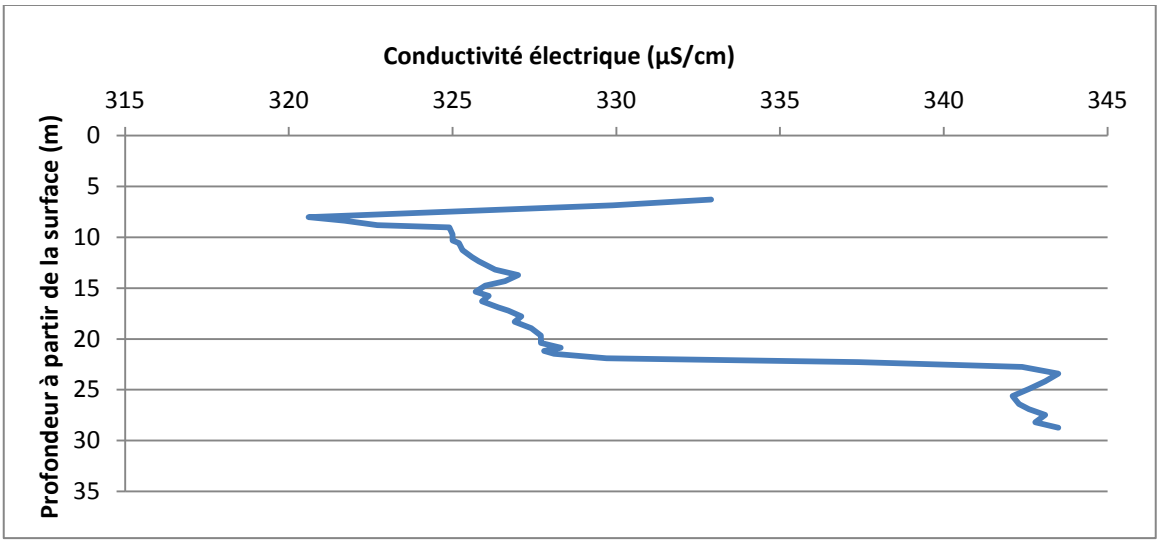


Figure 1: Profil de conductivité électrique de la colonne d'eau dans le puits

La figure ci-dessus représente un profil de conductivité électrique de la colonne d'eau de votre puits. La conductivité électrique est une mesure des composantes dissoutes dans l'eau. Le niveau d'eau est situé à environ 6 mètres sous la surface. La conductivité électrique varie entre 320 et 345 µS/cm, ce qui indique une qualité de l'eau excellente. Il semble que la conductivité électrique augmente en profondeur, avec un changement important à environ 23 mètres. À cette profondeur, il est possible que des fractures alimentent votre puits avec de l'eau à condutivité électrique plus élevée. Cependant, il est à noter que l'écart de conductivité électrique de l'eau entre la surface et la profondeur est du même ordre de grandeur que l'incertitude sur la mesure.

Sommaire de la technique

Deux méthodes sont utilisées pour évaluer le statut du scellement de tubage :

1. La première a mesuré la conductivité hydraulique (K) autour du puits et permet de vérifier si l'eau s'infiltre plus facilement autour du puits que dans les surfaces environnantes. Un test statistique compare les valeurs mesurées. Si la valeur de K autour du puits est significativement plus grande que celles des alentours, le scellement de tubage est potentiellement fautif.

2. La seconde méthode consiste à injecter une solution saline (NaCl) lors des essais d'infiltration au puits. Un suivi quotidien de la conductivité électrique dans la colonne d'eau du puits est effectué pour déceler la présence du traceur, laquelle démontrerait, le cas échéant, la présence d'un court-circuit hydraulique, ce qui signifie que les eaux de surface peuvent s'infiltrer en ruisselant sur le tubage du puits.

Résultats

1. Comparaison des conductivités hydrauliques (K)

Les essais d'infiltration ont été effectués les 16 et 17 août 2008. La conductivité hydraulique (K) mesurée au puits est plus grande que celle mesurée dans les environs. En langage statistique, cette différence n'est que « marginalement significative », ce qui signifie que cette technique démontre un scellement potentiellement fautif. L'essai de traçage avait pour but de corroborer ou de démentir cette affirmation.

2. Essai de traçage

L'injection du traceur s'est effectuée le 16 août. L'essai s'est déroulé en trois étapes. Pour commencer, la zone autour du puits fut saturée par l'injection d'eau du puits (environ 360L). Ensuite, un total de 360L de solution saline, avec une conductivité électrique (EC) d'environ 14 000 µS/cm, a été injecté autour du puits. Finalement, 180L d'eau de puits furent versés dans le but de pousser le traceur en profondeur. La figure suivante montre les profils de conductivité électrique jusqu'à 11 jours après l'injection. Aucun des profils ne démontre de variations importantes ce qui signifie que le traceur n'a pas été détecté.

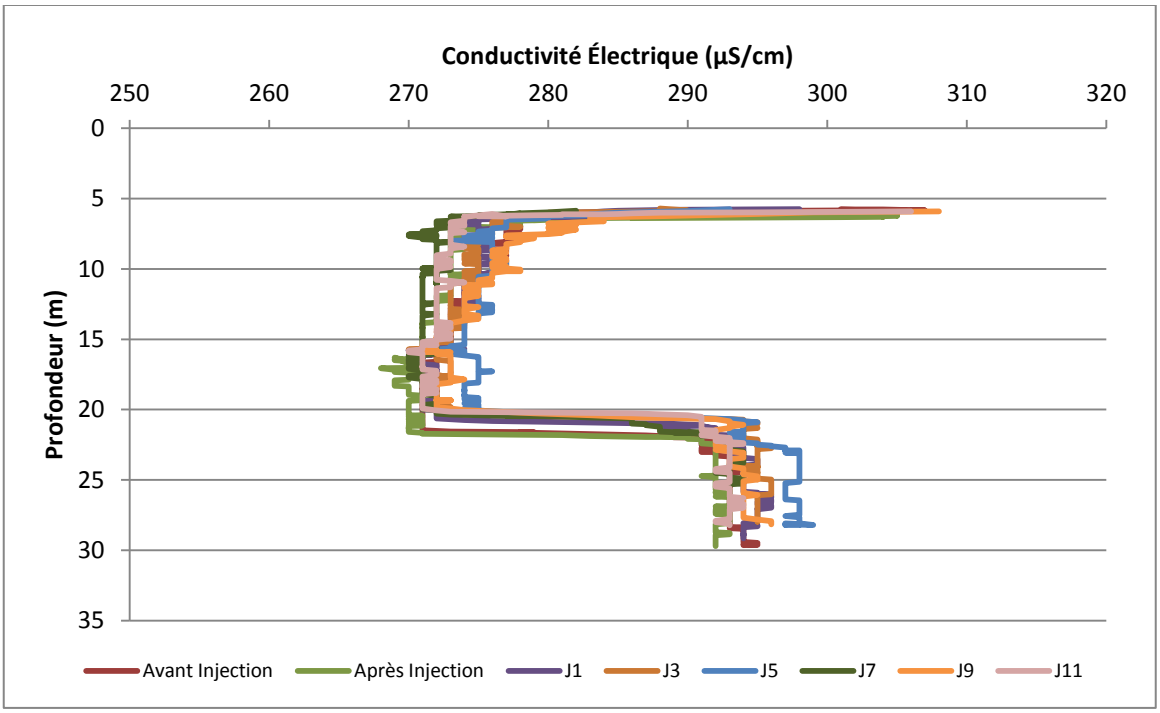


Figure 2 : Profils de conductivité électrique de la colonne d'eau avant et après l'injection de la solution saline.

Analyse bactériologique

Les bactéries sont naturellement présentes dans les eaux de surface et dans les sols. Elles sont transportées dans les eaux souterraines par le processus d'infiltration. Plusieurs facteurs affectent le mouvement des bactéries. Ces facteurs peuvent être reliés aux bactéries (type, taille, dynamique de la population) ou aux caractéristiques du sol (physique, chimique ou biologique). La plupart des bactéries sont filtrées dans le premier horizon du sol mais la présence de « macro-pores » peut contribuer au mouvement des bactéries en profondeur. Les macro-pores sont en fait des pores de grandes dimensions formées par l'activité biologique, les racines ou bien des fissures dans un milieu argileux. Ces macro-pores affectent la capacité du sol à filtrer les bactéries, ce qui leur permet de pénétrer plus profondément et rapidement.

La contamination bactérienne dans un puits peut provenir de plusieurs sources. Dans une municipalité comme Chelsea, où l'agriculture n'est que localisée et quasi-inexistante, la construction d'un puits (type, âge et profondeur), son emplacement, la

distance au système septique ainsi que des facteurs reliés à la géologie sont les principales sources contribuant à la présence de bactéries dans un puits.

La figure ci-dessous présente les résultats de l'analyse bactériologique sous forme de graphique. On remarque une présence constante de bactéries de juillet à octobre, le nombre de coliformes totaux dépassant la limite provinciale de 10 ufc/100mL. Il est également possible d'observer une présence sporadique en décembre 2008, mars et mai 2009, mais le nombre de coliformes est sous la limite provinciale. La présence de coliformes fécaux a été détectée en mai 2009 et lors des essais d'infiltration autour du puits à l'été 2008 (4 et 2 ufc/100mL).

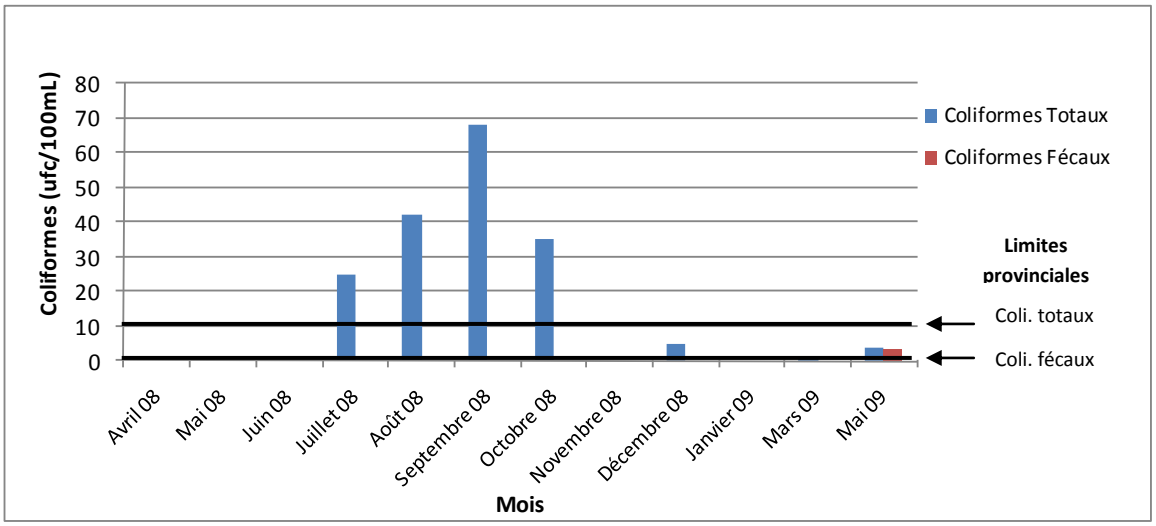


Figure 3: Résultats des analyses bactériologiques (coliformes totaux et fécaux) des échantillons d'avril 2008 à mai 2009.

Analyse Chimique

Naturellement, l'eau dissout les minéraux lorsqu'elle s'écoule dans le sol. Le processus de dissolution est habituellement lent dans la roche Précambrienne comparativement aux jeunes roches sédimentaires telles le grès ou la calcite. Des sources anthropogéniques, telles l'épandage de sels routiers, les fertilisants et les systèmes septiques peuvent également contribuer à la teneur en minéraux dissouts dans les eaux souterraines.

Les échantillons d'eau furent analysés à l'université d'Ottawa pour identifier diverses composantes dissoutes. Les résultats sont présentés dans le tableau suivant. Ce tableau donne également la moyenne annuelle ainsi que les lignes directrices relatives à certains paramètres. Les concentrations sont mesurées en milligrammes par litre (mg/L).

Mois	pH	Fluorure (mg/L)	Chlorure (mg/L)	Nitrate -N (mg/L)	Sulfates (mg/L)	Calcium (mg/L)	Magnésium (mg/L)	Sodium (mg/L)	Dureté (mg/L de CaCO3)
Avril 08	8.3	0.7	26.1	bdl	33.8	25.7	11.8	53.0	112.6
Mai 08	8.3	0.7	24.1	bdl	34.6	26.1	11.9	56.6	114.3
Juin 08	7.9	0.7	NA	bdl	34.4	24.1	10.7	47.9	104.4
Juillet 08	8.5	0.7	26.6	bdl	34.0	24.1	11.2	54.5	106.5
Août 08	8.0	0.7	26.9	bdl	34.6	25.3	12.3	56.6	113.7
Septembre 08	6.9	0.8	28.8	bdl	36.6	23.3	11.1	51.9	103.7
Octobre 08	7.8	0.8	27.7	bdl	36.0	23.8	11.3	55.2	105.9
Novembre 08	7.9	0.7	17.9	bdl	18.6	22.1	10.7	56.3	99.1
Décembre 08	8.0	0.8	27.8	bdl	35.5	23.8	11.1	52.9	105.3
Janvier 09	8.0	0.8	27.3	bdl	35.8	24.5	11.3	54.2	107.5
Mars 09	7.0	0.8	27.3	bdl	36.1	23.2	10.6	49.9	101.4
Avril 09	7.5	0.8	28.2	bdl	36.1	24.3	11.2	52.5	106.9
Mai 09	7.6	0.8	27.5	bdl	36.9	22.2	10.8	49.0	99.9
Moyenne	7.8	0.8	26.3		34.1	24.0	11.2	53.1	106.3
Ligne directrice		1.5 CMP	250.0 OE	10.0 CMP	500.0 OE			20.0 OE	100 OE

LDP = Ligne directrice opérationnelle
CMP= Concentration Maximale Permise
OE= Objectif Esthétique
Bdl= Sous limite de détection

Les paramètres mesurés lors de notre étude sont des indicateurs de la qualité de l'eau. Il est important de considérer que dans certain cas, leur présence n'a pas nécessairement un impact sur la santé. Le tableau décrit certain de ces paramètre ainsi que ce que les effets possible de leur présence.

Paramètres mesurés	Définitions/Sources	Effets possibles
pH	Mesure de l'acidité de l'eau	• Une eau acide (pH<6.5) peut avoir un effet corrosif
Fluorure	Présence naturelle	• Affecte la dentition des enfants • Des concentrations très élevées peuvent affecter le développement des os
Chlorure	Présence naturelle ou causée par l'activité humaine	• Effet corrosif sur la plomberie • Goût salé
Nitrates	Fertilisants, système septique	• Effets sur la santé
Sulfates	Présence naturelle ou causée par l'activité humaine	• L'eau à un effet laxatif
Sodium	Présence naturelle ou causée par l'activité humaine	• Hypertension (personne à risque)
Dureté	Causée par la présence de Calcium et Magnésium dans l'eau	• Aucun effet sur la santé • Réduit l'efficacité des savons • Effets sur la tuyauterie (dépôts et blocage) • Tache et salie le linge

Sources : Pratiques de gestion optimale-Les puits

Recommandations pour la qualité de l'eau potable au Canada

Catégorie	Concentration de carbonate de Calcium (mg/L)
Eau Douce	0 à <60
Eau modérément dure	60 à <120
Eau dure	120 à <180
Eau très dure	180 et plus

Source : Santé Canada

Sommaire et suggestions

Intégrité du scellement de tubage

Même si l'eau s'infiltre plus rapidement autour de puits que dans les surfaces avoisinantes, l'essai de traçage n'a pas démontré la présence d'une connexion hydraulique avec la surface, le scellement de tubage du puits serait donc efficace pour prévenir l'infiltration d'eau à la tête du puits.

Source possible de contamination

Il semblerait que les coliformes totaux soient présents en nombre plus important de juillet à octobre et de façon sporadique par la suite. Il y aurait donc une source constante alimentant le puits. Le scellement de tubage ne semblerait pas être une voie préférentielle à la contamination. De plus, aucun insecte ne fut détecté dans le couvercle. Il est difficile de déterminer la source de contamination. La possibilité la plus probable serait la proximité du lac.

Analyse chimique

Tous les paramètres respectent les lignes directrices à l'exception du sodium qui est légèrement plus élevé que l'objectif esthétique. La dureté est également près de la ligne directrice opérationnelle (LDO). La moyenne annuelle est de 106 mg/L de $CaCO_3$ alors que la LDO est de 100 mg/L de $CaCO_3$. L'eau est donc considérée comme légèrement dure, mais ceci ne constitue aucun danger pour la santé.

Suggestions

- Un bon couvercle devrait garder les insectes hors du puits. Même si aucun insecte ne fut détecté à l'intérieur, il est recommandé de vérifier l'intérieur et de s'assurer que le couvercle soit assez étanche pour ne pas laisser entrer les insectes, mais assez dégagé pour laisser passer l'air. Ceci pourrait prévenir le nombre de coliformes totaux dans le puits.

- Il est important de faire un suivi continu sur l'état de votre puits. Une fois l'an, vous devriez regarder dans le puits avec une lampe de poche. Recherchez la présence de fissures et de trous dans le cuvelage et près de l'embranchement des tuyaux vers la maison. Prenez des notes et comparez au fil des ans. Des mesures correctives peuvent être entreprises, par un puisatier, si un problème est détecté.
- Il est recommandé de faire une analyse bactériologique au moins 1 fois par année, et à l'occasion, notamment après une pluie importante et la fonte des neiges.
- Finalement, il serait impératif de faire installer un système de stérilisation de l'eau, tel les systèmes aux rayons ultra-violets.

L'information présentée dans ce rapport provient des sources suivantes :

*****Ces sources sont également excellentes pour en savoir plus sur les puits, les sources de contamination ainsi que sur la qualité de l'eau**

Conboy M.J, Smith S., 2005. A comprehensive consumer's guide for private water wells ISBN 0-9780387-0-3
www.wellwise.ca

Recommandations pour la qualité de l'eau potable au Canada -La dureté
http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/hardness-durete/index-fra.php

Ministère du développement durable, environnement et parcs- *La qualité de l'eau de mon puits*
http://www.mddep.gouv.qc.ca/eau/potable/depliant/index.htm

Publications : Ministère de l'agriculture, de l'alimentation et des affaires rurales (Ontario)
http://www.omafra.gov.on.ca/french/environment/water/publications.htm

Ministère de la santé et des soins de longue durée
http://www.health.gov.on.ca/english/public/pub/watersafe/watersafe_wellknow.html

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Sciences de la Terre Earth Sciences

Étude sur la contamination des puits domestiques Municipalité de Chelsea, Québec



Rapport présenté à :
W11
Chelsea, QC

Rapport préparé par :
Pascale St-Germain
Doctorante
Université d'Ottawa

Mai 2010

Remerciements

Merci d'avoir participé à cette étude. Vos efforts furent importants dans l'avancement de notre compréhension sur les voies préférentielles de contamination des puits. Nous sommes très reconnaissants pour nous avoir donné l'accès à votre propriété, pour votre hospitalité ainsi que votre aide dans le prélèvement mensuel des échantillons.

Notes importantes

Les idées présentées dans ce rapport sont des suggestions qui pourraient améliorer la qualité de l'eau de votre puits. Elles pourraient possiblement être utiles dans la réduction du nombre de coliformes mais ne résoudront pas nécessairement le problème général. Nous avons fait notre possible pour évaluer la source probable de contamination, mais plusieurs facteurs peuvent affecter la qualité de l'eau d'un puits. Ce rapport a pour but de vous aider à comprendre votre puits et n'inclut pas toutes les conclusions de l'étude. Ces suggestions doivent être considérées avec prudence.

Avant d'investir dans votre puits (amélioration du puits ou système de traitement de l'eau) il serait important de demander l'avis d'un professionnel certifié et de faire analyser votre eau par un laboratoire indépendant.

Merci beaucoup pour votre compréhension.

Pascale St-Germain
Doctorante
Université d'Ottawa
Département des Sciences de la Terre

Glossaire

Roc Précambrien :	Socle rocheux composé de roches ignées et métamorphiques datant de plus de 542 Millions d'années
Dépôts meubles :	Sédiments non consolidés recouvrant le socle rocheux
Mer de Champlain :	Mer créée lors de la fonte du Glacier *Inlandsis laurentidien*, il y a environ 10 000 ans, submergeant principalement la région de Montréal et une partie du sud-est ontarien.
Voies préférentielles :	Présence de macro pores favorisant l'écoulement de l'eau sans le potentiel atténuant du sol, permettant aux contaminants de se faire transporter plus rapidement et plus profondément
Puits foré :	Puits creusé dans le socle rocheux à l'aide d'une foreuse
Aquifère :	Unité géologique capable de contenir et de transmettre de l'eau en quantité suffisante
Aquifère captif :	Aquifère recouvert d'une couche imperméable isolant l'aquifère de la surface du sol
Aquifère libre :	Aquifère non recouvert d'une couche imperméable et exposé à la pression atmosphérique
Aquitard :	Unité géologique imperméable capable de contenir de l'eau mais incapable de la transmettre en quantité suffisante
Infiltration :	Mouvement de l'eau de la surface jusque dans le sol
Conductivité hydraulique :	Capacité d'un milieu poreux à transmettre l'eau
Conductivité électrique (EC) :	Capacité de l'eau à transmettre un courant électrique; donne une mesure du montant total des composantes dissoutes dans l'eau. L'unité de mesure de la conductivitéélectrique est le Siemens par cm (S/cm) ou microsiemens par cm (µS/cm = 10^{-6} S/cm). A titre comparatif, la EC varie de quelques dizaines de µS/cm dans le cas des eaux de pluie à quelques centaines de millier de µS/cm dans le cas des eaux salées. Dans la région de Chelsea, elle varie entre environ 80 et 1600 µS/cm.
Coliformes totaux :	Groupe de bactéries fermentant le lactose à 38°C. Ces bactéries sont présentes dans les matières fécales des humains et des animaux ainsi que dans le sol et la végétation.

Coliformes fécaux :	Bactéries provenant du système digestif des humains et animaux. Indique une présence possible de pathogènes dans l'eau.
Macro-pores :	Pores de grandes dimensions formées par l'activité biologique, les racines ou bien les fissures dans un milieu argileux.

Représentation schématique d'un puits domestique

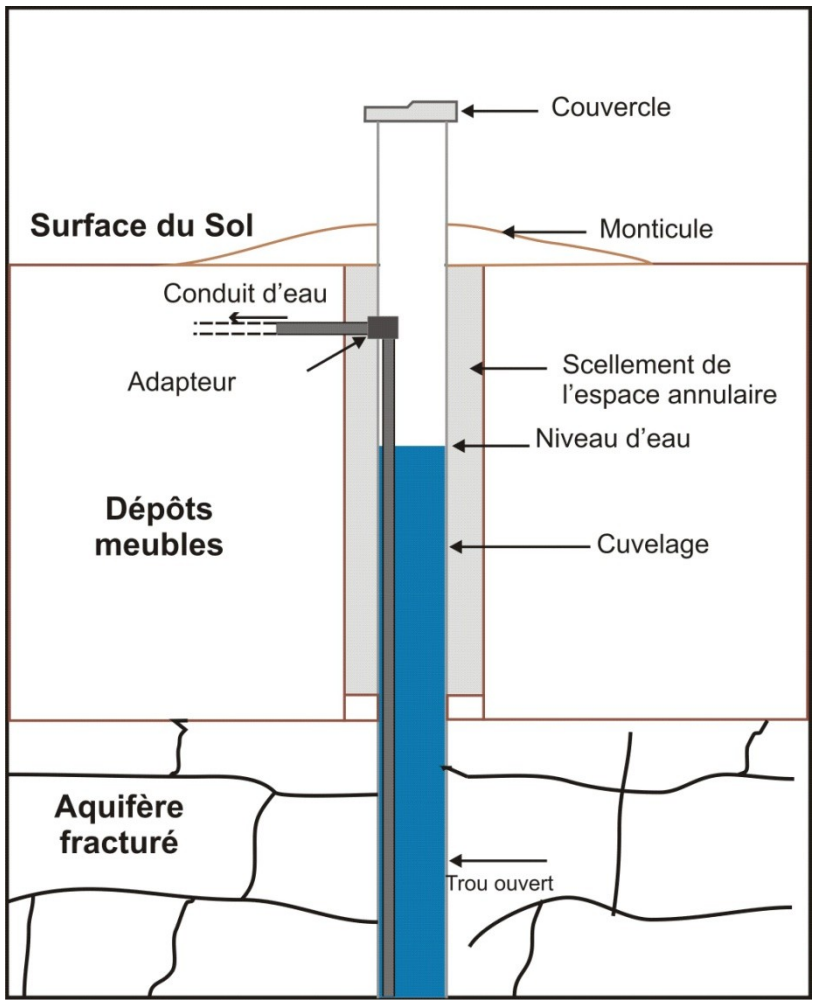


Image modifiée de : *Pratiques de gestion optimale-Les puits*

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L'objectif de ce rapport est de vous sensibiliser à la qualité de l'eau de votre puits et aux mesures existantes pour préserver ou améliorer sa qualité. Ce rapport présente un sommaire des travaux effectués, les principaux résultats ainsi que quelques suggestions, si nécessaire.

Description du site

Votre puits est foré dans le roc précambrien sur lequel repose une mince couche de dépôts meubles, principalement composés de sable, silt et argile déposés lors de la dernière glaciation, il y a environ 10 000 ans. La profondeur du puits est d'environ 65 mètres et le niveau de l'eau est situé à 5 mètres de la surface du sol.

L'eau de votre puits provient d'un aquifère. Un aquifère peut être défini comme une unité géologique capable de contenir et de transmettre de l'eau. Cet aquifère est également considéré comme étant « libre » car il n'est pas recouvert d'une couche imperméable. Ce type d'aquifère est généralement plus vulnérable à la contamination car il n'y a pas de couche imperméable protégeant naturellement l'aquifère des contaminants de surface.

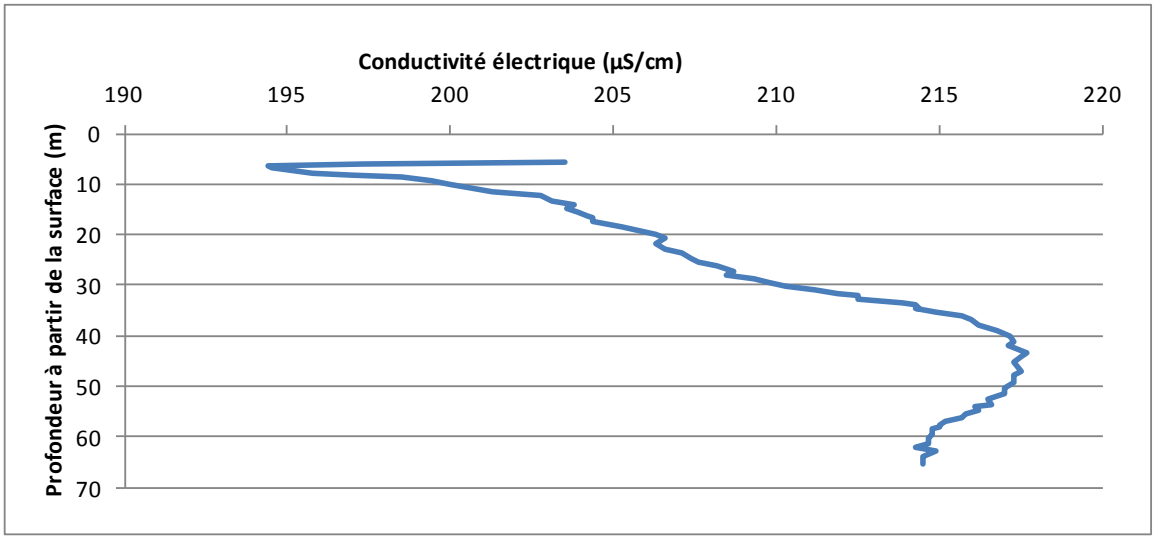


Figure 1: Profil de conductivité électrique de la colonne d'eau dans le puits

La figure ci-dessus représente un profil de conductivité électrique de la colonne d'eau de votre puits. La conductivité électrique est une mesure des composantes dissoutes dans l'eau. Le niveau d'eau est situé à environ 5 mètres sous la surface dusol. La conductivité électrique varie entre 195 et 220 µS/cm, ce qui indique une qualité de l'eau excellente. La conductivité électrique augmente en profondeur, avec un changement plus marqué entre 40 et 50 mètres. À cette profondeur, il est possible que des fractures alimentent votre puits avec de l'eau à condutivité électrique plus élevée. Cependant, il est à noter que l'écart de conductivité électrique de l'eau entre la surface et la profondeur est du même ordre de grandeur que l'incertitude sur la mesure.

Sommaire de la technique

Deux méthodes sont utilisées pour évaluer le statut du scellement de tubage :

1. La première a mesuré la conductivité hydraulique (K) autour du puits et permet de vérifier si l'eau s'infiltre plus facilement autour du puits que dans les surfaces environnantes. Un test statistique compare les valeurs mesurées. Si la valeur de K autour du puits est significativement plus grande que celles des alentours, le scellement de tubage est potentiellement fautif.

2. La seconde méthode consiste à injecter une solution saline (NaCl) lors des essais d'infiltration au puits. Un suivi quotidien de la conductivité électrique dans la colonne d'eau du puits est effectué pour déceler la présence du traceur, laquelle démontrerait, le cas échéant, la présence d'un court-circuit hydraulique, ce qui signifie que les eaux de surface peuvent s'infiltrer en ruisselant sur le tubage du puits.

Résultats

1. Comparaison des conductivités hydrauliques (K)

Les essais d'infiltration ont été effectués du 28 au 30 mai 2008. La conductivité hydraulique (K) mesurée au puits n'est pas plus élevée que celle mesurée dans les environs. En langage statistique, cette différence n'est pas «significative », ce qui signifie que cette technique ne démontre pas que le scellement est fautif. L'essai de traçage avait pour but de corroborer ou démentir cette affirmation.

2. Essai de traçage

L'injection du traceur s'est effectuée le 29 mai. L'essai s'est déroulé en trois étapes. Pour commencer, la zone autour du puits fut saturée par l'injection d'eau du puits (environ 200L). Ensuite, un total de 360L de solution saline, avec une conductivité électrique (EC) d'environ 8000 µS/cm, a été injecté autour du puits. Finalement, 240L d'eau de puits furent versés dans le but de pousser le traceur en profondeur. La figure suivante montre les profils de conductivité électrique, quelques jours après l'injection. L'arrivée du traceur, dans la colonne d'eau, commencerait une journée après son injection. La présence du traceur est beaucoup plus évidente dans le profil représentant la colonne d'eau après 2 jours.

Cinq jours après l'injection, il semblerait que la conductivité électrique de la colonne diminue de façon importante. Cette diminution pourrait être attribuée à l'infiltration d'eau de pluie, contribuant à la recharge du puits, trois jours après un évènement de précipitation.

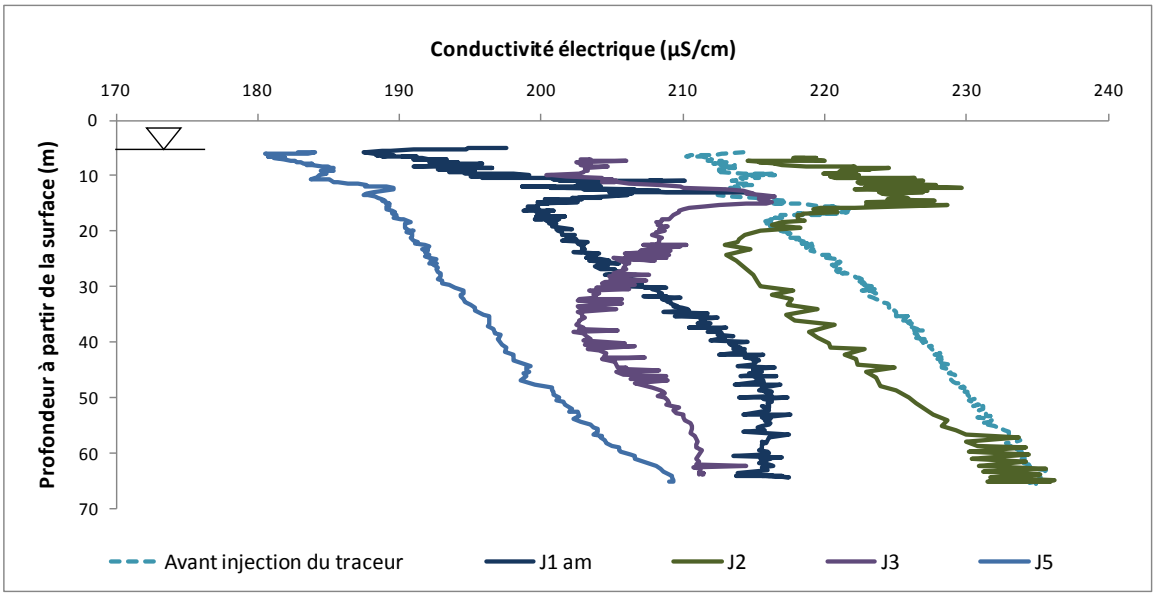


Figure 2 : Profils de conductivité électrique de la colonne d'eau avant et après l'injection de la solution saline.

Analyse bactériologique

Les bactéries sont naturellement présentes dans les eaux de surface et dans les sols. Elles sont transportées dans les eaux souterraines par le processus d'infiltration. Plusieurs facteurs affectent le mouvement des bactéries. Ces facteurs peuvent être reliés aux bactéries (type, taille, dynamique de la population) ou aux caractéristiques du sol (physique, chimique ou biologique). La plupart des bactéries sont filtrées dans le premier horizon du sol mais la présence de « macro-pores » peut contribuer au mouvement des bactéries en profondeur. Les macro-pores sont en fait des pores de grandes dimensions formées par l'activité biologique, les racines ou bien des fissures dans un milieu argileux. Ces macro-pores affectent la capacité du sol à filtrer les bactéries, ce qui leur permet de pénétrer plus profondément et rapidement.

La contamination bactérienne dans un puits peut provenir de plusieurs sources. Dans une municipalité comme Chelsea, où l'agriculture n'est que localisée et quasi-inexistante, la construction d'un puits (type, âge et profondeur), son emplacement, la

distance au système septique ainsi que des facteurs reliés à la géologie sont les principales sources contribuant à la présence de bactéries dans un puits.

La figure ci-dessous présente les résultats de l'analyse bactériologique sous forme de graphique. On remarque une présence constante de coliformes totaux de juillet à janvier. Le nombre de coliformes totaux dépasse la limite provinciale de 10 ufc/100mL à quelque reprise, soit en août, septembre et novembre. Il est également possible d'observer une présence de coliformes totaux de mars à mai 2009, mais le nombre de coliformes est sous la limite maximale. La présence de coliformes fécaux a été détectée en septembre 08, où le nombre de coliformes totaux était le plus important.

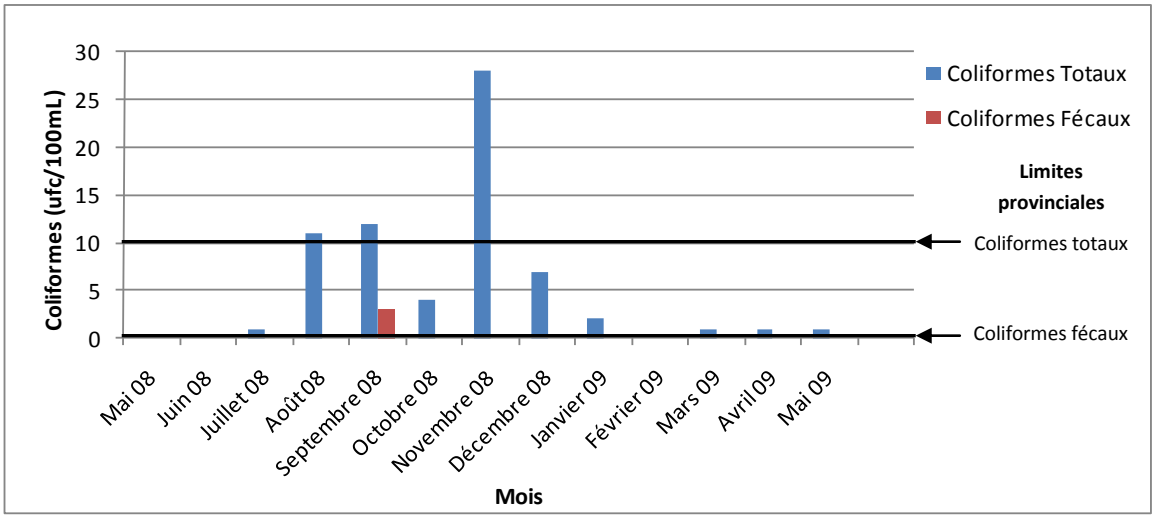


Figure 3: Résultats des analyses bactériologiques (coliformes totaux et fécaux) des échantillons d'avril 2008 à mai 2009.

Analyse Chimique

Naturellement, l'eau dissout les minéraux lorsqu'elle s'écoule dans le sol. Le processus de dissolution est habituellement lent dans la roche Précambrienne comparativement aux jeunes roches sédimentaires telles le grès ou la calcite. Des sources anthropogéniques, telles l'épandage de sels routiers, les fertilisants et les systèmes septiques peuvent également contribuer à la teneur en minéraux dissouts dans les eaux souterraines.

Les échantillons d'eau furent analysés à l'université d'Ottawa pour identifier diverses composantes dissoutes. Les résultats sont présentés dans le tableau suivant. Ce tableau donne également la moyenne annuelle ainsi que les lignes directrices relatives à certains paramètres. Les concentrations sont mesurées en milligrammes par litre (mg/L).

Mois	pH	Fluorure (mg/L)	Chlorure (mg/L)	Nitrate -N (mg/L)	Sulfate (mg/L)	Calcium (mg/L)	Magnésium (mg/L)	Sodium (mg/L)	Dureté (mg/L de $CaCO_3$)
Avril 08	6.9	bdl	9.1	bdl	15.5	32.7	7.1	6.0	110.9
Mai 08	6.7	bdl	15.3	bdl	15.5	35.2	7.6	6.5	119.6
Juin 08	6.8	bdl	16.9	bdl	17.4	48.7	10.3	7.1	164.1
Juillet 08	6.6	bdl	12.9	bdl	14.5	38.3	8.4	7.4	130.2
Août 08	6.5	bdl	16.1	0.6	17.5	48.7	11.1	8.9	167.4
Septembre 08	6.6	bdl	4.6	bdl	5.9	30.8	6.2	5.2	102.6
Octobre 08	6.9	bdl	20.2	1.0	25.8	56.4	12.3	9.7	191.6
Novembre 08	6.7	bdl	13.7	bdl	15.1	42.8	9.4	7.4	145.7
Décembre 08	6.6	bdl	14.7	bdl	17.3	40.0	8.8	7.3	136.1
Janvier 09	6.5	bdl	11.8	bdl	14.9	33.8	7.4	6.4	114.7
Février 09	6.7	bdl	15.1	bdl	18.1	39.3	8.8	7.7	134.3
Mars 09	6.7	bdl	11.5	bdl	14.5	28.7	6.2	5.7	97.0
Avril 09	6.6	bdl	14.5	bdl	14.5	27.7	6.3	5.7	95.1
Mai09	6.8	bdl	15.7	bdl	16.5	31.9	7.5	6.1	110.5
Moyenne	6.7		13.7	0.8	15.9	38.2	8.4	6.9	130.0
Ligne directrice		1.5 CMP	250.0 OE	10.0 CMP	500.0 OE			20.0 OE	100.0 LDO

LDP = Ligne directrice opérationnelle
CMP= Concentration Maximale Permise
OE= Objectif Esthétique
Bdl= Sous limite de détection

Les paramètres mesurés lors de notre étude sont des indicateurs de la qualité de l'eau. Il est important de considérer que dans certain cas, leur présence n'a pas nécessairement un impact sur la santé. Le tableau décrit certain de ces paramètre ainsi que ce que les effets possible de leur présence.

Paramètres mesurés	Définitions/Sources	Effets possibles
pH	Mesure de l'acidité de l'eau	• Une eau acide (pH<6.5) peut avoir un effet corrosif
Fluorure	Présence naturelle	• Affecte la dentition des enfants • Des concentrations très élevées peuvent affecter le développement des os
Chlorure	Présence naturelle ou causée par l'activité humaine	• Effet corrosif sur la plomberie • Goût salé
Nitrates	Fertilisants, système septique	• Effets sur la santé
Sulfates	Présence naturelle ou causée par l'activité humaine	• L'eau à un effet laxatif
Sodium	Présence naturelle ou causée par l'activité humaine	• Hypertension (personne à risque)
Dureté	Causée par la présence de Calcium et Magnésium dans l'eau	• Aucun effet sur la santé • Réduit l'efficacité des savons • Effets sur la tuyauterie (dépôts et blocage) • Tache et salie le linge

Sources : Pratiques de gestion optimale-Les puits

Recommandations pour la qualité de l'eau potable au Canada

Catégorie	Concentration de carbonate de Calcium (mg/L)
Eau Douce	0 à <60
Eau modérément dure	60 à <120
Eau dure	120 à <180
Eau très dure	180 et plus

Source : Santé Canada

Sommaire et suggestions

Intégrité du scellement de tubage

Malgré le fait que le taux d'infiltration autour du puits soit semblable aux surfaces avoisinantes, il semblerait qu'une connexion hydraulique, entre la surface et la colonne d'eau, existe au puits. L'essai de traçage ayant démontré cette connexion, l'espace annulaire du puits serait donc une voie préférentielle à l'infiltration des eaux de surface. Les analyses bactériologiques indiquent aussi une connexion possible.

Source possible de contamination

Il semblerait que les coliformes totaux soient présents en nombre plus important d'août à novembre, et en présence constante, mais moindre, pour les autres mois. Il y aurait donc une source constante alimentant le puits. Comme la contamination est plus importante lors des mois estivaux, il est possible que l'infiltration d'eaux de surface soit la principale cause de la présence de bactéries. La construction du puits et les caractéristiques du site (mince couche de sol et drainage vers le puits) sont probablement les facteurs responsables.

Analyse chimique

Tous les paramètres respectent les lignes directrices à l'exception de la dureté. La moyenne annuelle est de 130 mg/L de $CaCO_3$ alors que la ligne directrice opérationnelle est de 100 mg/L de $CaCO_3$. L'eau est donc considérée comme légèrement dure.

Suggestions

- L'espace annulaire étant une voie préférentielle à la contamination, il est important de réduire le ruissellement vers le puits. Pour ce faire, il est recommandé d'élever le sol à la tête du puits, ce qui évitera l'eau de ruissellement de s'accumuler et s'infiltrer à cet endroit.

- Un bon couvercle devrait garder les insectes hors du puits. Des évidences d'insectes furent détectées à l'intérieur, il est donc recommandé d'installer un couvercle étanche aux insectes (mais non à l'air). Ceci pourrait réduire le nombre de coliformes totaux dans le puits.
- Il est important de faire un suivi continu sur l'état de votre puits. Une fois l'an, vous devriez regarder dans le puits avec une lampe de poche. Recherchez la présence de fissures et de trous dans le cuvelage et près de l'embranchement des tuyaux vers la maison. Prenez des notes et comparez au fil des ans. Des mesures correctives peuvent être entreprises, par un puisatier, si un problème est détecté.
- Il est recommandé de faire une analyse bactériologique au moins 1 fois par année, et à l'occasion, notamment après une pluie importante et la fonte des neiges.
- Finalement, il serait impératif de faire installer un système de stérilisation de l'eau, tel les systèmes aux rayons ultra-violets.

L'information présentée dans ce rapport provient des sources suivantes :

*****Ces sources sont également excellentes pour en savoir plus sur les puits, les sources de contamination ainsi que sur la qualité de l'eau**

Conboy M.J, Smith S., 2005. A comprehensive consumer's guide for private water wells ISBN 0-9780387-0-3
www.wellwise.ca

Recommandations pour la qualité de l'eau potable au Canada -La dureté
http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/hardness-durete/index-fra.php

Ministère du développement durable, environnement et parcs- *La qualité de l'eau de mon puits*
http://www.mddep.gouv.qc.ca/eau/potable/depliant/index.htm

Publications : Ministère de l'agriculture, de l'alimentation et des affaires rurales (Ontario)
http://www.omafra.gov.on.ca/french/environment/water/publications.htm

Ministère de la santé et des soins de longue durée
http://www.health.gov.on.ca/english/public/pub/watersafe/watersafe_wellknow.html

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Faculté des sciences Faculty of Science
Sciences de la Terre Earth Sciences

Contamination of Private Well Study
Municipality of Chelsea, Québec



Report presented to:
W12
Chelsea, QC

Report prepared by:
Pascale St-Germain
PhD Candidate
University of Ottawa

May 2010

Acknowledgements

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Before investing in your well (well upgrade or water treatment system) I would suggest seeking advice from professionals and getting your water tested independently by an accredited laboratory before future investment in a treatment system.

Thank you very much for your understanding

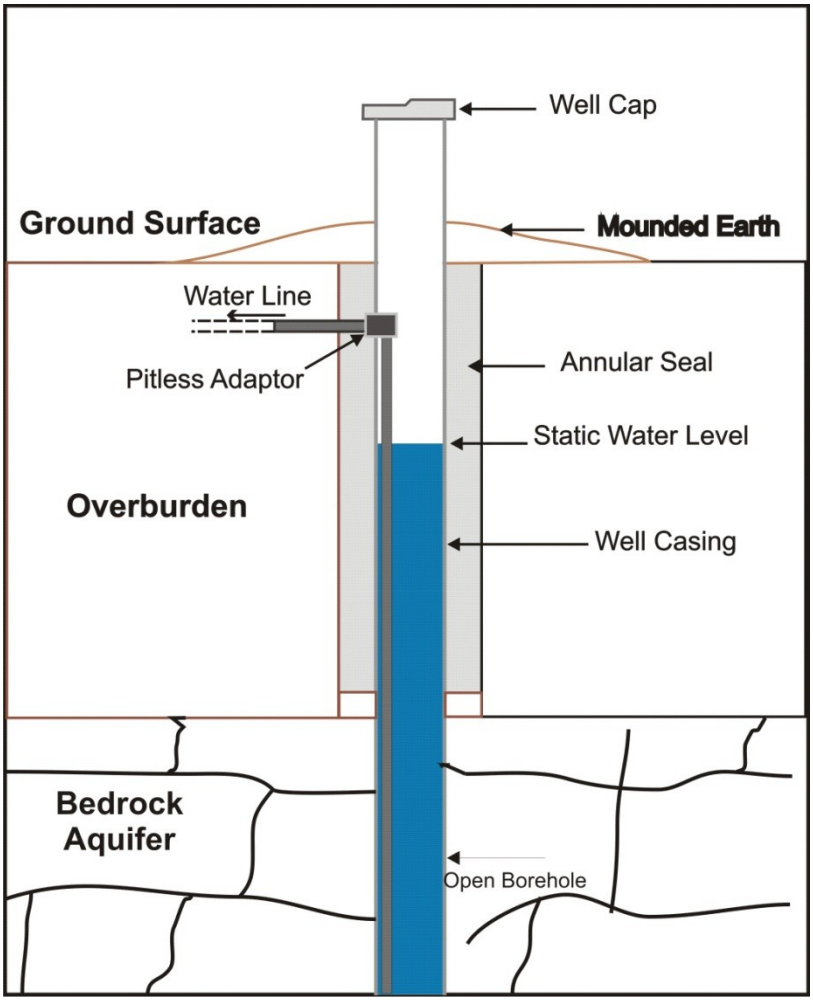
Pascale St-Germain
PhD candidate
University of Ottawa
Department of Earth Sciences

Glossary

Precambrian bedrock:	Fracture bedrock mainly composed of igneous and metamorphic rocks that are more than 542 million years old.
Overburden:	Unconsolidated sediments overlaying the bedrock and composed of grains of various sizes.
Champlain Sea:	Inland sea created about 10 000 year ago resulting from the melting of the *Inlandsis laurentidien* ice sheet. The sea principally covered the Montreal area but also some areas in south eastern Ontario.
Preferential pathways:	Direct movement of water through macro pores without the natural attenuation potential from the soil. This allows bacteria (or contaminant) to get carried faster and deeper.
Drilled well:	Well drilled into the fractured bedrock
Aquifer:	Geological unit capable of storing and transmitting water in sufficient quantity.
Confined aquifer:	Aquifer overlain by an impermeable layer. This layer protects the aquifer from surficial contaminant.
Unconfined aquifer:	Aquifer not overlain by an impermeable layer and exposed to atmospheric pressure.
Aquitard:	Geological unit capable of storing water but incapable of transmitting water in sufficient quantities.
Infiltration:	Movement of water from ground surface into the soil.
Hydraulic conductivity:	Ability of a porous media to transmit water.
Electrical conductivity (EC):	Ability of the water to conduct an electrical current. It is a general indication of the amount of total dissolved solids (TDS) in the water. EC is measure in Siemens per cm (S/cm) or microSiemens per cm (µS/cm = 10^{-6} S/cm). It ranges from several tens of µS/cm for rain water to several thousands of µS/cm for sea water. In the Chelsea area, the EC values range from approximately 90 to 1600 µS/cm.
Total coliforms:	Bacteria present in human and animal feces but also in the soil and vegetation
Faecal coliforms:	Bacteria originating from digestive tracts of humans and animals. Their presence indicates faecal pollution and the potential for pathogens to be present into the water

Macropore: Pore of greater dimension resulting from biological activity in the soil, from roots and cracks in clay.

Drilled well



Source: Modified from Best Management Practice – Water Well

Introduction

The objective of the project was to improve the understanding of private well contamination resulting from the infiltration of surface water. The risk of contamination in drilled wells was evaluated based on site characteristics and well construction.

Your well was tested every month for bacteria in order to assess the seasonality of contamination. Chemical analysis of the well water was carried out to understand the groundwater pathways and to establish possible links to potential contamination sources.

The objective of this report is to increase your awareness of possible water quality issues in your well and of the possible remedial actions that could taken preserve or improve the quality of your well water. It contains a summary of the work conducted, the data obtained, conclusions and some suggestions.

Site Description

Your well is drilled into the Precambrian bedrock, which is overlain by a layer of clay. This clay layer is a minimum of 5 metres thick and resulted from deposition in the Champlain Sea during the last glaciation (about 10,000 years ago). The well is approximately 60 metres deep and the static water level is located at 25 metres below ground surface.

Your well draws water from a confined aquifer. An aquifer is defined as a geologic unit capable of storing and transmitting water. This aquifer is also considered confined because there is an impermeable protective layer overlaying it. Usually, these types of aquifer are less vulnerable to contamination because of the presence of a confining layer. The confining layer provides an impermeable barrier, thereby naturally protecting the well against surface contamination.

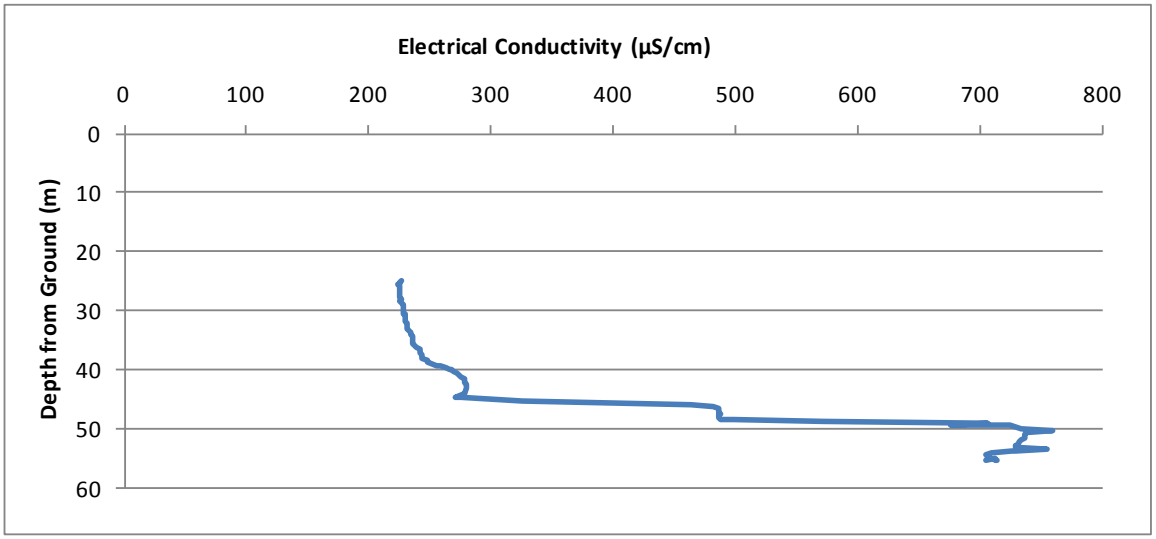


Figure 1: Electrical conductivity profile of the water column

The figure above displays the electrical conductivity (EC) profile of the well water column. The electrical conductivity is the ability of the water to conduct an electric current and it is a measure of the amount of dissolved solids in the well. For your well, the values range from 200 to 800 µS/cm with an important change at a depth of 45 to 50 metres from ground level. It is interpreted that at this depth, a fracture with a higher EC water connects with the water column.

Bacteria

Bacteria are naturally present in surface water and soil. They are carried to the groundwater system through the infiltration process. A number of factors may affect the movement of bacteria in soil. These are directly related to the bacteria (type, size and population dynamic) and the soil properties (chemical, biological and physical). Usually, most of the bacteria are filtered through the upper soil profile, but water can carry bacteria deeper using larger pore structures. These structures, called macropores, result from many things: earthworms, decayed roots and crack in clayey soil are some examples. Macropores reduce the efficiency of the soil to filter bacteria allowing them to travel deeper and faster.

Bacterial contamination in a well is a product of many factors. In a municipality like Chelsea, where agriculture is not a common practice, well construction (type, age, depth), location, the presence of septic system and the geology (bedrock and surficial) would be the primary contributors to bacterial contamination.

The well showed two contamination events during the sampling period. This is illustrated in the figure below. A total of 14 samples were collected and analysed for total and faecal coliforms. The presence of total coliforms was detected in five samples, over five consecutive months. Two samples exceeded the regulation limit of 10 cfu/100mL (colony forming units / 100 millilitres). Faecal coliforms were not detected during the sampling period.

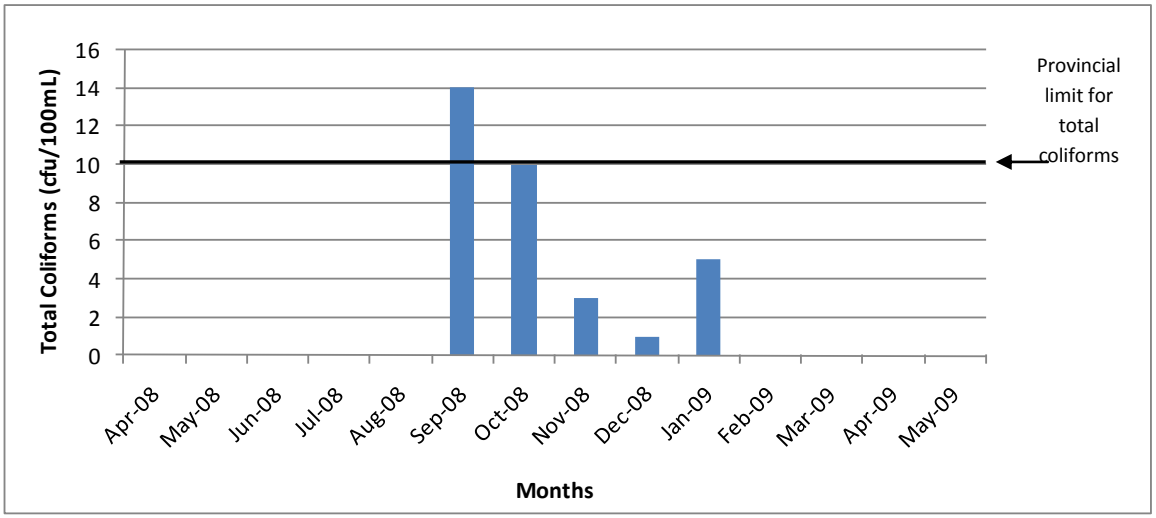


Figure 2: Results of the bacterial analysis (total and faecal coliforms) of the water samples, from April 2008 to May 2009.

Chemical analysis

As water naturally flows into the subsurface, it dissolves minerals along its pathway. The dissolution process is relatively slow in Precambrian bedrock compared to younger sedimentary rocks such as limestone or sandstone. However, other non natural sources may contribute to dissolved solids such as road salt application, septic systems or fertilizers.

Water samples were analysed for various dissolved species at the University of Ottawa. The results of the analyses are given in the following table. This table also shows the yearly average and the provincial guideline, if applicable. The concentrations are measured in milligrams per litre (mg/L)

Sampling date	pH	Fluoride (mg/L)	Chloride (mg/L)	Nitrate - N (mg/L)	Sulphate (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Hardness (mg/L as $CaCO_3$)
Apr-08	8.4	0.9	61.9	bdl	124.4	19.5	6.8	116.6	76.6
May-08	8.7	0.7	66.5	bdl	136.2	20.8	6.2	124.3	77.7
Jun-08	7.7	1.1	56.9	bdl	98.2	18.6	6.1	91.4	71.6
Jul-08	8.5	0.7	74.1	bdl	155.9	19.4	5.7	120.5	72.1
Aug-08	8.7	0.8	76.1	bdl	164.0	18.5	5.7	116.9	69.6
Sep-08	7.1	0.7	42.4	bdl	95.5	11.4	3.7	74.6	43.6
Oct-08	7.3	1.5	63.0	bdl	80.1	17.2	6.6	89.9	70.2
Nov-08	7.7	1.2	78.2	bdl	118.7	17.2	5.8	113.6	66.8
Dec-08	8.3	0.9	80.5	bdl	153.8	17.3	5.3	129.5	65.1
Jan-09	8.0	1.0	74.4	bdl	151.2	18.3	5.7	123.9	69.5
Feb-09	8.0	1.3	59.6	bdl	95.8	16.9	5.8	101.8	66.4
Mar-09	7.5	0.9	73.7	bdl	153.9	15.9	4.7	115.7	59.3
Apr-09	7.6	0.9	71.8	bdl	143.0	17.6	5.6	108.2	67.3
May-09	8.1	1.2	62.5	bdl	111.2	15.8	5.6	95.0	62.8
Average	8.0	1.0	67.3		127.3	17.5	5.7	108.7	67.0
Guideline		1.5 MAC	250.0 AO	10.0 MAC	500.0 AO			20.0 AO	100.0

OG = Operational Guideline
MAC= Maximum Allowable Concentration
AO= Aesthetic Objective
Bdl= below detection limit

The dissolved solids measured during this study are water quality indicators. It is important to realize that their presence may not have an impact on health. The following table describes the parameters and their possible effects.

Parameters	Definition/sources	Possible effects/concerns
pH	Measure of the acidity of water	• An acid water (pH<6.5) can have a corrosive effect • Low pH increases metals in solution, which could yield health concerns
Fluoride	Natural occurrence	• Mottled teeth • Bone development (high concentrations)
Chloride	Natural occurrence or human related activities	• Corrosive effect on plumbing • Salty taste
Nitrates	Human related activities	• Health Concerns
Sulphates	Natural occurrence or human related activities	• Water has laxative effect
Sodium	Natural occurrence or human related activities	• Health concerns • Salty taste
Hardness	Caused by the presence of calcium and magnesium and occasionally iron in the water	• No health effect • Soap scum • Scale buildup on plumbing fixture and pipes • Stained and mottled laundry

Sources: Best Management Practices –Water Well

Guidelines for Hardness

Category	Concentration of calcium carbonate (mg/L)
Soft	0 to <60
Medium Hard	60 to <120
Hard	120 to <180
Very Hard	180 and more

Source : Health Canada

Summary and Suggestions

Possible sources of contamination

The September contamination event could have resulted from surface water infiltration in the well, since a significant amount of rain occurred the week preceding sample collection.

It was observed that the well cap is not insect-proof and spider webs were present in the well cap. The presence of bugs most likely contributes to a small concentration of bacteria into the well.

Chemical analysis

Most constituent concentrations are below guidelines/regulations with the exception of sodium (Na) which is slightly above the guideline of 20 mg/L.

Suggestions

- In your situation, the presence of bacteria is recurrent and extra care should be taken for any use of water related to human consumption. The installation of a filtration system that kills microorganisms should be considered.
- A potential preferential pathway to surface water infiltration is the well annular space. To diminish the infiltration at the wellhead, it is recommended that the soil be mounded around the casing, which will deviate the runoff away from the wellhead, allowing the natural soil process to attenuate the bacteria present in the water.
- A good well cap should keep bugs out of the well. Proper insect-proof cap are available and will easily fit on your well. This will not stop the contamination but will prevent insects entering the well, which can increase the concentration of total coliforms.
- Every year, examine into the inside of the well with a flash light. You can look for cracks in the casing caused by corrosion. Also check for holes around the pitless adaptor (area where pipes are connected). A record should be kept and

comparisons made year to year. Corrective action can be suggested a licensed well contractor if something wrong is detected.

- It is recommended to get your water tested for bacteria at least 1 time a year, especially after important rainfall events and snowmelt.

The information presented in this report comes from the following sources:

*****These are also excellent sources for more information on water wells**

Conboy M.J, Smith S., 2005. A comprehensive consumer's guide for private water wells ISBN 0-9780387-0-3
www.wellwise.ca

Guidelines for Canadian Water Quality-Hardness
http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/hardness-durete/index-eng.php

Ministère du développement durable, environnement et parcs (MDDEP) -*La qualité de l'eau de mon puits* (French only)
http://www.mddep.gouv.qc.ca/eau/potable/depliant/index.htm

Ontario Ministry of Agriculture Food and Rural Affairs/Agriculture and Agri-food Canada. 2003 *Best Management Practices –Water Well*
http://www.omafra.gov.on.ca/english/environment/water/publications.htm

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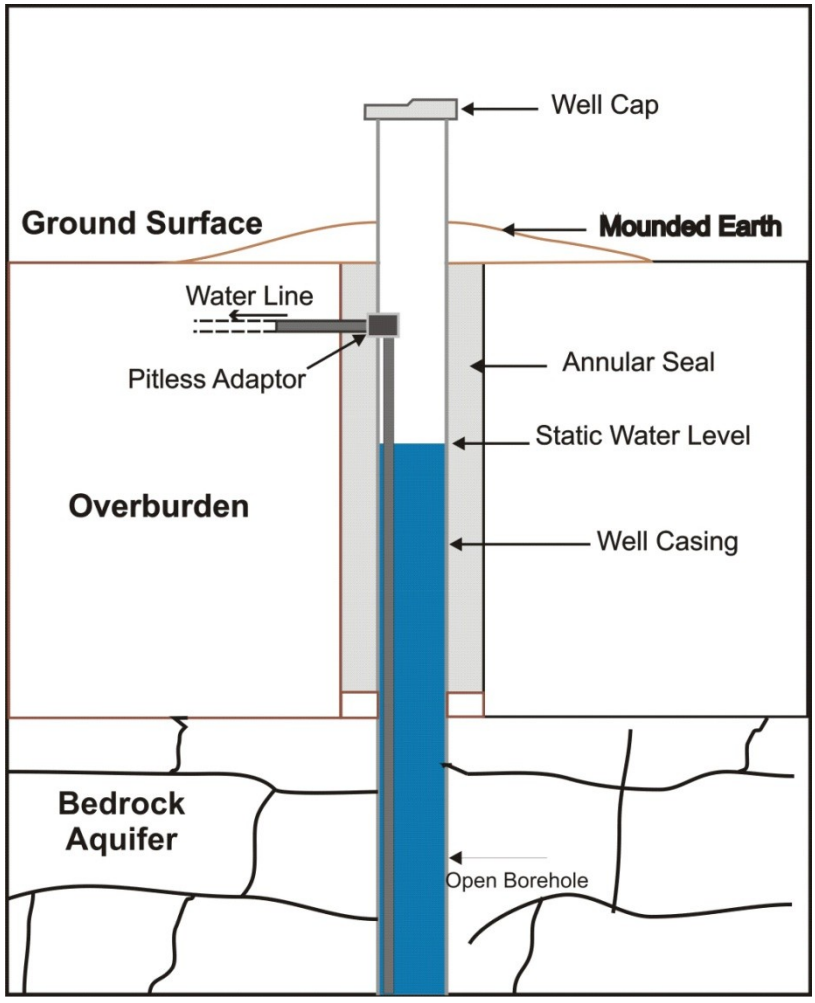
Pascale St-Germain
PhD candidate
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Glossary

Precambrian bedrock:	Fracture bedrock mainly composed of igneous and metamorphic rocks that are more than 542 million years old.
Overburden:	Unconsolidated sediments overlaying the bedrock and composed of grains of various sizes.
Champlain Sea:	Inland sea created about 10 000 year ago resulting from the melting of the *Inlandsis laurentidien* ice sheet. The sea principally covered the Montreal area but also some areas in south eastern Ontario.
Preferential pathways:	Direct movement of water through macro pores without the natural attenuation potential from the soil. This allows bacteria (or contaminant) to get carried faster and deeper.
Drilled well:	Well drilled into the fractured bedrock
Aquifer:	Geological unit capable of storing and transmitting water in sufficient quantity.
Confined aquifer:	Aquifer overlain by an impermeable layer. This layer protects the aquifer from surficial contaminant.
Unconfined aquifer:	Aquifer not overlain by an impermeable layer and exposed to atmospheric pressure.
Aquitard:	Geological unit capable of storing water but incapable of transmitting water in sufficient quantities.
Infiltration:	Movement of water from ground surface into the soil.
Hydraulic conductivity:	Ability of a porous media to transmit water.
Electrical conductivity (EC):	Ability of the water to conduct an electrical current. It is a general indication of the amount of total dissolved solids (TDS) in the water. EC is measure in Siemens per cm (S/cm) or microSiemens per cm (µS/cm = 10^{-6} S/cm). It ranges from several tens of µS/cm for rain water to several thousands of µS/cm for sea water. In the Chelsea area, the EC values range from approximately 90 to 1600 µS/cm.
Total coliforms:	Bacteria present in human and animal feces but also in the soil and vegetation

Faecal coliforms:	Bacteria originating from digestive tracts of humans and animals. Their presence indicates faecal pollution and the potential for pathogens to be present into the water.
Macropore:	Pore of greater dimension resulting from biological activity in the soil, from roots and cracks in clay

Drilled well



Source: Modified from Best Management Practice – Water Well

Introduction

The objective of the project was to improve the understanding of private well contamination resulting from the infiltration of surface water. The risk of contamination in drilled wells was evaluated based on site characteristics and well construction.

Your well was tested every month for bacteria in order to assess the seasonality of contamination. Chemical analysis of the well water was carried out to understand the groundwater pathways and to establish possible links to potential contamination sources.

The objective of this report is to increase your awareness of possible water quality issues in your well and of the possible remedial actions that could taken preserve or improve the quality of your well water. It contains a summary of the work conducted, the data obtained, conclusions and some suggestions.

Site Description

Your well is drilled into the Precambrian bedrock, which is overlain by less than 1 metre of till. Till is a mixture of sediments of variable grain sizes deposited during the last glaciation (about 10,000 years ago). The well is approximately 90 metres deep and the static water level is located 5.4 metres below ground surface.

Your well draws water from an unconfined aquifer. An aquifer is defined as a geologic unit capable of storing and transmitting water. This aquifer is also considered unconfined because there is no impermeable protective layer overlaying it. Usually, these types of aquifer are more vulnerable to contamination since there is no confining layer. The confining layer provides an impermeable barrier, thereby naturally protecting the well against surface contamination.

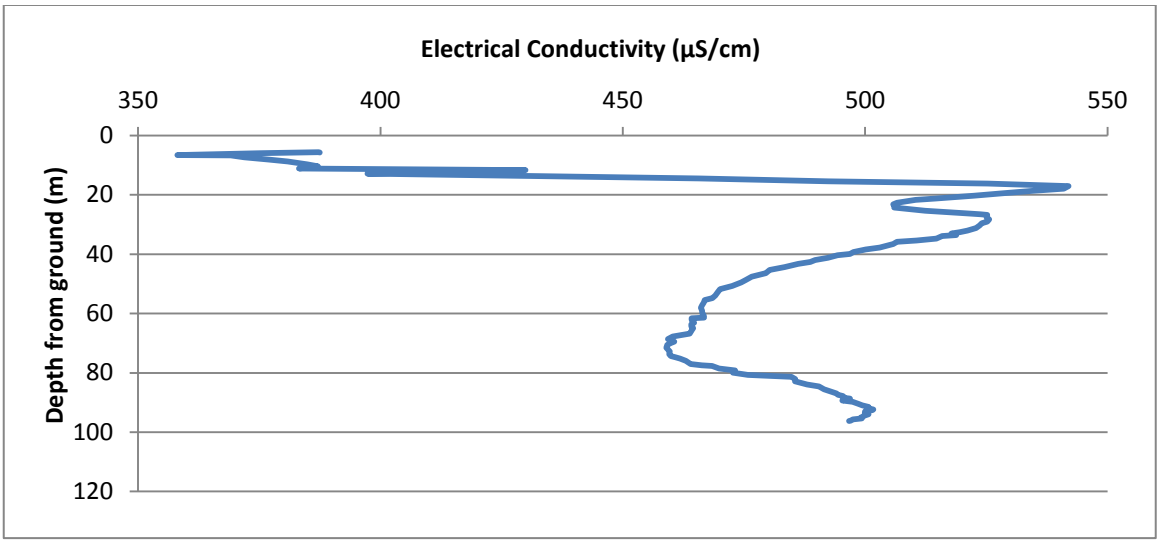


Figure 1: Electrical conductivity profile of the water column

The figure above displays the electrical conductivity (EC) profile of the well water column. The electrical conductivity is the ability of the water to conduct an electric current and it is a measure of the amount of dissolved solids in the well. For this well, the values range from 350 to 550 µS/cm. There is EC changes through the water column, where the main fractures seems to be from 20 to 40 metres. It is interpreted that at this depth, a fracture with a higher EC water connects with the water column.

Bacteria

Bacteria are naturally present in surface water and soil. They are carried to the groundwater system through the infiltration process. A number of factors may affect the movement of bacteria in soil. These are directly related to the bacteria (type, size and population dynamic) and the soil properties (chemical, biological and physical). Usually, most of the bacteria are filtered through the upper soil profile, but water can carry bacteria deeper using larger pore structures. These structures, called macropores, result from many things: earthworms, decayed roots and crack in clayey soil are some examples. Macropores reduce the efficiency of the soil to filter bacteria allowing them to travel deeper and faster. Bacterial contamination in a well is a product of many factors. In a municipality like Chelsea, where agriculture is not a common practice, well construction (type, age,

depth), location, the presence of septic system and the geology (bedrock and surficial) would be the primary contributors to bacterial contamination.

Total and faecal coliforms were not detected in the well during the April 2008 to May 2009 sampling period.

Chemical analysis

As water naturally flows into the subsurface, it dissolves minerals along its pathway. The dissolution process is relatively slow in Precambrian bedrock compared to younger sedimentary rocks such as limestone or sandstone. However, other non natural sources may contribute to dissolved solids such as road salt application, septic systems or fertilizers.

Water samples were analysed for various dissolved species at the University of Ottawa. The results of the analyses are given in the following table. This table also shows the yearly average and the provincial guideline, if applicable. The concentrations are measured in milligrams per litre (mg/L)

Sampling date	pH	Fluoride (mg/L)	Chloride (mg/L)	Nitrate as N (mg/L)	Sulphate (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Hardness (mg/L as $CaCO_3$)
Apr-08	7.59	NA	NA	NA	NA	119.8	12.7	23.0	351.9
May-08	7.38	bdl	34.2	1.1	90.0	99.0	10.3	21.0	289.9
Jun-08	7.37	bdl	39.1	1.7	90.3	95.6	8.7	19.7	274.9
Jul-08	7.26	bdl	45.6	1.3	100.8	99.5	9.1	22.9	286.1
Aug-08	7.3	bdl	46.1	1.8	112.5	110.6	10.9	27.9	321.4
Sep-08	6.7	bdl	13.7	0.5	19.3	129.0	11.6	24.6	370.1
Oct-08	7.2	bdl	64.9	2.8	118.8	135.0	12.4	29.0	388.5
Nov-08	7.0	bdl	61.6	4.3	123.7	130.0	12.4	24.8	376.0
Dec-08	7.0	bdl	72.6	3.4	132.8	133.5	12.3	27.0	384.5
Jan-09	7.0	bdl	69.5	3.1	112.3	127.9	12.7	23.1	372.2
Feb-09	7.0	bdl	52.5	2.5	83.8	128.3	12.2	25.4	370.9
Mar-09	7.1	bdl	82.9	3.0	118.9	125.5	11.5	25.7	361.0
Apr-09	6.8	bdl	59.4	2.0	77.2	86.2	7.0	16.6	244.3
May-09	7.2	bdl	56.6	1.2	93.7	81.9	8.6	20.7	240.0
Average	7.1		53.7	2.2	98.0	114.4	10.9	23.7	330.8
Guideline		1.5 MAC	250.0 AO	10.0 MAC	500.0 AO			20.0 AO	100.0

OG = Operational Guideline
MAC= Maximum Allowable Concentration
AO= Aesthetic Objective
Bdl= below detection limit

The dissolved solids measured during this study are water quality indicators. It is important to realize that their presence may not have an impact on health. The following table describes the parameters and their possible effects.

Parameters	Definition/sources	Possible effects/concerns
pH	Measure of the acidity of water	• An acid water (pH<6.5) can have a corrosive effect • Low pH increases metals in solution, which could yield health concerns
Fluoride	Natural occurrence	• Mottled teeth • Bone development (high concentrations)
Chloride	Natural occurrence or human related activities	• Corrosive effect on plumbing • Salty taste
Nitrates	Human related activities	• Health Concerns
Sulphates	Natural occurrence or human related activities	• Water has laxative effect
Sodium	Natural occurrence or human related activities	• Health concerns • Salty taste
Hardness	Caused by the presence of calcium and magnesium and occasionally iron in the water	• No health effect • Soap scum • Scale buildup on plumbing fixture and pipes • Stained and mottled laundry

Sources: Best Management Practices –Water Well

Guidelines for Hardness

Category	Concentration of calcium carbonate (mg/L)
Soft	0 to <60
Medium Hard	60 to <120
Hard	120 to <180
Very Hard	180 and more

Source : Health Canada

Summary and Suggestions

Possible sources of contamination

It was observed that the well cap is not insect-proof and spider webs were present in the well cap. In some case, the presence of bugs contributes to a small concentration of bacteria into the well.

Chemical analysis

The amount of dissolved constituent in your water is relatively high, which indicates that your well water is mainly coming from a deeper groundwater system. The yearly average for the sodium is slightly above the aesthetic objective. The water of your well is considered very hard for domestic usage.

Concentrations of nitrate were detected in the well, but the levels are below the maximum allowed concentration. It would be important to monitor this parameter. It is recommended by the MDDEP to have this parameter analysed every few years. If the level gets above 5 mg-N/L, then yearly monitoring is recommended.

Suggestions

- A good well cap should keep bugs out of the well. Proper insect-proof cap are available and will easily fit on your well. This will not stop the contamination but will prevent insects entering the well, which can increase the concentration of total coliforms.
- A potential preferential pathway to surface water infiltration is the well annular space. To diminish the infiltration at the wellhead, it is recommended that the soil be mounded around the casing, which will deviate the runoff away from the wellhead, allowing the natural soil process to attenuate the bacteria present in the water.
- Every year, examine into the inside of the well with a flash light. You can look for cracks in the casing caused by corrosion. Also check for holes around the pitless adaptor (area where pipes are connected). A record should be kept and

comparisons made year to year. Corrective action can be suggested a licensed well contractor if something wrong is detected.

- It is important to consider activities around the wellhead, especially uphill from the well. For example: if the driveway is located uphill from the well and runoff water flow towards the well. Extra care should be taken to make sure there are no leaks from cars and salt should not be used as de-icing agent. To prevent nitrate contamination, no fertilizers should be used uphill or near the well recharge area.
- Even if total and faecal coliforms are not problematic, it is recommended to get your water tested for bacteria at least 1 time a year, especially after important rainfall events and snowmelt.

The information presented in this report comes from the following sources:

*****These are also excellent sources for more information on water wells**

Conboy M.J, Smith S., 2005. A comprehensive consumer's guide for private water wells ISBN 0-9780387-0-3
www.wellwise.ca

Guidelines for Canadian Water Quality-Hardness
http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/hardness-durete/index-eng.php

Ministère du développement durable, environnement et parcs (MDDEP) -*La qualité de l'eau de mon puits* (French only)
http://www.mddep.gouv.qc.ca/eau/potable/depliant/index.htm

Ontario Ministry of Agriculture Food and Rural Affairs/Agriculture and Agri-food Canada. 2003 *Best Management Practices –Water Well*
http://www.omafra.gov.on.ca/english/environment/water/publications.htm

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Sciences de la Terre Earth Sciences

Étude sur la contamination des puits domestiques Municipalité de Chelsea, Québec



Rapport présenté à :
W14
Chelsea, QC

Rapport préparé par :
Pascale St-Germain
Doctorante
Université d'Ottawa

Mai 2010

Remerciements

Merci d'avoir participé à cette étude. Vos efforts furent importants dans l'avancement de notre compréhension sur les voies préférentielles de contamination des puits. Nous sommes très reconnaissants pour nous avoir donné l'accès à votre propriété, pour votre hospitalité ainsi que votre aide dans le prélèvement mensuel des échantillons.

Notes importantes

Les idées présentées dans ce rapport sont des suggestions qui pourraient améliorer la qualité de l'eau de votre puits. Elles pourraient possiblement être utiles dans la réduction du nombre de coliformes mais ne résoudront pas nécessairement le problème général. Nous avons fait notre possible pour évaluer la source probable de contamination, mais plusieurs facteurs peuvent affecter la qualité de l'eau d'un puits. Ce rapport a pour but de vous aider à comprendre votre puits et n'inclut pas toutes les conclusions de l'étude. Ces suggestions doivent être considérées avec prudence.

Avant d'investir dans votre puits (amélioration du puits ou système de traitement de l'eau) il serait important de demander l'avis d'un professionnel certifié et de faire analyser votre eau par un laboratoire indépendant.

Merci beaucoup pour votre compréhension.

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Glossaire

Roc Précambrien : Socle rocheux composé de roches ignées et métamorphiques datant de plus de 542 Millions d'années

Dépôts meubles : Sédiments non consolidés recouvrant le socle rocheux

Mer de Champlain : Mer créée lors de la fonte du Glacier *Inlandsis laurentidien*, il y a environ 10 000 ans, submergeant principalement la région de Montréal et une partie du sud-est ontarien.

Voies préférentielles : Présence de macro pores favorisant l'écoulement de l'eau sans le potentiel atténuant du sol, permettant aux contaminants de se faire transporter plus rapidement et plus profondément

Puits foré : Puits creusé dans le socle rocheux à l'aide d'une foreuse

Aquifère : Unité géologique capable de contenir et de transmettre de l'eau en quantité suffisante

Aquifère captif : Aquifère recouvert d'une couche imperméable isolant l'aquifère de la surface du sol

Aquifère libre : Aquifère non recouvert d'une couche imperméable et exposé à la pression atmosphérique

Aquitard : Unité géologique imperméable capable de contenir de l'eau mais incapable de la transmettre en quantité suffisante

Infiltration : Mouvement de l'eau de la surface jusque dans le sol

Conductivité hydraulique : Capacité d'un milieu poreux à transmettre l'eau

Conductivité électrique (EC) : Capacité de l'eau à transmettre un courant électrique; donne une mesure du montant total des composantes dissoutes dans l'eau. L'unité de mesure de la conductivitéélectrique est le Siemens par cm (S/cm) ou microsiemens par cm (µS/cm = 10^{-6} S/cm). A titre comparatif, la EC varie de quelques dizaines de µS/cm dans le cas des eaux de pluie à quelques centaines de millier de µS/cm dans le cas des eaux salées. Dans la région de Chelsea, elle varie entre environ 80 et 1600 µS/cm.

Coliformes totaux : Groupe de bactéries fermentant le lactose à 38°C. Ces bactéries sont présentes dans les matières fécales des humains et des animaux ainsi que dans le sol et la végétation.

Coliformes fécaux : Bactéries provenant du système digestif des humains et animaux. Indique une présence possible de pathogènes dans l'eau.

Macro-pores : Pores de grandes dimensions formées par l'activité biologique, les racines ou bien les fissures dans un milieu argileux.

Représentation schématique d'un puits domestique

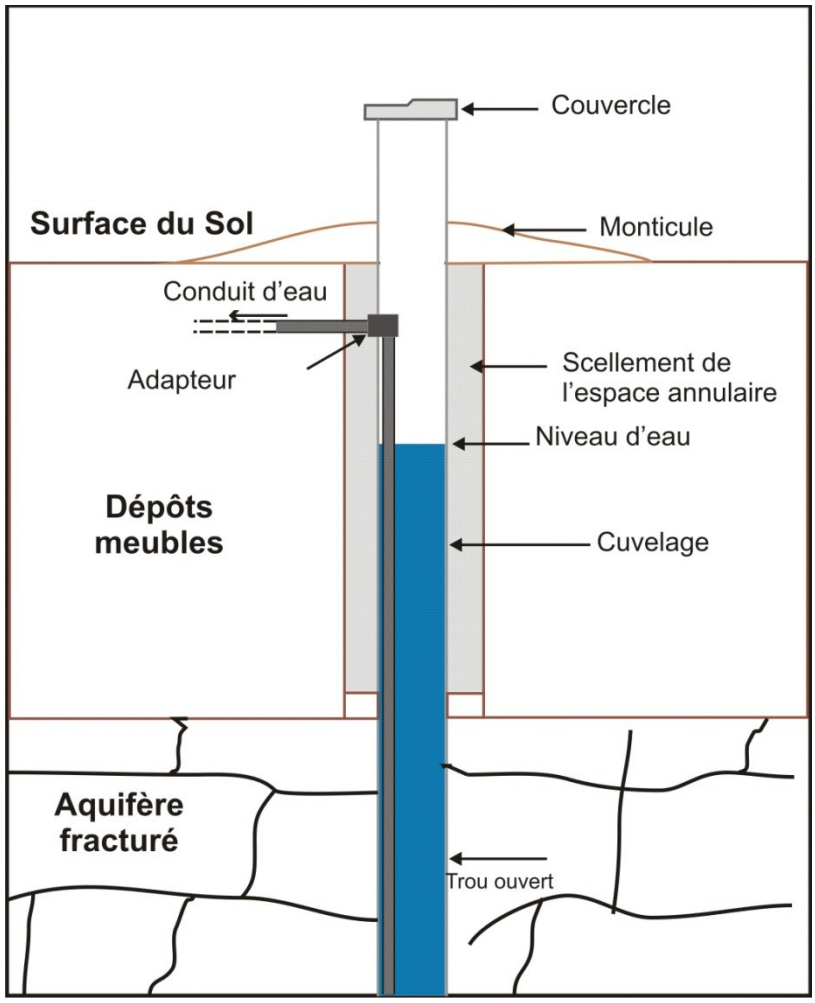


Image modifiée de : *Pratiques de gestion optimale-Les puits*

Introduction

L'objectif de ce projet est d'améliorer nos connaissances en ce qui a trait à la contamination des puits d'eau potable résultant de l'infiltration des eaux de surfaces. Notre but est d'évaluer le risque de contamination des puits forés en se basant sur les caractéristiques du site et sur la construction du puits.

En effectuant une analyse bactériologique mensuelle, il fut possible d'avoir une meilleure idée sur la saisonnalité de la contamination. L'analyse chimique de l'eau fût utilisée pour comprendre l'évolution des eaux souterraines et pour effectuer un lien avec une source possible de contamination.

L'objectif de ce rapport est de vous sensibiliser à la qualité de l'eau de votre puits et aux mesures existantes pour préserver ou améliorer sa qualité. Ce rapport présente un sommaire des travaux effectués, les principaux résultats ainsi que quelques suggestions, si nécessaire.

Description du site

Votre puits est foré dans le roc précambrien sur lequel repose une mince couche de dépôts meubles, principalement composés de sable, silt et argile déposés lors de la dernière glaciation, il y a environ 10 000 ans. La profondeur du puits est d'environ 67 mètres et le niveau de l'eau est situé à 16 mètres de la surface du sol.

L'eau de votre puits provient d'un aquifère. Un aquifère peut être défini comme une unité géologique capable de contenir et de transmettre de l'eau. Cet aquifère est également considéré comme étant « libre » car il n'est pas recouvert d'une couche imperméable. Ce type d'aquifère est généralement plus vulnérable à la contamination car il n'y a pas de couche imperméable protégeant naturellement l'aquifère des contaminants de surface.

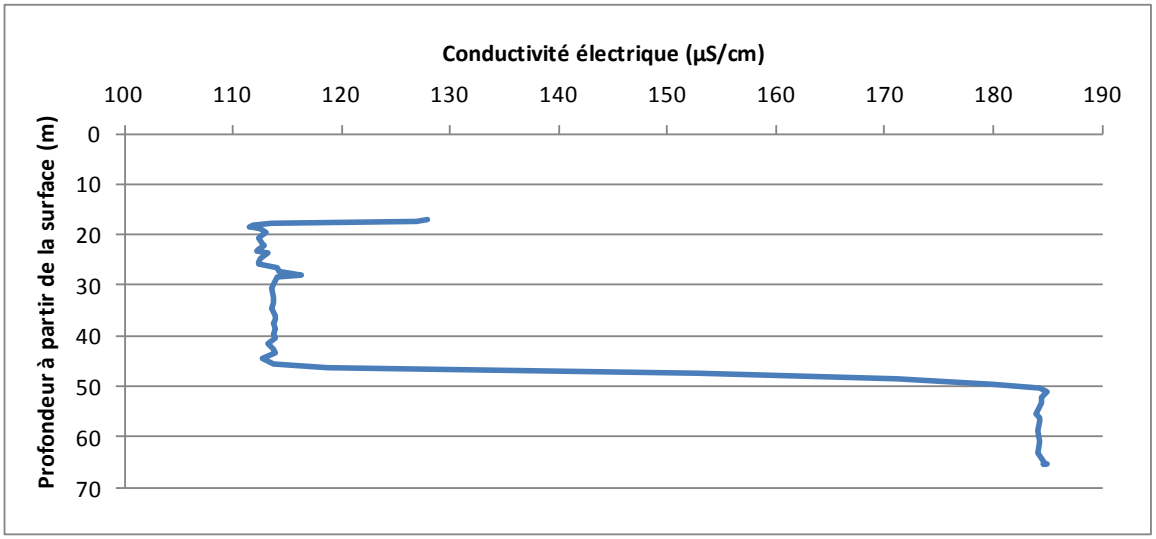


Figure 1: Profil de conductivité électrique de la colonne d'eau dans le puits

La figure ci-dessus représente un profil de conductivité électrique de la colonne d'eau de votre puits. La conductivité électrique est une mesure des composantes dissoutes dans l'eau. Le niveau d'eau est situé à environ 16 mètres sous la surface du sol. La conductivité électrique varie entre 110 et 190 µS/cm, ce qui indique une qualité de l'eau excellente. Il semble que la conductivité électrique augmente en profondeur, avec un changement important à environ 50 mètres. À cette profondeur, il est possible que des fractures alimentent votre puits avec de l'eau à condutivité électrique plus élevée.

Analyse bactériologique

Les bactéries sont naturellement présentes dans les eaux de surface et dans les sols. Elles sont transportées dans les eaux souterraines par le processus d'infiltration. Plusieurs facteurs affectent le mouvement des bactéries. Ces facteurs peuvent être reliés aux bactéries (type, taille, dynamique de la population) ou aux caractéristiques du sol (physique, chimique ou biologique). La plupart des bactéries sont filtrées dans le premier horizon du sol mais la présence de « macro-pores » peut contribuer au mouvement des bactéries en profondeur. Les macro-pores sont en fait des pores de grandes dimensions formées par l'activité biologique, les racines ou bien des fissures dans un milieu argileux.

Ces macro-pores affectent la capacité du sol à filtrer les bactéries, ce qui leur permet de pénétrer plus profondément et rapidement.

La contamination bactérienne dans un puits peut provenir de plusieurs sources. Dans une municipalité comme Chelsea, où l'agriculture n'est que localisée et quasi-inexistante, la construction d'un puits (type, âge et profondeur), son emplacement, la distance au système septique ainsi que des facteurs reliés à la géologie sont les principales sources contribuant à la présence de bactéries dans un puits.

La présence de coliformes totaux a été détectée à une reprise, soit en août 2008. Le nombre était alors de 68 ufc/100mL. L'échantillon fut prélevé après l'installation d'une nouvelle pompe. Il est normal de détecter des coliformes totaux parce que de l'équipement neuf a été inséré dans le puits sans être désinfecté. La présence de coliformes fécaux n'a jamais été détectée dans les échantillons prélevés.

Analyse Chimique

Naturellement, l'eau dissout les minéraux lorsqu'elle s'écoule dans le sol. Le processus de dissolution est habituellement lent dans la roche Précambrienne comparativement aux jeunes roches sédimentaires telles le grès ou la calcite. Des sources anthropogéniques, telles l'épandage de sels routiers, les fertilisants et les systèmes septiques peuvent également contribuer à la teneur en minéraux dissouts dans les eaux souterraines.

Les échantillons d'eau furent analysés à l'université d'Ottawa pour identifier diverses composantes dissoutes. Les résultats sont présentés dans le tableau suivant. Ce tableau donne également la moyenne annuelle ainsi que les lignes directrices relatives à certains paramètres. Les concentrations sont mesurées en milligrammes par litre (mg/L).

Mois	pH	Fluorure (mg/L)	Chlorure (mg/L)	Nitrate -N (mg/L)	Sulfate (mg/L)	Calcium (mg/L)	Magnésium (mg/L)	Sodium (mg/L)	Dureté (mg/L de $CaCO_3$)
Avril 08	7.6	1.6	0.9	bdl	17.6	41.0	6.0	4.6	127.2
Mai 08	7.8	1.3	0.6	bdl	16.4	37.0	5.2	4.1	113.8
Juin 08	7.6	1.6	0.7	bdl	17.4	50.9	7.6	4.9	158.4
Juillet 08	6.9	1.5	0.7	bdl	16.3	37.0	5.2	4.1	113.8
Août 08	7.2	1.6	0.7	bdl	16.8	40.7	6.2	4.6	127.0
Septembre 08	7.9	2.0	25.9	bdl	19.6	38.7	6.1	25.4	122.0
Octobre 08	7.5	1.9	1.6	0.2	19.6	41.0	6.2	6.6	128.1
Novembre 08	7.2	1.4	1.1	0.4	13.5	41.3	5.4	4.3	125.5
Décembre 08	6.9	1.6	1.0	bdl	16.1	38.8	5.4	4.1	119.2
Janvier 09	6.8	1.6	0.9	bdl	15.7	37.2	5.2	3.8	114.2
Mars 09	7.1	1.4	1.1	bdl	15.3	35.7	4.8	3.7	108.7
Avril 09	6.9	1.3	1.3	bdl	13.1	31.6	4.1	2.9	95.7
Mai 09	6.9	1.8	0.9	bdl	17.1	31.4	5.1	3.7	99.6
Moyenne	7.3	1.6	2.9		16.5	38.6	5.6	5.9	119.5
Ligne directrice		1.5 CMP	250.0 OE	10.0 CMP	500.0 OE			20.0 OE	100.0 LDO

LDP = Ligne directrice opérationnelle OE= Objectif Esthétique

CMP= Concentration Maximale Permise Bdl= Sous limite de détection

Les paramètres mesurés lors de notre étude sont des indicateurs de la qualité de l'eau. Il est important de considérer que dans certain cas, leur présence n'a pas nécessairement un impact sur la santé. Le tableau décrit certain de ces paramètre ainsi que ce que les effets possible de leur présence.

Paramètres mesurés	Définitions/Sources	Effets possibles
pH	Mesure de l'acidité de l'eau	• Une eau acide (pH<6.5) peut avoir un effet corrosif
Fluorure	Présence naturelle	• Affecte la dentition des enfants • Des concentrations très élevées peuvent affecter le développement des os
Chlorure	Présence naturelle ou causée par l'activité humaine	• Effet corrosif sur la plomberie • Goût salé
Nitrates	Fertilisants, système septique	• Effets sur la santé
Sulfates	Présence naturelle ou causée par l'activité humaine	• L'eau à un effet laxatif
Sodium	Présence naturelle ou causée par l'activité humaine	• Hypertension (personne à risque)
Dureté	Causée par la présence de Calcium et Magnésium dans l'eau	• Aucun effet sur la santé • Réduit l'efficacité des savons • Effets sur la tuyauterie (dépôts et blocage) • Tache et salie le linge

Sources : Pratiques de gestion optimale-Les puits

Recommandations pour la qualité de l'eau potable au Canada

Catégorie	Concentration de carbonate de Calcium (mg/L)
Eau Douce	0 à <60
Eau modérément dure	60 à <120
Eau dure	120 à <180
Eau très dure	180 et plus

Source : Santé Canada

Sommaire et suggestions

Source possible de contamination

L'analyse bactériologique de l'eau de votre puits est relativement bonne. La présence de coliformes totaux fût en toute probabilité reliée à l'installation d'une nouvelle pompe.

Analyse chimique

Tous les paramètres respectent les lignes directrices à l'exception de la concentration de fluorure et de la dureté. Pour la concentration en fluorure, la moyenne annuelle est 1.6 mg/L alors que la concentration maximale permise est de 1.5 mg/L. La moyenne est légèrement au dessus de la limite. Pour la dureté, la moyenne annuelle est de 120 mg/L de $CaCO_3$ alors que la ligne directrice opérationnelle est de 100 mg/L de $CaCO_3$. L'eau est donc considérée dure.

Suggestions

- Il est important de faire un suivi continu sur l'état de votre puits. Une fois l'an, vous devriez regarder dans le puits avec une lampe de poche. Recherchez la présence de fissures et de trous dans le cuvelage et près de l'embranchement des tuyaux vers la maison. Prenez des notes et comparez au fil des ans. Des mesures correctives peuvent être entreprises, par un puisatier, si un problème est détecté.
- Même si la présence de coliformes dans votre puits n'est pas problématique, il est recommandé de faire une analyse bactériologique au moins 1 fois par année, et à l'occasion, notamment après une pluie importante et la fonte des neiges.

L'information présentée dans ce rapport provient des sources suivantes :

*****Ces sources sont également excellentes pour en savoir plus sur les puits, les sources de contamination ainsi que sur la qualité de l'eau**

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Étude sur la contamination des puits domestiques Municipalité de Chelsea, Québec



Rapport présenté à :
W15
Chelsea, QC

Rapport préparé par :
Pascale St-Germain
Candidate au doctorat
Université d'Ottawa

Mai 2010

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Notes importantes

Les idées présentées dans ce rapport sont des suggestions qui pourraient améliorer la qualité de l'eau de votre puits. Elles pourraient possiblement être utiles dans la réduction du nombre de coliformes mais ne résoudront pas nécessairement le problème général. Nous avons fait notre possible pour évaluer la source probable de contamination, mais plusieurs facteurs peuvent affecter la qualité de l'eau d'un puits. Ce rapport a pour but de vous aider à comprendre votre puits et n'inclut pas toutes les conclusions de l'étude. Ces suggestions doivent être considérées avec prudence.

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Glossaire

Roc Précambrien :	Socle rocheux composé de roches ignées et métamorphiques datant de plus de 542 Millions d'années
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Conductivité hydraulique :	Capacité d'un milieu poreux à transmettre l'eau
Conductivité électrique (EC) :	Capacité de l'eau à transmettre un courant électrique; donne une mesure du montant total des composantes dissoutes dans l'eau. L'unité de mesure de la conductivitéélectrique est le Siemens par cm (S/cm) ou microsiemens par cm (µS/cm = 10^{-6} S/cm). A titre comparatif, la EC varie de quelques dizaines de µS/cm dans le cas des eaux de pluie à quelques centaines de millier de µS/cm dans le cas des eaux salées. Dans la région de Chelsea, elle varie entre environ 80 et 1600 µS/cm.
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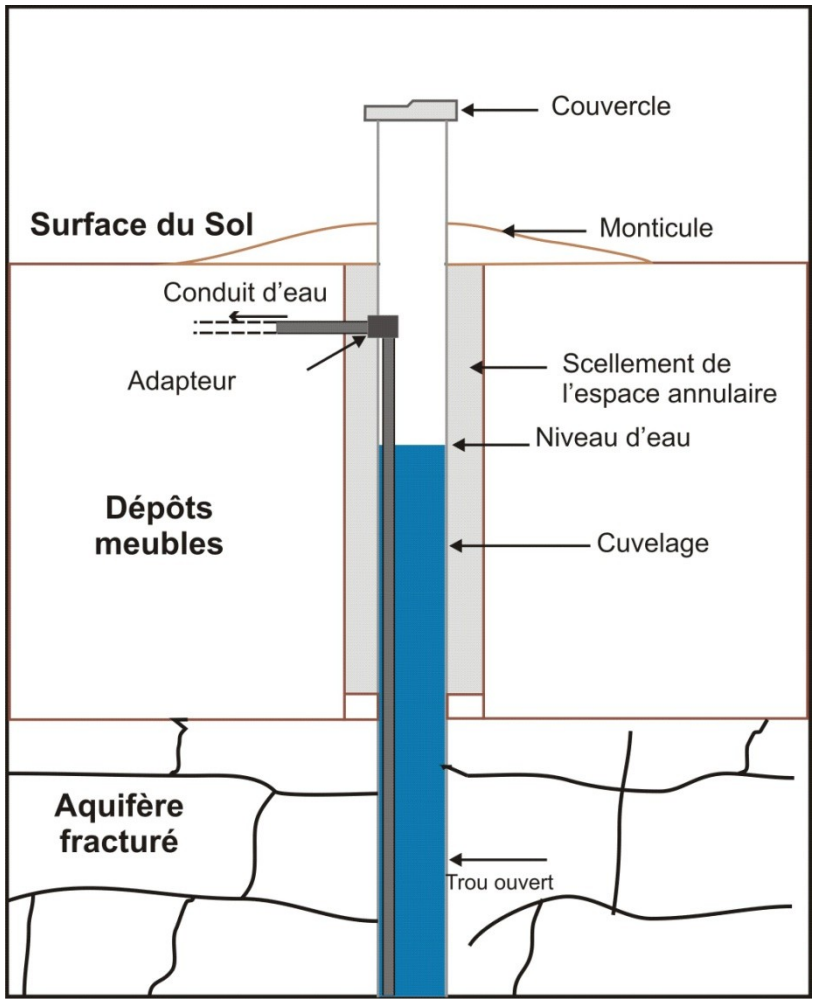


Image modifiée de : *Pratiques de gestion optimale-Les puits*

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En effectuant une analyse bactériologique mensuelle, il fut possible d'avoir une meilleure idée sur la saisonnalité de la contamination. L'analyse chimique de l'eau fût utilisée pour comprendre l'évolution des eaux souterraines et pour effectuer un lien avec une source possible de contamination.

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Description du site

Votre puits est foré dans le roc précambrien sur lequel repose une mince couche de dépôts meubles, principalement composés de sable, silt et argile déposés lors de la dernière glaciation, il y a environ 10 000 ans. La profondeur du puits est d'environ 37 mètres et le niveau de l'eau est situé à 2 mètres de la surface du sol.

L'eau de votre puits provient d'un aquifère. Un aquifère peut être défini comme une unité géologique capable de contenir et de transmettre de l'eau. Cet aquifère est également considéré comme étant « libre » car il n'est pas recouvert d'une couche imperméable. Ce type d'aquifère est généralement plus vulnérable à la contamination car il n'y a pas de couche imperméable protégeant naturellement l'aquifère des contaminants de surface.

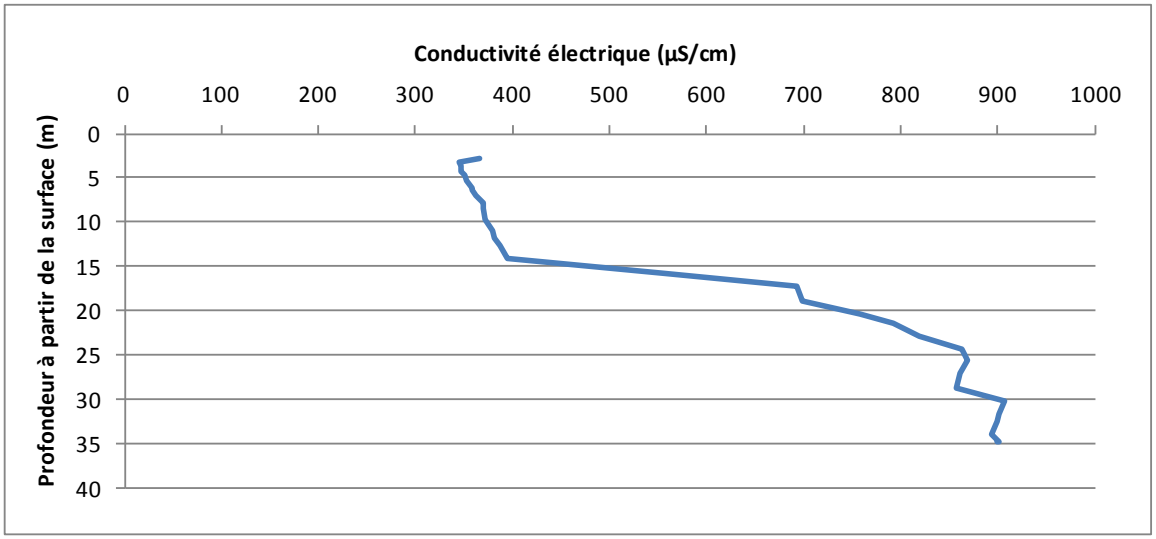


Figure 1: Profil de conductivité électrique de la colonne d'eau dans le puits

La figure ci-dessus représente un profil de conductivité électrique de la colonne d'eau de votre puits. La conductivité électrique est une mesure des composantes dissoutes dans l'eau. Le niveau d'eau est situé à environ 3 mètres sous la surface du sol. La conductivité électrique varie entre 350 et 900 µS/cm. La conductivité électrique augmente en profondeur, avec un changement plus marqué vers 15 mètres de profondeur. À cette profondeur, il est possible que des fractures alimentent votre puits avec de l'eau à condutivité électrique plus élevée.

Sommaire de la technique

Deux méthodes sont utilisées pour évaluer le statut du scellement de tubage :

1. La première a mesuré la conductivité hydraulique (K) autour du puits et permet de vérifier si l'eau s'infiltre plus facilement autour du puits que dans les surfaces environnantes. Un test statistique compare les valeurs mesurées. Si la valeur de K autour du puits est significativement plus grande que celles des alentours, le scellement de tubage est potentiellement fautif.
2. La seconde méthode consiste à injecter une solution saline (NaCl) lors des essais d'infiltration au puits. Un suivi quotidien de la conductivité électrique dans

la colonne d'eau du puits est effectué pour déceler la présence du traceur, laquelle démontrerait, le cas échéant, la présence d'un court-circuit hydraulique, ce qui signifie que les eaux de surface peuvent s'infiltrer en ruisselant sur le tubage du puits.

Résultats

1. Comparaison des conductivités hydrauliques (K)

Les essais d'infiltration ont été effectués les 19 et 20 août 2008. La conductivité hydraulique (K) mesurée au puits n'est pas plus élevée que celle mesurée dans les environs. En langage statistique, cette différence n'est pas «significative », ce qui signifie que le scellement n'est techniquement pas fautif. L'essai de traçage avait pour but de corroborer ou de démentir cette affirmation.

2. Essai de traçage

L'injection du traceur s'est effectuée le 20 août et le suivi s'est effectué jusqu'au 1er septembre. L'essai s'est déroulé en trois étapes. Pour commencer, la zone autour du puits fut saturée par l'injection d'eau du puits (environ 360L). Ensuite, un total de 360L de solution saline, avec une conductivité électrique (EC) d'environ 11 000 µS/cm, a été injecté autour du puits. Finalement, 180L d'eau de puits furent versés dans le but de pousser le traceur en profondeur. La figure suivante montre certains profils de conductivité électrique jusqu'à 12 jours après l'injection. Aucun des profils ne démontre de variations importantes ce qui signifie que le traceur n'a pas été détecté.

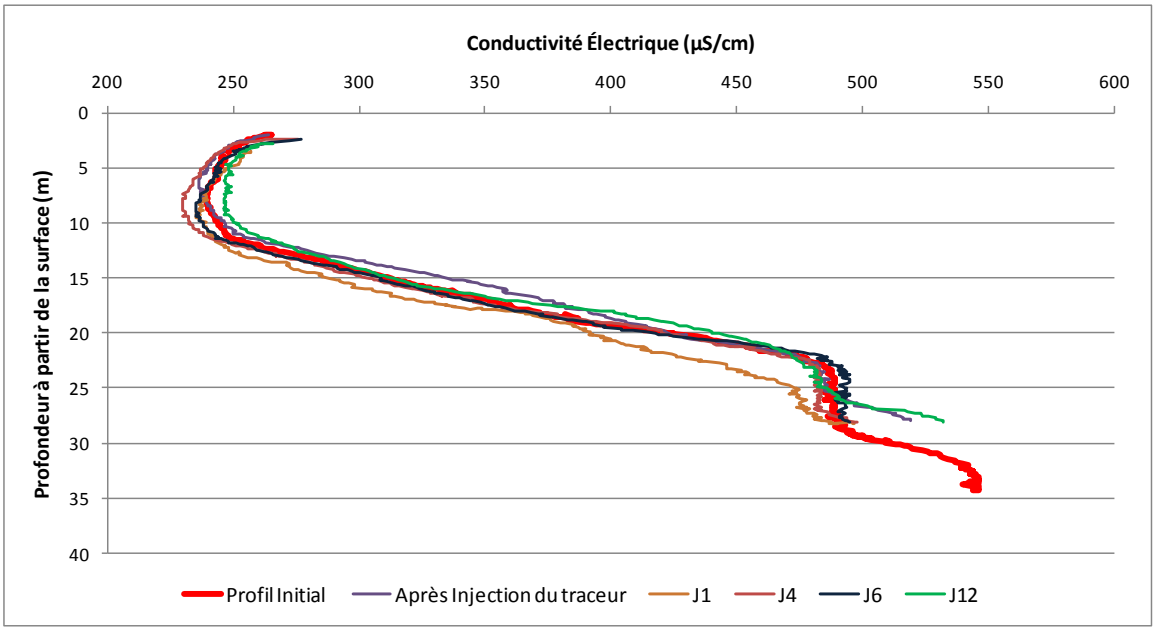


Figure 2 : Profils de conductivité électrique de la colonne d'eau avant et après l'injection de la solution saline.

Analyse bactériologique

Les bactéries sont naturellement présentes dans les eaux de surface et dans les sols. Elles sont transportées dans les eaux souterraines par le processus d'infiltration. Plusieurs facteurs affectent le mouvement des bactéries. Ces facteurs peuvent être reliés aux bactéries (type, taille, dynamique de la population) ou aux caractéristiques du sol (physique, chimique ou biologique). La plupart des bactéries sont filtrées dans le premier horizon du sol mais la présence de « macro-pores » peut contribuer au mouvement des bactéries en profondeur. Les macro-pores sont en fait des pores de grandes dimensions formées par l'activité biologique, les racines ou bien des fissures dans un milieu argileux. Ces macro-pores affectent la capacité du sol à filtrer les bactéries, ce qui leur permet de pénétrer plus profondément et rapidement.

La contamination bactérienne dans un puits peut provenir de plusieurs sources. Dans une municipalité comme Chelsea, où l'agriculture n'est que localisée et quasi-inexistante, la construction d'un puits (type, âge et profondeur), son emplacement, la distance au système septique ainsi que des facteurs reliés à la géologie sont les principales sources contribuant à la présence de bactéries dans un puits.

La présence de coliformes totaux et fécaux n'a pas été détectée lors de la période d'échantillonnage qui s'est déroulée d'avril 2008 à mai 2009.

Analyse Chimique

Naturellement, l'eau dissout les minéraux lorsqu'elle s'écoule dans le sol. Le processus de dissolution est habituellement lent dans la roche Précambrienne comparativement aux jeunes roches sédimentaires telles le grès ou la calcite. Des sources anthropogéniques, telles l'épandage de sels routiers, les fertilisants et les systèmes septiques peuvent également contribuer à la teneur en minéraux dissouts dans les eaux souterraines.

Les échantillons d'eau furent analysés à l'université d'Ottawa pour identifier diverses composantes dissoutes. Les résultats sont présentés dans le tableau suivant. Ce tableau donne également la moyenne annuelle ainsi que les lignes directrices relatives à certains paramètres. Les concentrations sont mesurées en milligrammes par litre (mg/L).

Mois	pH	Fluorure (mg/L)	Chlorure (mg/L)	Nitrate -N (mg/L)	Sulfate (mg/L)	Calcium (mg/L)	Magnésium (mg/L)	Sodium (mg/L)	Dureté (mg/L de $CaCO_3$)
Avril 08	7.1	0.8	99.7	0.7	120.7	138.3	10.0	56.1	386.6
Mai 08	7.3	0.9	79.2	0.4	99.6	124.6	8.8	49.6	347.8
Juin 08	7.3	0.9	72.7	0.2	92.7	112.7	7.5	41.9	312.8
Juillet 08	6.9	0.7	50.8	0.3	82.9	112.7	7.9	45.2	314.1
Août 08	7.2	0.7	63.8	0.2	93.4	120.8	8.9	47.0	338.3
Septembre 08	7.3	0.7	28.6	bdl	72.2	65.4	3.1	16.2	176.3
Octobre 08	7.1	0.9	100.2	0.6	98.2	133.8	8.8	47.5	370.6
Novembre 08	7.0	0.7	67.9	0.6	42.9	145.5	9.6	54.1	403.3
Décembre 08	7.0	0.9	150.1	1.1	111.8	153.5	10.6	59.3	427.4
Janvier 09	6.8	0.9	117.1	1.0	99.7	135.5	9.9	56.6	379.5
Février 09	6.9	bdl	72.4	0.4	48.8	131.7	9.4	56.4	368.0
Mars 09	7.0	0.9	131.4	1.0	114.0	137.0	9.6	56.1	382.3
Avril 09	7.0	1.0	106.1	0.6	103.0	120.3	9.2	49.6	338.4
Mai09	7.1	1.0	97.5	0.3	110.1	104.3	8.2	42.9	294.4
Moyenne	7.1	0.8	88.4	0.6	92.1	124.0	8.7	48.5	345.7
Ligne directrice		1.5 CMP	250.0 OE	10.0 CMP	500.0 OE			20.0 OE	100.0 LDO

LDP = Ligne directrice opérationnelle
CMP= Concentration Maximale Permise
OE= Objectif Esthétique
Bdl= Sous limite de détection

Les paramètres mesurés lors de notre étude sont des indicateurs de la qualité de l'eau. Il est important de considérer que dans certain cas, leur présence n'a pas nécessairement un impact sur la santé. Le tableau décrit certain de ces paramètre ainsi que ce que les effets possible de leur présence.

Paramètres mesurés	Définitions/Sources	Effets possibles
pH	Mesure de l'acidité de l'eau	• Une eau acide (pH<6.5) peut avoir un effet corrosif
Fluorure	Présence naturelle	• Affecte la dentition des enfants • Des concentrations très élevées peuvent affecter le développement des os
Chlorure	Présence naturelle ou causée par l'activité humaine	• Effet corrosif sur la plomberie • Goût salé
Nitrates	Fertilisants, système septique	• Effets sur la santé
Sulfates	Présence naturelle ou causée par l'activité humaine	• L'eau à un effet laxatif
Sodium	Présence naturelle ou causée par l'activité humaine	• Hypertension (personne à risque)
Dureté	Causée par la présence de calcium et magnésium dans l'eau	• Aucun effet sur la santé • Réduit l'efficacité des savons • Effets sur la tuyauterie (dépôts et blocage) • Tache et salie le linge

Sources : Pratiques de gestion optimale-Les puits

Recommandations pour la qualité de l'eau potable au Canada

Catégorie	Concentration de carbonate de Calcium (mg/L)
Eau Douce	0 à <60
Eau modérément dure	60 à <120
Eau dure	120 à <180
Eau très dure	180 et plus

Source : Santé Canada

Sommaire et suggestions

Intégrité du scellement de tubage

La conductivité hydraulique autour du puits était semblable à celles des surfaces avoisinantes. L'essai de traçage n'a pas démontré une connexion hydraulique avec la surface. L'anneau de bentonite présent dans l'espace annulaire du puits serait donc efficace pour prévenir l'infiltration d'eau à la tête du puits.

Analyse chimique

Tous les paramètres respectent les lignes directrices à l'exception du sodium, qui est plus élevé que l'objectif esthétique, ainsi que la dureté. La moyenne annuelle pour la dureté est de 346 mg/L de $CaCO_3$ alors que la ligne directrice opérationnelle est de 100 mg/L de $CaCO_3$. L'eau est donc considérée comme très dure, mais un adoucisseur est déjà en place.

Il est également possible de constater une faible présence de nitrates dans le puits. Les concentrations ne sont pas actuellement problématiques car la limite maximale permise est de 10 mg/L.

Suggestions

- Il est important de faire un suivi continu sur l'état de votre puits. Une fois l'an, vous devriez regarder dans le puits avec une lampe de poche. Recherchez la présence de fissures et de trous dans le cuvelage et près de l'embranchement des tuyaux vers la maison. Prenez des notes et comparez au fil des ans. Des mesures correctives peuvent être entreprises, par un puisatier, si un problème est détecté.
- La présence de nitrate, quoique faible, indique une contamination possible provenant d'un système septique ou de l'application de fertilisants à proximité de la zone de recharge. Il est recommandé par le MDDEP de faire un suivi deux fois par année si la concentration dépasse 5 mg/L.

- Finalement, même si la contamination par les coliformes n'est pas problématique, il est recommandé de faire une analyse bactériologique au moins 1 fois par année, et à l'occasion, notamment après une pluie importante et la fonte des neiges.

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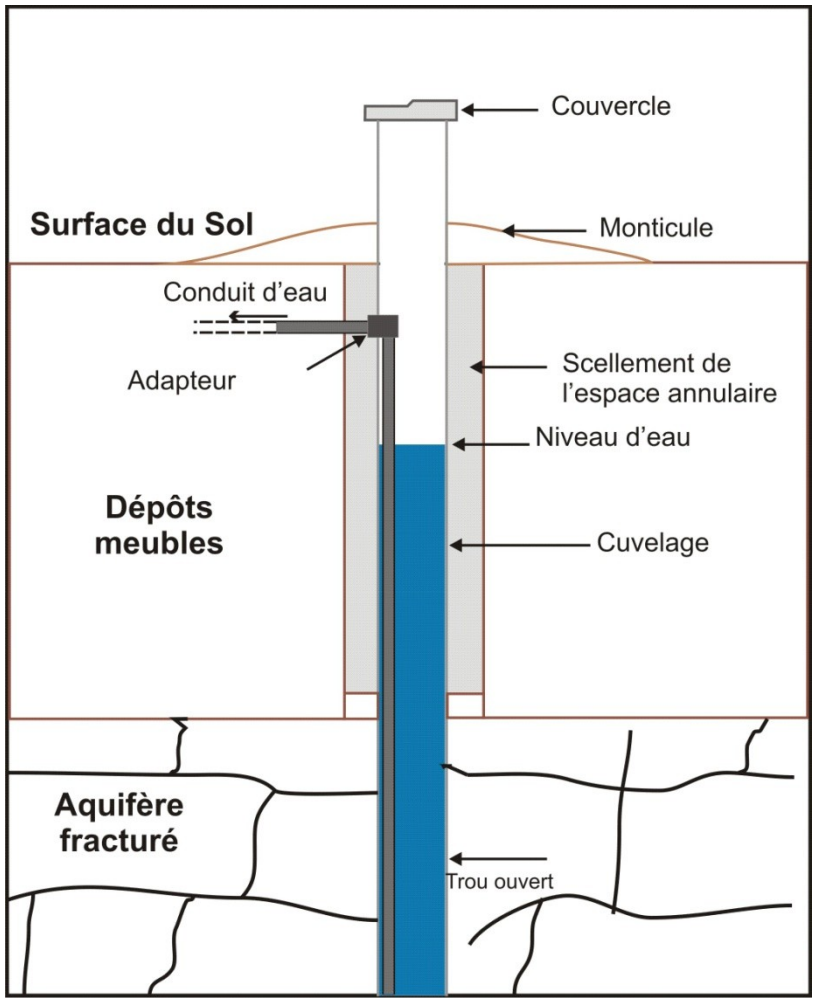


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L'eau de votre puits provient d'un aquifère. Un aquifère peut être défini comme une unité géologique capable de contenir et de transmettre de l'eau. Cet aquifère est également considéré comme étant « libre » car il n'est pas recouvert d'une couche imperméable. Ce type d'aquifère est généralement plus vulnérable à la contamination car il n'y a pas de couche imperméable protégeant naturellement l'aquifère des contaminants de surface.

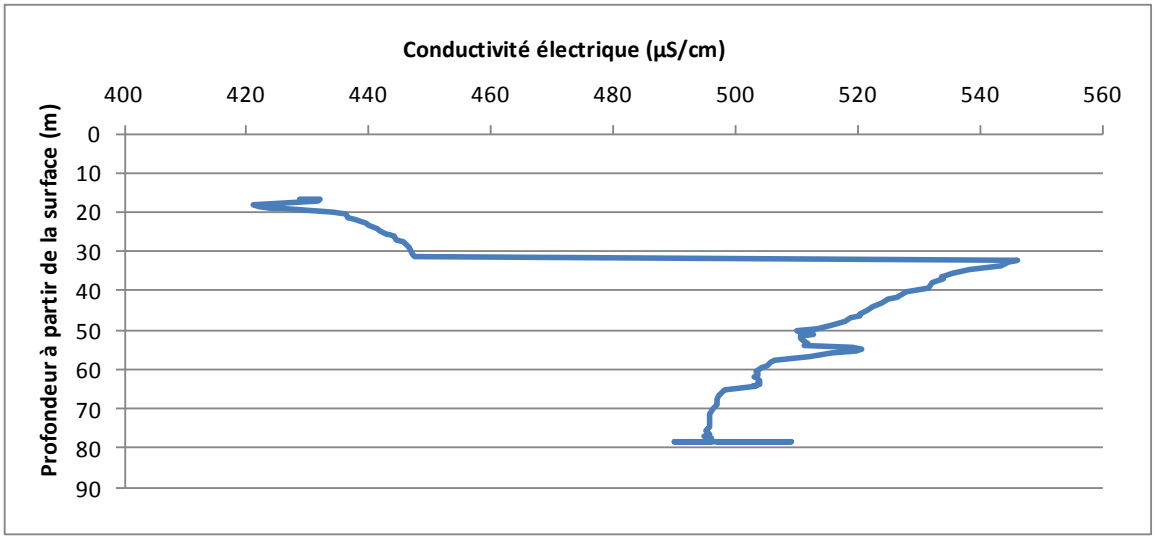


Figure 1: Profil de conductivité électrique de la colonne d'eau dans le puits

La figure ci-dessus représente un profil de conductivité électrique de la colonne d'eau de votre puits. La conductivité électrique est une mesure des composantes dissoutes dans l'eau. Le niveau d'eau est situé à environ 16 mètres sous la surface du sol. La conductivité électrique varie entre 420 et 550 µS/cm. La conductivité électrique augmente en profondeur, avec un changement important à environ 30 mètres. À cette profondeur, il est possible que des fractures alimentent votre puits avec de l'eau à condutivité électrique plus élevée. Cependant, il est à noter que l'écart de conductivité électrique de l'eau entre la surface et la profondeur est du même ordre de grandeur que l'incertitude sur la mesure.

Sommaire de la technique

Deux méthodes sont utilisées pour évaluer le statut du scellement de tubage :

1. La première a mesuré la conductivité hydraulique (K) autour du puits et permet de vérifier si l'eau s'infiltre plus facilement autour du puits que dans les surfaces environnantes. Un test statistique compare les valeurs mesurées. Si la valeur de K autour du puits est significativement plus grande que celles des alentours, le scellement de tubage est potentiellement fautif.

2. La seconde méthode consiste à injecter une solution saline (NaCl) lors des essais d'infiltration au puits. Un suivi quotidien de la conductivité électrique dans la colonne d'eau du puits est effectué pour déceler la présence du traceur, laquelle démontrerait, le cas échéant, la présence d'un court-circuit hydraulique, ce qui signifie que les eaux de surface peuvent s'infiltrer en ruisselant sur le tubage du puits.

Résultats

1. Comparaison des conductivités hydrauliques (K)

Les essais d'infiltration ont été effectués les 3 et 4 août 2008. Le suivi s'est effectué jusqu'au 14 août 2008.

La conductivité hydraulique (K) mesurée au puits n'était pas plus élevée que celle mesurée dans les environs. En langage statistique, cette différence n'est pas «significative », ce qui signifie que le scellement n'est techniquement pas fautif. L'essai de traçage avait pour but de corroborer ou de démentir cette affirmation.

2. Essai de traçage

L'injection du traceur s'est effectuée le 3 août. L'essai s'est déroulé en trois étapes. Pour commencer, la zone autour du puits fut saturée par l'injection d'eau du puits (environ 180L). Ensuite, un total de 360L de solution saline, avec une conductivité électrique (EC) d'environ 11 000 µS/cm, a été injecté autour du puits. Finalement, 330L d'eau de puits furent versés dans le but de pousser le traceur en profondeur. La figure suivante montre certains profils de conductivité électrique jusqu'à 3 jours après l'injection. L'arrivée du traceur, dans la colonne d'eau, commencerait après son injection. La présence du traceur est beaucoup plus évidente dans le profil représentant la colonne d'eau après deux jours (J2). Trois jours après l'injection (J3), il semblerait que la conductivité électrique de la colonne diminue et revienne à un état plus uniforme, signifiant la fin de l'arrivée de traceur

dans le puits. L'uniformité des valeurs de conductivité électrique reste constante jusqu'à la fin de la période de suivi.

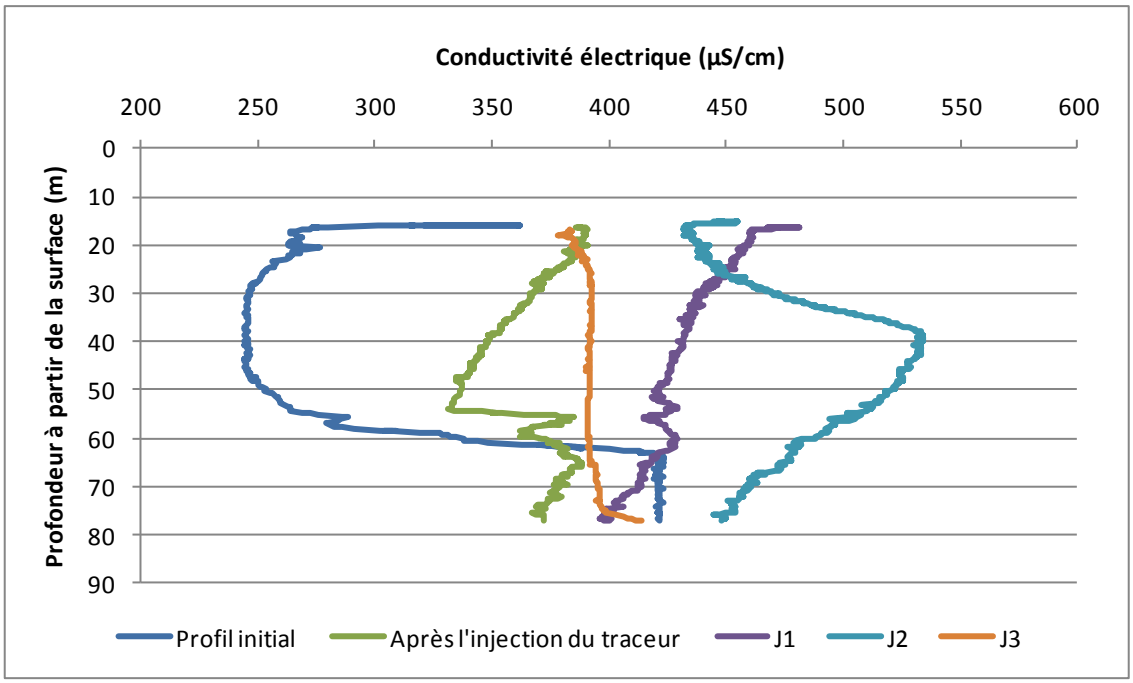


Figure 2 : Profils de conductivité électrique de la colonne d'eau avant et après l'injection de la solution saline.

Analyse bactériologique

Les bactéries sont naturellement présentes dans les eaux de surface et dans les sols. Elles sont transportées dans les eaux souterraines par le processus d'infiltration. Plusieurs facteurs affectent le mouvement des bactéries. Ces facteurs peuvent être reliés aux bactéries (type, taille, dynamique de la population) ou aux caractéristiques du sol (physique, chimique ou biologique). La plupart des bactéries sont filtrées dans le premier horizon du sol mais la présence de « macro-pores » peut contribuer au mouvement des bactéries en profondeur. Les macro-pores sont en fait des pores de grandes dimensions formées par l'activité biologique, les racines ou bien des fissures dans un milieu argileux. Ces macro-pores affectent la capacité du sol à filtrer les bactéries, ce qui leur permet de pénétrer plus profondément et rapidement.

La contamination bactérienne dans un puits peut provenir de plusieurs sources. Dans une municipalité comme Chelsea, où l'agriculture n'est que localisée et quasi-inexistante, la construction d'un puits (type, âge et profondeur), son emplacement, la distance au système septique ainsi que des facteurs reliés à la géologie sont les principales sources contribuant à la présence de bactéries dans un puits.

La figure ci-dessous présente les résultats de l'analyse bactériologique sous forme de graphique. On remarque une présence constante de coliformes totaux tout au long de la période d'échantillonnage. Le nombre de coliformes totaux dépasse la limite provinciale de 10 ufc/100mL à six reprises. La présence de coliformes fécaux a été détectée de juillet à septembre 2008 ainsi qu'en février 2009.

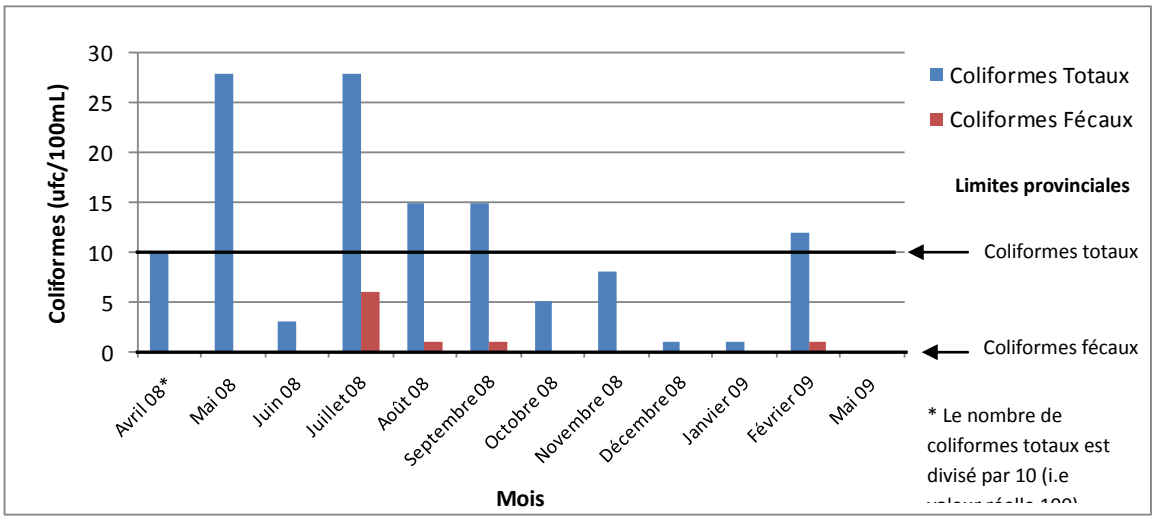


Figure 3: Résultats des analyses bactériologiques (coliformes totaux et fécaux) des échantillons d'avril 2008 à mai 2009.

Analyse Chimique

Naturellement, l'eau dissout les minéraux lorsqu'elle s'écoule dans le sol. Le processus de dissolution est habituellement lent dans la roche Précambrienne comparativement aux jeunes roches sédimentaires telles le grès ou la calcite. Des sources anthropogéniques, telles l'épandage de sels routiers, les fertilisants et les systèmes septiques peuvent également contribuer à la teneur en minéraux dissouts dans les eaux souterraines.

Les échantillons d'eau furent analysés à l'université d'Ottawa pour identifier diverses composantes dissoutes. Les résultats sont présentés dans le tableau suivant. Ce tableau donne également la moyenne annuelle ainsi que les lignes directrices relatives à certains paramètres. Les concentrations sont mesurées en milligrammes par litre (mg/L).

Mois	pH	Fluorure (mg/L)	Chlorure (mg/L)	Nitrate -N (mg/L)	Sulphate (mg/L)	Calcium (mg/L)	Magnésium (mg/L)	Sodium (mg/L)	Dureté (mg/L de $CaCO_3$)
Avril 08	6.3	bdl	46.8	0.6	17.3	35.1	8.2	7.9	121.3
Mai 08	6.6	bdl	96.9	0.6	27.8	50.2	11.6	19.6	173.3
Juin 08	6.6	bdl	95.3	0.7	32.9	77.7	14.6	28.9	254.2
Juillet 08	6.7	bdl	NA	0.1	18.9	89.5	15.6	15.5	287.7
Août 08	6.5	bdl	31.6	0.3	15.2	62.9	12.3	23.3	207.9
Septembre 08	7.8	bdl	25.4	bdl	6.2	47.7	14.3	13.6	178.1
Octobre 08	7.1	bdl	NA	0.3	24.3	90.6	15.3	14.3	289.6
Novembre 08	6.7	bdl	31.9	bdl	22.7	58.6	11.6	27.5	194.2
Décembre 08	6.4	bdl	122.3	0.6	40.7	72.4	16.4	25.0	248.4
Janvier 09	6.6	bdl	87.7	0.5	39.7	65.8	13.6	21.0	220.4
Février 09	6.3	bdl	NA	0.2	15.3	58.7	13.6	13.2	202.7
Avril 09	6.5	bdl	81.7	0.3	31.1	42.1	9.7	9.8	145.1
Mai09	6.8	bdl	101.7	0.5	45.8	54.9	12.2	19.1	187.7
Moyenne	6.7		72.1	0.4	26.0	62.0	13.0	18.4	208.5
Ligne directrice		1.5 CMP	250.0 OE	10.0 CMP	500.0 OE			20.0 OE	100.0 LDO

LDP = Ligne directrice opérationnelle
CMP= Concentration Maximale Permise
OE= Objectif Esthétique
Bdl= Sous limite de détection

Les paramètres mesurés lors de notre étude sont des indicateurs de la qualité de l'eau. Il est important de considérer que dans certain cas, leur présence n'a pas nécessairement un impact sur la santé. Le tableau décrit certain de ces paramètre ainsi que ce que les effets possible de leur présence.

Paramètres mesurés	Définitions/Sources	Effets possibles
pH	Mesure de l'acidité de l'eau	• Une eau acide (pH<6.5) peut avoir un effet corrosif
Fluorure	Présence naturelle	• Affecte la dentition des enfants • Des concentrations très élevées peuvent affecter le développement des os
Chlorure	Présence naturelle ou causée par l'activité humaine	• Effet corrosif sur la plomberie • Goût salé
Nitrates	Fertilisants, système septique	• Effets sur la santé
Sulfates	Présence naturelle ou causée par l'activité humaine	• L'eau à un effet laxatif
Sodium	Présence naturelle ou causée par l'activité humaine	• Hypertension (personne à risque)
Dureté	Causée par la présence de Calcium et Magnésium dans l'eau	• Aucun effet sur la santé • Réduit l'efficacité des savons • Effets sur la tuyauterie (dépôts et blocage) • Tache et salie le linge

Sources : Pratiques de gestion optimale-Les puits

Recommandations pour la qualité de l'eau potable au Canada

Catégorie	Concentration de carbonate de Calcium (mg/L)
Eau Douce	0 à <60
Eau modérément dure	60 à <120
Eau dure	120 à <180
Eau très dure	180 et plus

Source : Santé Canada

Sommaire et suggestions

Intégrité du scellement de tubage

Malgré le fait que le taux d'infiltration autour du puits soit semblable aux surfaces avoisinantes, il semblerait qu'une connexion hydraulique, entre la surface et la colonne d'eau, existe au puits. L'essai de traçage ayant démontré cette connexion, l'espace annulaire du puits serait donc une voie préférentielle à l'infiltration des eaux de surface. Les analyses bactériologiques indiquent aussi une connexion possible.

Source possible de contamination

Il semblerait que les coliformes totaux soient présents en nombre plus important d'août à novembre, mais en présence continue pour les autre mois. Il y aurait donc une source constante alimentant le puits. Comme la contamination est plus importante lors des mois estivaux, il est possible que l'infiltration d'eaux de surface soit la principale cause de la présence de bactéries. La construction du puits et les caractéristiques du site (mince couche de sol et drainage vers le puits) sont probablement les facteurs responsables.

Analyse chimique

Tous les paramètres respectent les lignes directrices à l'exception de la dureté. La moyenne annuelle est de 209 mg/L de $CaCO_3$ alors que ligne directrice opérationnelle est de 100 mg/L de $CaCO_3$. L'eau est donc considérée comme dure.

Il est également possible de constater une faible présence de nitrates dans le puits. Les concentrations ne sont pas actuellement problématiques car la limite maximale permise est de 10 mg/L.

Suggestions

- L'espace annulaire étant une voie préférentielle à la contamination, il est important de réduire le ruissellement vers le puits. Pour ce faire, il est recommandé d'élever le

sol à la tête du puits, ce qui évitera l'eau de ruissellement de s'accumuler et s'infiltrer à cet endroit.

- La présence de nitrate, quoique faible, indique une contamination possible provenant d'un système septique ou de l'application de fertilisants à proximité de la zone de recharge. Il est recommandé par le MDDEP de faire un suivi deux fois par année si la concentration dépasse 5 mg/L.
- Il est important de faire un suivi continu sur l'état de votre puits. Une fois l'an, vous devriez regarder dans le puits avec une lampe de poche. Recherchez la présence de fissures et de trous dans le cuvelage et près de l'embranchement des tuyaux vers la maison. Prenez des notes et comparez au fil des ans. Des mesures correctives peuvent être entreprises, par un puisatier, si un problème est détecté.
- Il est recommandé de faire une analyse bactériologique au moins 1 fois par année, et à l'occasion, notamment après une pluie importante et la fonte des neiges.
- Finalement, il serait impératif de faire installer un système de stérilisation de l'eau, tel les systèmes aux rayons ultra-violets.

L'information présentée dans ce rapport provient des sources suivantes :

*****Ces sources sont également excellentes pour en savoir plus sur les puits, les sources de contamination ainsi que sur la qualité de l'eau**

Conboy M.J, Smith S., 2005. A comprehensive consumer's guide for private water wells ISBN 0-9780387-0-3
www.wellwise.ca

Recommandations pour la qualité de l'eau potable au Canada -La dureté
http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/hardness-durete/index-fra.php

Ministère du développement durable, environnement et parcs- *La qualité de l'eau de mon puits*
http://www.mddep.gouv.qc.ca/eau/potable/depliant/index.htm

Publications : Ministère de l'agriculture, de l'alimentation et des affaires rurales (Ontario)
http://www.omafra.gov.on.ca/french/environment/water/publications.htm

Ministère de la santé et des soins de longue durée
http://www.health.gov.on.ca/english/public/pub/watersafe/watersafe_wellknow.html

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Faculté des sciences Faculty of Science
Sciences de la Terre Earth Sciences

Étude sur la contamination des puits domestiques Municipalité de Chelsea, Québec



Rapport présenté à :
W17
Chelsea, QC

Rapport préparé par :
Pascale St-Germain
Candidate au doctorat
Université d'Ottawa

Mai 2010

Remerciements

Merci d'avoir participé à cette étude. Vos efforts furent importants dans l'avancement de notre compréhension sur les voies préférentielles de contamination des puits. Nous sommes très reconnaissants pour nous avoir donné l'accès à votre propriété, pour votre hospitalité ainsi que votre aide dans le prélèvement mensuel des échantillons.

Notes importantes

Les idées présentées dans ce rapport sont des suggestions qui pourraient améliorer la qualité de l'eau de votre puits. Elles pourraient possiblement être utiles dans la réduction du nombre de coliformes mais ne résoudront pas nécessairement le problème général. Nous avons fait notre possible pour évaluer la source probable de contamination, mais plusieurs facteurs peuvent affecter la qualité de l'eau d'un puits. Ce rapport a pour but de vous aider à comprendre votre puits et n'inclut pas toutes les conclusions de l'étude. Ces suggestions doivent être considérées avec prudence.

Avant d'investir dans votre puits (amélioration du puits ou système de traitement de l'eau) il serait important de demander l'avis d'un professionnel certifié et de faire analyser votre eau par un laboratoire indépendant.

Merci beaucoup pour votre compréhension.

Pascale St-Germain
Candidate au doctorat
Université d'Ottawa
Département des Sciences de la Terre

Glossaire

Roc Précambrien :	Socle rocheux composé de roches ignées et métamorphiques datant de plus de 542 Millions d'années
Dépôts meubles :	Sédiments non consolidés recouvrant le socle rocheux
Mer de Champlain :	Mer créée lors de la fonte du Glacier *Inlandsis laurentidien*, il y a environ 10 000 ans, submergeant principalement la région de Montréal et une partie du sud-est ontarien.
Voies préférentielles :	Présence de macro pores favorisant l'écoulement de l'eau sans le potentiel atténuant du sol, permettant aux contaminants de se faire transporter plus rapidement et plus profondément
Puits foré :	Puits creusé dans le socle rocheux à l'aide d'une foreuse
Aquifère :	Unité géologique capable de contenir et de transmettre de l'eau en quantité suffisante
Aquifère captif :	Aquifère recouvert d'une couche imperméable isolant l'aquifère de la surface du sol
Aquifère libre :	Aquifère non recouvert d'une couche imperméable et exposé à la pression atmosphérique
Aquitard :	Unité géologique imperméable capable de contenir de l'eau mais incapable de la transmettre en quantité suffisante
Infiltration :	Mouvement de l'eau de la surface jusque dans le sol
Conductivité hydraulique :	Capacité d'un milieu poreux à transmettre l'eau
Conductivité électrique (EC) :	Capacité de l'eau à transmettre un courant électrique; donne une mesure du montant total des composantes dissoutes dans l'eau. L'unité de mesure de la conductivitéélectrique est le Siemens par cm (S/cm) ou microsiemens par cm (µS/cm = 10^{-6} S/cm). A titre comparatif, la EC varie de quelques dizaines de µS/cm dans le cas des eaux de pluie à quelques centaines de millier de µS/cm dans le cas des eaux salées. Dans la région de Chelsea, elle varie entre environ 80 et 1600 µS/cm.
Coliformes totaux :	Groupe de bactéries fermentant le lactose à 38°C. Ces bactéries sont présentes dans les matières fécales des humains et des animaux ainsi que dans le sol et la végétation

Coliformes fécaux :	Bactéries provenant du système digestif des humains et animaux. Indique une présence possible de pathogènes dans l'eau
Macro-pores :	Pores de grandes dimensions formées par l'activité biologique, les racines ou bien les fissures dans un milieu argileux

Représentation schématique d'un puits domestique

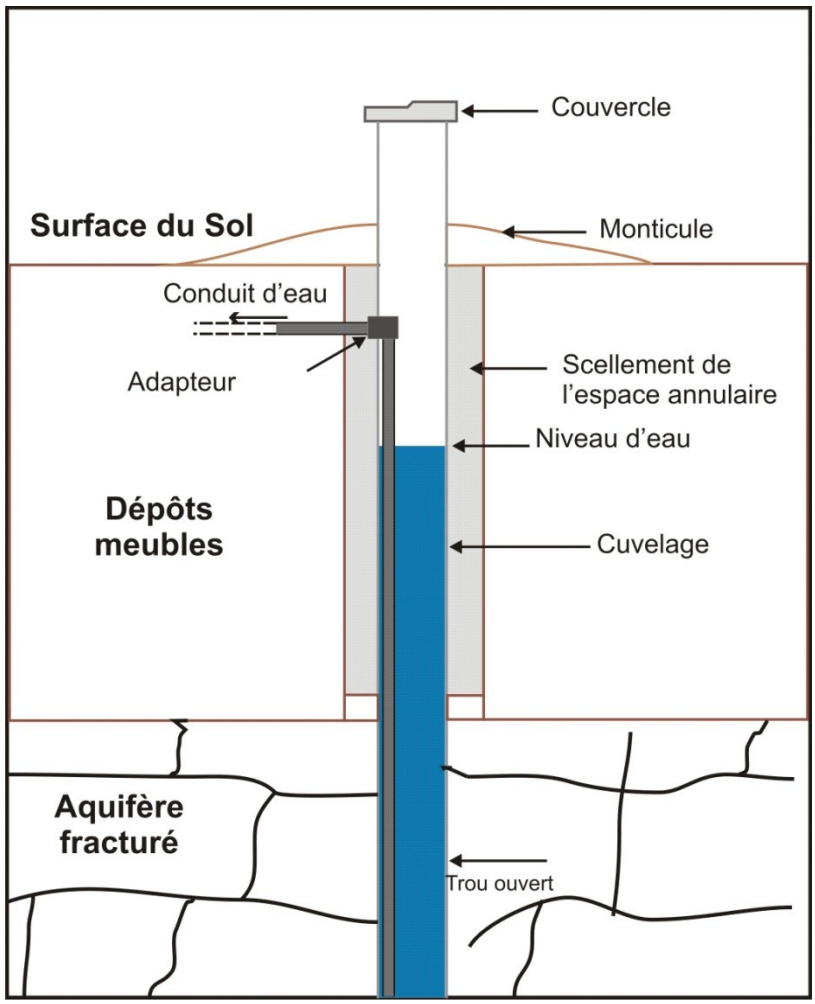


Image modifiée de : *Pratiques de gestion optimale-Les puits*

Introduction

L'objectif de ce projet est d'améliorer nos connaissances en ce qui a trait à la contamination des puits d'eau potable résultant de l'infiltration des eaux de surfaces. Notre but est d'évaluer le risque de contamination des puits forés en se basant sur les caractéristiques du site et sur la construction du puits.

En effectuant une analyse bactériologique mensuelle, il fut possible d'avoir une meilleure idée sur la saisonnalité de la contamination. L'analyse chimique de l'eau fût utilisée pour comprendre l'évolution des eaux souterraines et pour effectuer un lien avec une source possible de contamination.

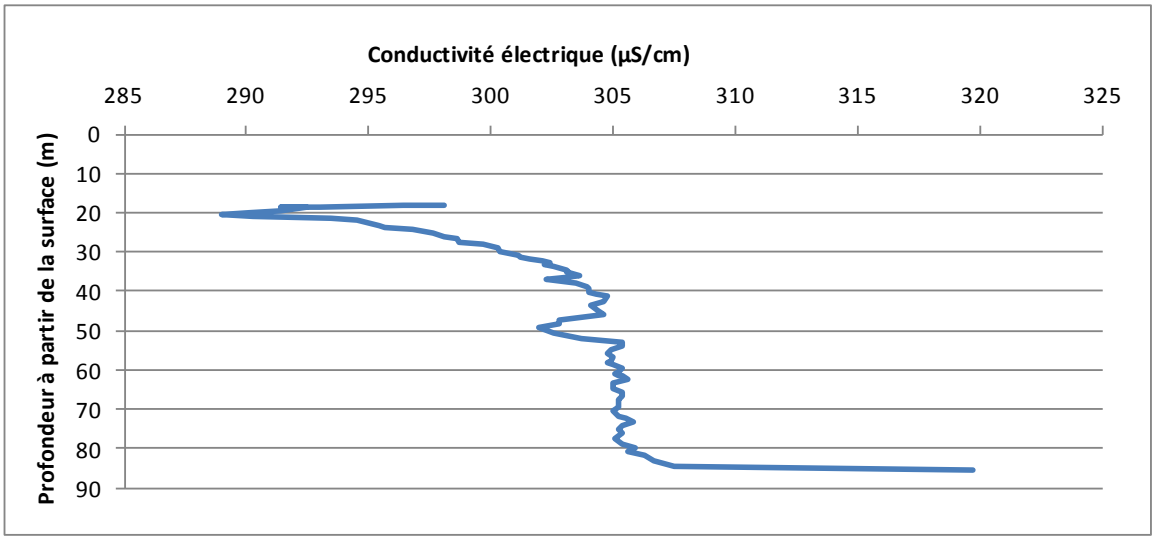
L'objectif de ce rapport est de vous sensibiliser à la qualité de l'eau de votre puits et aux mesures existantes pour préserver ou améliorer sa qualité. Ce rapport présente un sommaire des travaux effectués, les principaux résultats ainsi que quelques suggestions, si nécessaire.

Description du site

Votre puits est foré dans le roc précambrien sur lequel repose une mince couche de dépôts meubles, principalement composés de sable, silt et argile déposés lors de la dernière glaciation, il y a environ 10 000 ans. La profondeur du puits est d'environ 94 mètres et le niveau de l'eau est situé à 18 mètres de la surface du sol.

L'eau de votre puits provient d'un aquifère. Un aquifère peut être défini comme une unité géologique capable de contenir et de transmettre de l'eau. Cet aquifère est également considéré comme étant « libre » car il n'est pas recouvert d'une couche imperméable. Ce type d'aquifère est généralement plus vulnérable à la contamination car il n'y a pas de couche imperméable protégeant naturellement l'aquifère des contaminants de surface.

a)



b)

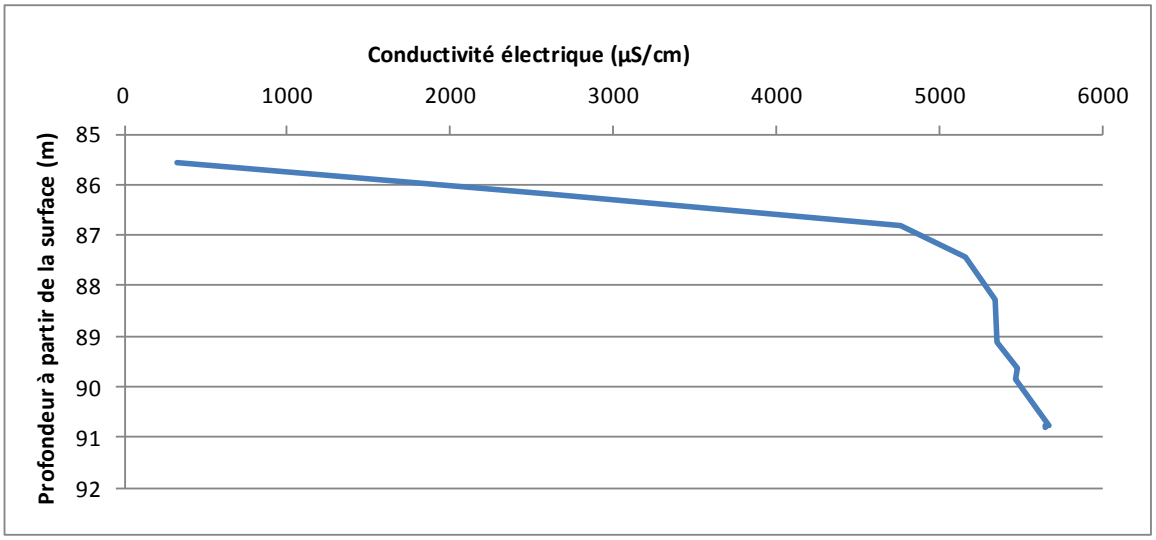


Figure 1: Profils de conductivité électrique de la colonne d'eau dans le puits. a) de 18 à 85 mètres b) 85 mètres et plus

Les figures ci-dessus représentent un profil de conductivité électrique de la colonne d'eau de votre puits. La conductivité électrique est une mesure des composantes dissoutes dans l'eau. Le niveau d'eau est situé à environ 18 mètres sous la surface du sol. La conductivité électrique varie entre 290 et 5500 µS/cm. Il est surprenant d'observer un si grand contraste dans une même colonne d'eau. La conductivité électrique augmente en

profondeur, avec un changement très marqué à plus ou mois 85 mètres. À cette profondeur, il est possible que des fractures alimentent votre puits avec de l'eau à condutivité électrique plus élevée.

Analyse bactériologique

Les bactéries sont naturellement présentes dans les eaux de surface et dans les sols. Elles sont transportées dans les eaux souterraines par le processus d'infiltration. Plusieurs facteurs affectent le mouvement des bactéries. Ces facteurs peuvent être reliés aux bactéries (type, taille, dynamique de la population) ou aux caractéristiques du sol (physique, chimique ou biologique). La plupart des bactéries sont filtrées dans le premier horizon du sol mais la présence de « macro-pores » peut contribuer au mouvement des bactéries en profondeur. Les macro-pores sont en fait des pores de grandes dimensions formées par l'activité biologique, les racines ou bien des fissures dans un milieu argileux. Ces macro-pores affectent la capacité du sol à filtrer les bactéries, ce qui leur permet de pénétrer plus profondément et rapidement.

La contamination bactérienne dans un puits peut provenir de plusieurs sources. Dans une municipalité comme Chelsea, où l'agriculture n'est que localisée et quasi-inexistante, la construction d'un puits (type, âge et profondeur), son emplacement, la distance au système septique ainsi que des facteurs reliés à la géologie sont les principales sources contribuant à la présence de bactéries dans un puits.

La figure ci-dessous présente les résultats de l'analyse bactériologique sous forme de graphique. On remarque une présence sporadique de coliformes totaux de juillet à décembre. Le nombre de coliformes totaux dépasse la limite provinciale de 10 ufc/100mL qu'une seule fois, soit en août 2008. La présence de coliformes fécaux n'a pas été détectée lors de la période d'échantillonnage.

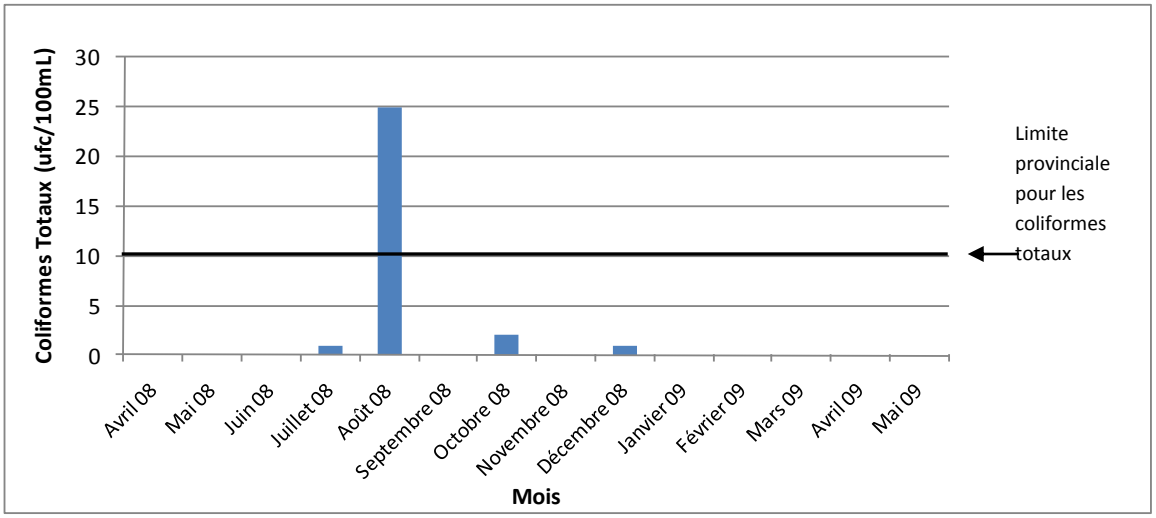


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Analyse Chimique

Naturellement, l'eau dissout les minéraux lorsqu'elle s'écoule dans le sol. Le processus de dissolution est habituellement lent dans la roche Précambrienne comparativement aux jeunes roches sédimentaires telles le grès ou la calcite. Des sources anthropogéniques, telles l'épandage de sels routiers, les fertilisants et les systèmes septiques peuvent également contribuer à la teneur en minéraux dissouts dans les eaux souterraines.

Les échantillons d'eau furent analysés à l'université d'Ottawa pour identifier diverses composantes dissoutes. Les résultats sont présentés dans le tableau suivant. Ce tableau donne également la moyenne annuelle ainsi que les lignes directrices relatives à certains paramètres. Les concentrations sont mesurées en milligrammes par litre (mg/L).

Mois	pH	Fluorure (mg/L)	Chlorure (mg/L)	Nitrate -N (mg/L)	Sulfate (mg/L)	Calcium (mg/L)	Magnésium (mg/L)	Sodium (mg/L)	Dureté (mg/L de $CaCO_3$)
Avril 08	5.9	1.2	1.0	bdl	46.4	51.4	5.1	36.4	149.3
Mai 08	7.7	1.2	1.3	bdl	52.3	79.7	7.9	54.9	231.7
Juin 08	7.8	1.2	1.0	bdl	49.9	47.8	4.6	32.7	138.4
Juillet 08	7.8	1.3	1.0	bdl	45.8	47.2	4.8	37.6	137.5
Août 08	7.4	1.3	1.1	bdl	NA	52.1	5.3	39.8	152.2
Septembre 08	7.4	bdl	0.4	bdl	14.1	46.9	4.8	36.0	137.1
Octobre 08	7.4	1.4	1.4	bdl	62.7	48.6	4.8	37.7	141.3
Novembre 08	7.4	bdl	1.5	bdl	65.4	47.2	4.7	36.0	137.1
Décembre 08	7.1	1.4	1.2	bdl	60.5	48.5	4.8	37.2	141.0
Janvier 09	7.2	1.5	1.4	bdl	64.7	45.6	4.5	36.6	132.7
Février 09	7.1	1.5	1.3	bdl	70.9	46.7	4.6	36.9	135.7
Mars 09	7.1	1.5	1.4	bdl	69.9	49.5	4.7	38.5	143.2
Avril 09	7.3	1.5	1.5	bdl	85.6	46.6	4.7	35.6	135.9
Mai09	7.1	1.5	1.5	bdl	80.8	42.5	4.4	32.6	124.1
Moyenne	7.2	1.4	1.2		59.1	50.0	5.0	37.8	145.5
Ligne directrice		1.5 CMP	250.0 OE	10.0 CMP	500.0 OE			20.0 OE	100.0 LDO

LDP = Ligne directrice opérationnelle
CMP= Concentration Maximale Permise
OE= Objectif Esthétique
Bdl= Sous limite de détection

Les paramètres mesurés lors de notre étude sont des indicateurs de la qualité de l'eau. Il est important de considérer que dans certain cas, leur présence n'a pas nécessairement un impact sur la santé. Le tableau décrit certain de ces paramètre ainsi que ce que les effets possible de leur présence.

Paramètres mesurés	Définitions/Sources	Effets possibles
pH	Mesure de l'acidité de l'eau	• Une eau acide (pH<6.5) peut avoir un effet corrosif
Fluorure	Présence naturelle	• Affecte la dentition des enfants • Des concentrations très élevées peuvent affecter le développement des os
Chlorure	Présence naturelle ou causée par l'activité humaine	• Effet corrosif sur la plomberie • Goût salé
Nitrates	Fertilisants, système septique	• Effets sur la santé
Sulfates	Présence naturelle ou causée par l'activité humaine	• L'eau à un effet laxatif
Sodium	Présence naturelle ou causée par l'activité humaine	• Hypertension (personne à risque)
Dureté	Causée par la présence de Calcium et Magnésium dans l'eau	• Aucun effet sur la santé • Réduit l'efficacité des savons • Effets sur la tuyauterie (dépôts et blocage) • Tache et salie le linge

Sources : Pratiques de gestion optimale-Les puits

Recommandations pour la qualité de l'eau potable au Canada

Catégorie	Concentration de carbonate de Calcium (mg/L)
Eau Douce	0 à <60
Eau modérément dure	60 à <120
Eau dure	120 à <180
Eau très dure	180 et plus

Source : Santé Canada

Sommaire et suggestions

Source possible de contamination

L'analyse bactériologique de l'eau de votre puits est relativement bonne. La limite maximale a été dépassée qu'à une seule reprise. Ce dépassement fut peut-être causé par les fortes précipitations de juillet. Votre puits pourrait être sujet à l'infiltration d'eau de surface. La présence sporadique de coliformes totaux pourrait être causée par la présence d'insectes dans le couvercle, détectée lors des mesures de niveaux d'eau.

Analyse chimique

Tous les paramètres respectent les lignes directrices à l'exception des concentrations de sodium et de la dureté. La teneur en sodium est légèrement supérieure à l'objectif esthétique. Pour la dureté, la moyenne annuelle est de 146 mg/L de $CaCO_3$ alors que ligne directrice opérationnelle est de 100 mg/L de $CaCO_3$. L'eau est donc considérée comme dure.

Recommandations

- Un bon couvercle devrait garder les insectes hors du puits. Même si aucun insecte ne fut détecté à l'intérieur, il est donc recommandé de vérifier l'intérieur et de s'assurer que le couvercle soit assez étanche pour ne pas laisser entrer les insectes, mais assez dégagé pour laisser passer l'air. Ceci pourrait prévenir le nombre de coliformes totaux dans le puits.
- Il est important de faire un suivi continu sur l'état de votre puits. Une fois l'an, vous devriez regarder dans le puits avec une lampe de poche. Recherchez la présence de fissures et de trous dans le cuvelage et près de l'embranchement des tuyaux vers la maison. Prenez des notes et comparez au fil des ans. Des mesures correctives peuvent être entreprises, par un puisatier, si un problème est détecté.
- Il est recommandé de faire une analyse bactériologique au moins 1 fois par année, et à l'occasion, notamment après une pluie importante et la fonte des neiges.

- Finalement, si la contamination devient problématique, il serait impératif de faire installer un système de stérilisation de l'eau, tel les systèmes aux rayons ultra-violets.

L'information présentée dans ce rapport provient des sources suivantes :

*****Ces sources sont également excellentes pour en savoir plus sur les puits, les sources de contamination ainsi que sur la qualité de l'eau**

Conboy M.J, Smith S., 2005. A comprehensive consumer's guide for private water wells ISBN 0-9780387-0-3
www.wellwise.ca

Recommandations pour la qualité de l'eau potable au Canada -La dureté
http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/hardness-durete/index-fra.php

Ministère du développement durable, environnement et parcs- *La qualité de l'eau de mon puits*
http://www.mddep.gouv.qc.ca/eau/potable/depliant/index.htm

Publications : Ministère de l'agriculture, de l'alimentation et des affaires rurales (Ontario)
http://www.omafra.gov.on.ca/french/environment/water/publications.htm

Ministère de la santé et des soins de longue durée
http://www.health.gov.on.ca/english/public/pub/watersafe/watersafe_wellknow.html

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Faculté des sciences Faculty of Science
Sciences de la Terre Earth Sciences

Contamination of Private Well Study
Municipality of Chelsea, Québec



Report presented to:
W18
Chelsea, QC

Report prepared by:
Pascale St-Germain
PhD Candidate
University of Ottawa

May 2010

Acknowledgements

Thank you for your help with this study. Your assistance is valuable in our effort to better understand groundwater wells in fractured bedrock and potential contaminant pathways. We appreciate the access to your property, your hospitality and your collecting water samples for the purpose of this research.

Important note

The suggestions presented in this report are made to improve the quality of your well water. They may help reduce the number of coliforms in your well, but may not be the only solution to any problems. An attempt was made to find the most probable source of contamination; however, many factors can affect water quality. This report was prepared to give you a better understanding of your well and does not include all the conclusions found in the overall study. All suggestions should be treated with caution.

Before investing in your well (well upgrade or water treatment system) I would suggest seeking advice from professionals and getting your water tested independently by an accredited laboratory before future investment in a treatment system.

Thank you very much for your understanding

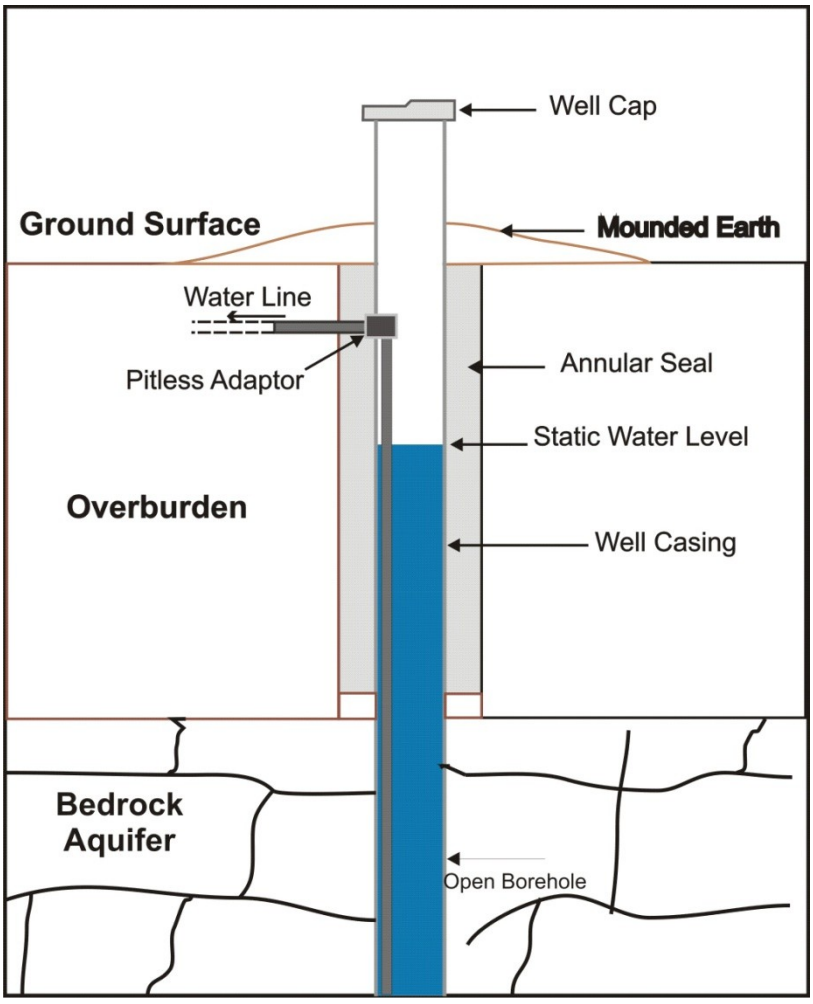
Pascale St-Germain
PhD candidate
University of Ottawa
Department of Earth Sciences

Glossary

Precambrian bedrock:	Fracture bedrock mainly composed of igneous and metamorphic rocks that are more than 542 million years old.
Overburden:	Unconsolidated sediments overlaying the bedrock and composed of grains of various sizes.
Champlain Sea:	Inland sea created about 10 000 year ago resulting from the melting of the *Inlandsis laurentidien* ice sheet. The sea principally covered the Montreal area but also some areas in south eastern Ontario.
Preferential pathways:	Direct movement of water through macro pores without the natural attenuation potential from the soil. This allows bacteria (or contaminant) to get carried faster and deeper.
Drilled well:	Well drilled into the fractured bedrock
Aquifer:	Geological unit capable of storing and transmitting water in sufficient quantity.
Confined aquifer:	Aquifer overlain by an impermeable layer. This layer protects the aquifer from surficial contaminant.
Unconfined aquifer:	Aquifer not overlain by an impermeable layer and exposed to atmospheric pressure.
Aquitard:	Geological unit capable of storing water but incapable of transmitting water in sufficient quantities.
Infiltration:	Movement of water from ground surface into the soil.
Hydraulic conductivity:	Ability of a porous media to transmit water.
Electrical conductivity (EC):	Ability of the water to conduct an electrical current. It is a general indication of the amount of total dissolved solids (TDS) in the water. EC is measure in Siemens per cm (S/cm) or microSiemens per cm (µS/cm = 10^{-6} S/cm). It ranges from several tens of µS/cm for rain water to several thousands of µS/cm for sea water. In the Chelsea area, the EC values range from approximately 90 to 1600 µS/cm.
Total coliforms:	Bacteria present in human and animal feces but also in the soil and vegetation
Faecal coliforms:	Bacteria originating from digestive tracts of humans and animals. Their presence indicates faecal pollution and the potential for pathogens to be present into the water

Macropore: Pore of greater dimension resulting from biological activity in the soil, from roots and cracks in clay

Drilled well



Source: Modified from Best Management Practice – Water Well

Introduction

The objective of the project was to improve the understanding of private well contamination resulting from the infiltration of surface water. The risk of contamination in drilled wells was evaluated based on site characteristics and well construction.

Your well was tested every month for bacteria in order to assess the seasonality of contamination. Chemical analysis of the well water was carried out to understand the groundwater pathways and to establish possible links to potential contamination sources.

The objective of this report is to increase your awareness of possible water quality issues in your well and of the possible remedial actions that could taken preserve or improve the quality of your well water. It contains a summary of the work conducted, the data obtained, conclusions and some suggestions.

Site Description

Your well is drilled into the Precambrian bedrock, which is overlain by less than 1 metre of till. Till is a mixture of sediments of variable grain sizes deposited during the last glaciation (about 10,000 years ago). The well is approximately 108 metres deep and the static water level is located 10.7 metres below ground surface.

Your well draws water from an unconfined aquifer. An aquifer is defined as a geologic unit capable of storing and transmitting water. This aquifer is also considered unconfined because there is no impermeable protective layer overlaying it. Usually, these types of aquifer are more vulnerable to contamination since there is no confining layer. The confining layer provides an impermeable barrier, thereby naturally protecting the well against surface contamination.

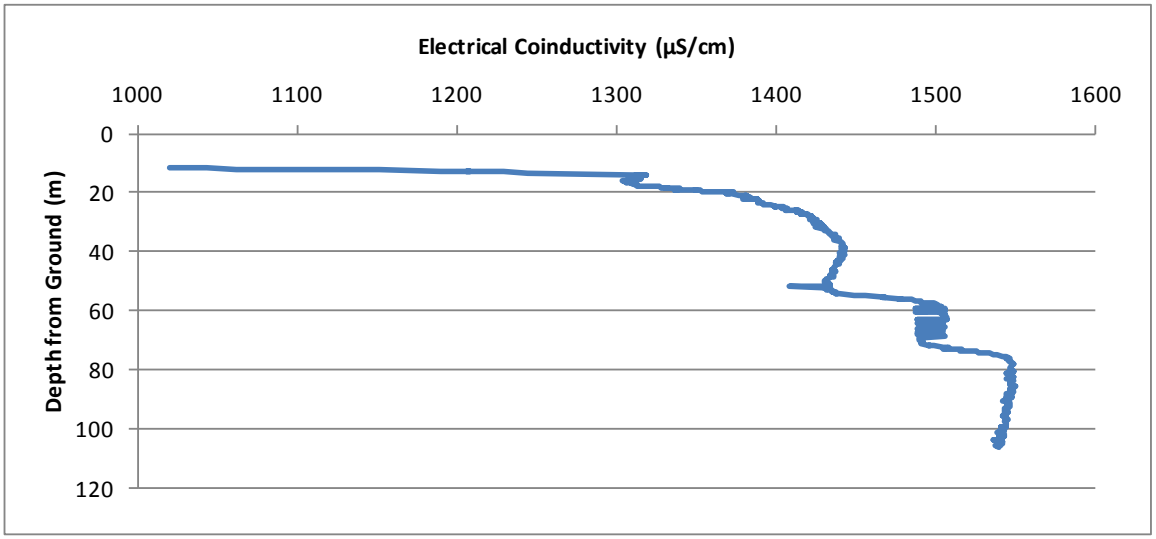


Figure 1: Electrical conductivity profile of the water column

The figure above displays the electrical conductivity (EC) profiles of the well water column. The electrical conductivity is the ability of the water to conduct a electric current and it is a measure of the dissolved solids in the well. For this well, the values range from 1000 to 1600 µS/cm. The EC increases towards the bottom of the well which is an indication of the surface water entering the well from the upper part of the water column.

Bacteria

Bacteria are naturally present in surface water and soil. They are carried to the groundwater system through the infiltration process. A number of factors may affect the movement of bacteria in soil. These are directly related to the bacteria (type, size and population dynamic) and the soil properties (chemical, biological and physical). Usually, most of the bacteria are filtered through the upper soil profile, but water can carry bacteria deeper using larger pore structures. These structures, called macropores, result from many things: earthworms, decayed roots and crack in clayey soil are some examples. Macropores reduce the efficiency of the soil to filter bacteria allowing them to travel deeper and faster.

Bacterial contamination in a well is a product of many factors. In a municipality like Chelsea, where agriculture is not a common practice, well construction (type, age, depth), location, the presence of septic system and the geology (bedrock and surficial) would be the primary contributors to bacterial contamination.

The well showed three contamination events during the April 2008 to May 2009 sampling period. These contamination events occurred in September October and February. Total coliforms were also detected in three other samples, but the counts were below the provincial limit of 10 cfu/100mL (colony forming units / 100 millilitres). Faecal coliforms were not detected during the sampling period.

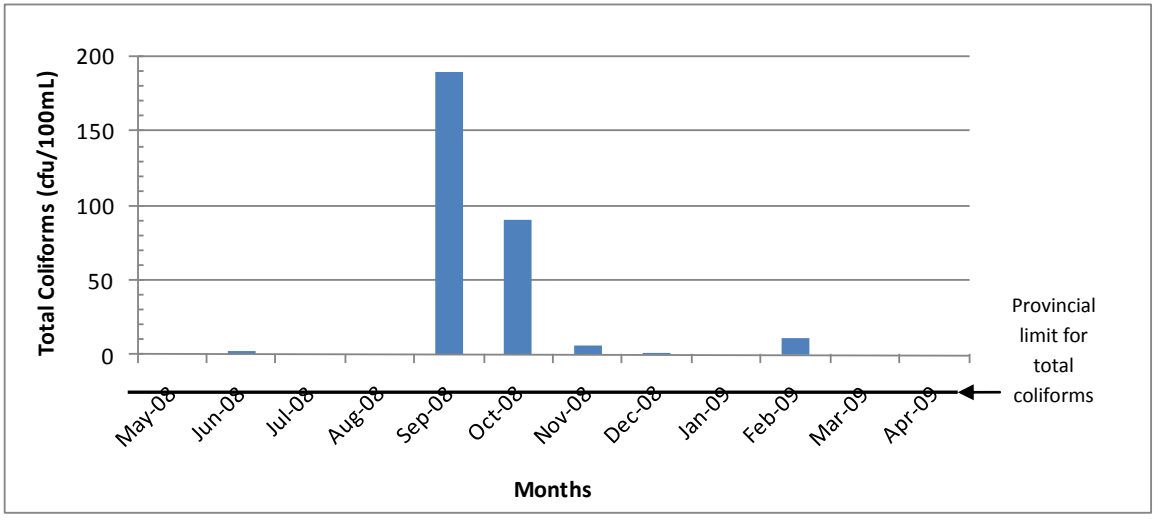


Figure 2: Results of the bacterial analysis (total and faecal coliforms) of the water samples, from April 2008 to May 2009.

Chemical analysis

As water naturally flows into the subsurface, it dissolves minerals along its pathway. The dissolution process is relatively slow in Precambrian bedrock compared to younger sedimentary rocks such as limestone or sandstone. However, other non natural sources may contribute to dissolved solids such as road salt application, septic systems or fertilizers.

Water samples were analysed for various dissolved species at the University of Ottawa. The results of the analyses are given in the following table. This table also shows the yearly average and the provincial guideline, if applicable. The concentrations are measured in milligrams per litre (mg/L)

Sampling date	pH	Fluoride (mg/L)	Chloride (mg/L)	Nitrate as N (mg/L)	Sulphate (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Hardness (mg/L as $CaCO_3$)
May-08	7.2	bdl	279.1	1.2	86.2	1.1	0.1	359.8	2.9
Jun-08	7.5	bdl	231.7	0.8	92.1	22.6	11.4	285.9	103.4
Jul-08	6.9	bdl	158.7	0.8	85.4	0.9	0.1	257.5	2.6
Aug-08	7.0	bdl	196.4	1.1	100.1	28.9	10.0	237.3	113.4
Sep-08	7.2	bdl	34.4	bdl	22.5	0.8	0.1	288.3	2.5
Oct-08	7.5	0.7	129.7	0.2	99.8	50.7	4.5	169.1	145.4
Nov-08	7.0	bdl	34.6	0.5	69.1	199.0	16.1	55.5	563.7
Jan-09	7.4	bdl	163.2	0.2	118.6	154.6	15.0	84.2	448.3
Feb-09	6.7	0.1	148.4	0.5	125.7	122.2	34.5	83.0	447.4
Mar-09	7.9	bdl	84.8	0.3	65.5	118.1	8.1	28.8	328.5
Apr-09	6.9	bdl	87.1	bdl	46.2	89.0	6.1	21.6	247.3
May-09	7.0	bdl	198.9	1.5	100.4	113.0	22.8	62.2	376.2
Average	7.2	0.4	145.6	0.7	84.3	75.1	10.7	161.1	231.8
Guideline		1.5 MAC	250.0 AO	10.0 MAC	500.0 AO			20.0 AO	100.0 AO

OG = Operational Guideline
MAC= Maximum Allowable Concentration
AO= Aesthetic Objective
Bdl= below detection limit

The dissolved solids measured during this study are water quality indicators. It is important to realize that their presence may not have an impact on health. The following table describes the parameters and their possible effects.

Parameters	Definition/sources	Possible effects/concerns
pH	Measure of the acidity of water	• An acid water (pH<6.5) can have a corrosive effect • Low pH increases metals in solution, which could yield health concerns
Fluoride	Natural occurrence	• Mottled teeth • Bone development (high concentrations)
Chloride	Natural occurrence or human related activities	• Corrosive effect on plumbing • Salty taste
Nitrates	Human related activities	• Health Concerns
Sulphates	Natural occurrence or human related activities	• Water has laxative effect
Sodium	Natural occurrence or human related activities	• Health concerns • Salty taste
Hardness	Caused by the presence of calcium and magnesium and occasionally iron in the water	• No health effect • Soap scum • Scale buildup on plumbing fixture and pipes • Stained and mottled laundry

Sources: Best Management Practices –Water Well

Guidelines for Hardness

Category	Concentration of calcium carbonate (mg/L)
Soft	0 to <60
Medium Hard	60 to <120
Hard	120 to <180
Very Hard	180 and more

Source : Health Canada

Summary and Suggestions

Possible sources of contamination

The well shows three distinct contamination events which exceeded regulation limits, however, the total coliforms were detected consistently. This may be an indicator of surface water reaching the well. The bacterial contamination could result from the shallow soil, the drainage toward the well or the presence of trees at the wellhead. The presence of total coliforms during winter months, when infiltration is minimal, may suggest that coliforms are present in the aquifer.

It was observed that the well cap is not insect-proof and spider webs were present in the well cap. The presence of bugs most likely contributes to a small concentration of bacteria into the well.

Chemical analysis

The amount of dissolved constituent in your water is relatively high, which indicates that your well water is mainly coming from a deeper groundwater system. The yearly average for the sodium is slightly above the aesthetic objective. The water of your well is considered very hard for domestic usage.

Concentrations of nitrate were detected in the well, but the levels are below the maximum allowed concentration. It would be important to monitor this parameter. It is recommended by the MDDEP to have this parameter analysed every few years. If the level gets above 5 mg-N/L, then yearly monitoring is recommended.

There is also a high concentration of chloride. Since the sodium is also high, this could be an indicator of de-icing road salt leaching into the well or from a septic system nearby.

Suggestions

- In your situation, the presence of bacteria is recurrent and extra care should be taken for any use of water related to human consumption. The installation of a filtration system that kills microorganisms should be considered.

- It is recommended to get your water tested for bacteria at least 1 time a year, especially after important rainfall events and snowmelt.
- A good well cap should keep bugs out of the well. Proper insect-proof cap are available and will easily fit on your well. This will not stop the contamination but will prevent insects entering the well, which can increase the concentration of total coliforms.
- Every year, examine into the inside of the well with a flash light. You can look for cracks in the casing caused by corrosion. Also check for holes around the pitless adaptor (area where pipes are connected). A record should be kept and comparisons made year to year. Corrective action can be suggested a licensed well contractor if something wrong is detected.
- It is important to consider activities around the wellhead, especially uphill from the well. For example: if the driveway is located uphill from the well and runoff water flow towards the well. Extra care should be taken to make sure there are no leaks from cars and salt should not be used as de-icing agent. To prevent nitrate contamination, no fertilizers should be used uphill or near the well recharge area.

The information presented in this report comes from the following sources:

*****These are also excellent sources for more information on water wells**

Conboy M.J, Smith S., 2005. A comprehensive consumer's guide for private water wells ISBN 0-9780387-0-3
www.wellwise.ca

Guidelines for Canadian Water Quality-Hardness
http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/hardness-durete/index-eng.php

Ministère du développement durable, environnement et parcs (MDDEP) -*La qualité de l'eau de mon puits* (French only)
http://www.mddep.gouv.qc.ca/eau/potable/depliant/index.htm

Ontario Ministry of Agriculture Food and Rural Affairs/Agriculture and Agri-food Canada. 2003 *Best Management Practices –Water Well*
http://www.omafra.gov.on.ca/english/environment/water/publications.htm

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Faculté des sciences Faculty of Science
Sciences de la Terre Earth Sciences

Étude sur la contamination des puits domestiques
Municipalité de Chelsea, Québec



Rapport présenté à :
W19
Chelsea, QC

Rapport préparé par :
Pascale St-Germain
Candidate au doctorat
Université d'Ottawa

Mai 2010

Remerciements

Merci d'avoir participé à cette étude. Vos efforts furent importants dans l'avancement de notre compréhension sur les voies préférentielles de contamination des puits. Nous sommes très reconnaissants pour nous avoir donné l'accès à votre propriété, pour votre hospitalité ainsi que votre aide dans le prélèvement mensuel des échantillons.

Notes importantes

Les idées présentées dans ce rapport sont des suggestions qui pourraient améliorer la qualité de l'eau de votre puits. Elles pourraient possiblement être utiles dans la réduction du nombre de coliformes mais ne résoudront pas nécessairement le problème général. Nous avons fait notre possible pour évaluer la source probable de contamination, mais plusieurs facteurs peuvent affecter la qualité de l'eau d'un puits. Ce rapport a pour but de vous aider à comprendre votre puits et n'inclut pas toutes les conclusions de l'étude. Ces suggestions doivent être considérées avec prudence.

Avant d'investir dans votre puits (amélioration du puits ou système de traitement de l'eau) il serait important de demander l'avis d'un professionnel certifié et de faire analyser votre eau par un laboratoire indépendant.

Merci beaucoup pour votre compréhension.

Pascale St-Germain
Candidate au doctorat
Université d'Ottawa
Département des Sciences de la Terre

Glossaire

Roc Précambrien : Socle rocheux composé de roches ignées et métamorphiques datant de plus de 542 Millions d'années

Dépôts meubles : Sédiments non consolidés recouvrant le socle rocheux

Mer de Champlain : Mer créée lors de la fonte du Glacier *Inlandsis laurentidien*, il y a environ 10 000 ans, submergeant principalement la région de Montréal et une partie du sud-est ontarien.

Voies préférentielles : Présence de macro pores favorisant l'écoulement de l'eau sans le potentiel atténuant du sol, permettant aux contaminants de se faire transporter plus rapidement et plus profondément

Puits foré : Puits creusé dans le socle rocheux à l'aide d'une foreuse

Aquifère : Unité géologique capable de contenir et de transmettre de l'eau en quantité suffisante

Aquifère captif : Aquifère recouvert d'une couche imperméable isolant l'aquifère de la surface du sol

Aquifère libre : Aquifère non recouvert d'une couche imperméable et exposé à la pression atmosphérique

Aquitard : Unité géologique imperméable capable de contenir de l'eau mais incapable de la transmettre en quantité suffisante

Infiltration : Mouvement de l'eau de la surface jusque dans le sol

Conductivité hydraulique : Capacité d'un milieu poreux à transmettre l'eau

Conductivité électrique (EC) : Capacité de l'eau à transmettre un courant électrique; donne une mesure du montant total des composantes dissoutes dans l'eau. L'unité de mesure de la conductivitéélectrique est le Siemens par cm (S/cm) ou microsiemens par cm (µS/cm = 10^{-6} S/cm). A titre comparatif, la EC varie de quelques dizaines de µS/cm dans le cas des eaux de pluie à quelques centaines de millier de µS/cm dans le cas des eaux salées. Dans la région de Chelsea, elle varie entre environ 80 et 1600 µS/cm.

Coliformes totaux : Groupe de bactéries fermentant le lactose à 38°C. Ces bactéries sont présentes dans les matières fécales des humains et des animaux ainsi que dans le sol et la végétation

Coliformes fécaux : Bactéries provenant du système digestif des humains et animaux. Indique une présence possible de pathogènes dans l'eau

Macro-pores : Pores de grandes dimensions formées par l'activité biologique, les racines ou bien les fissures dans un milieu argileux.

Représentation schématique d'un puits domestique

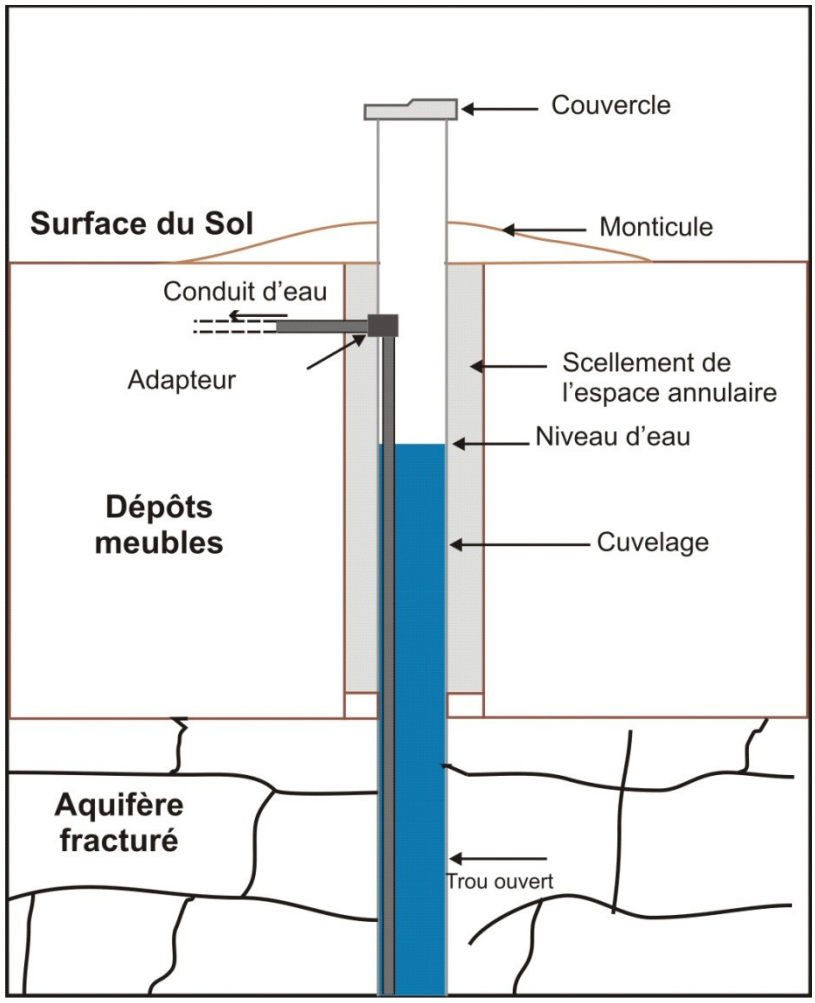


Image modifiée de : *Pratiques de gestion optimale-Les puits*

Introduction

L'objectif de ce projet est d'améliorer nos connaissances en ce qui a trait à la contamination des puits d'eau potable résultant de l'infiltration des eaux de surfaces. Notre but est d'évaluer le risque de contamination des puits forés en se basant sur les caractéristiques du site et sur la construction du puits.

En effectuant une analyse bactériologique mensuelle, il fut possible d'avoir une meilleure idée sur la saisonnalité de la contamination. L'analyse chimique de l'eau fût utilisée pour comprendre l'évolution des eaux souterraines et pour effectuer un lien avec une source possible de contamination.

L'objectif de ce rapport est de vous sensibiliser à la qualité de l'eau de votre puits et aux mesures existantes pour préserver ou améliorer sa qualité. Ce rapport présente un sommaire des travaux effectués, les principaux résultats ainsi que quelques suggestions, si nécessaire.

Description du site

Votre puits est foré dans le roc précambrien sur lequel repose une épaisse couche d'argile. Cette couche que l'on nomme couche de confinement, d'une dizaine de mètre d'épaisseur ou plus, s'est déposée lors de la dernière glaciation (environ 10 000 ans), lorsque la Mer de Champlain recouvrait partiellement la région. La profondeur du puits est d'environ 56 mètres et le niveau de l'eau est situé à 3 mètres de la surface du sol. La construction de votre puits est problématique. Le tubage d'acier devrait dépasser la surface d'au moins 20 cm et le sol autour du puits devrait être surélevé. Ceci préviendrait l'infiltration directe d'eau de surface lors de fortes périodes de pluies.

L'eau de votre puits provient d'un aquifère. Un aquifère peut être défini comme une unité géologique capable de contenir et de transmettre de l'eau. Cet aquifère est également considéré comme étant « captif » car il est recouvert d'une couche imperméable. Ce type d'aquifère est généralement moins vulnérable à la contamination car la couche de confinement (l'argile) est imperméable et protège naturellement l'aquifère des contaminants de surface.

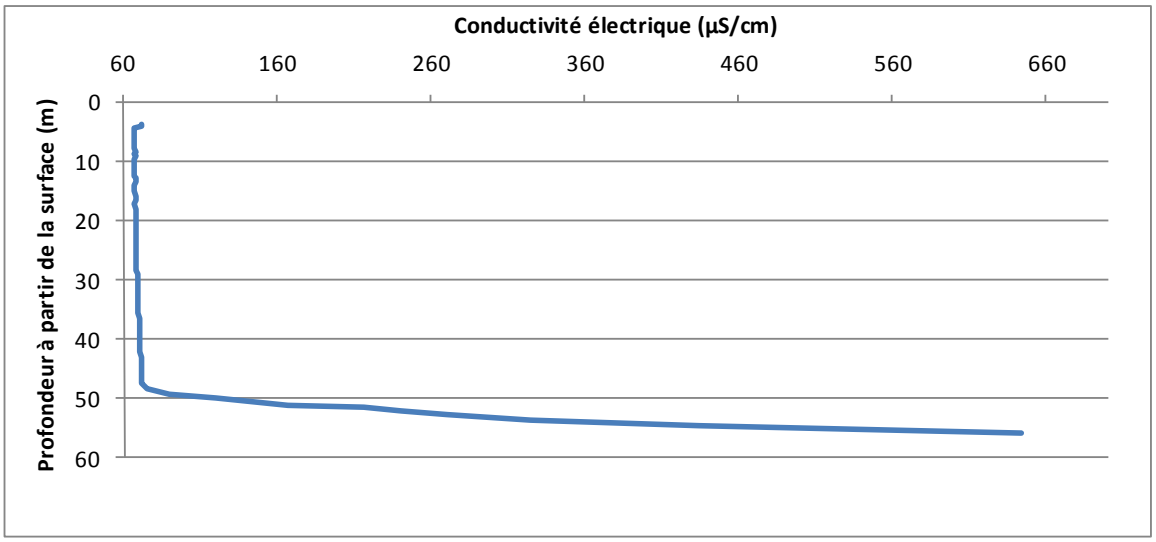


Figure 1: Profil de conductivité électrique de la colonne d'eau dans le puits

La figure ci-dessus représente un profil de conductivité électrique de la colonne d'eau de votre puits. La conductivité électrique est une mesure des composantes dissoutes dans l'eau. Le niveau d'eau est situé à environ 6 mètres sous la surface du sol. La conductivité électrique varie entre 60 et 650 µS/cm, ce qui est très intéressant parce que la conductivité électrique des premiers 50 mètres est extrêmement faible, très similaire à celle de l'eau de ruisellement. Après cette profondeur, la conductivité augmente drastiquement à environ 50 mètres. À cette profondeur, il est possible que des fractures alimentent votre puits avec de l'eau à condutivité électrique plus élevée.

Sommaire de la technique

Deux méthodes sont utilisées pour évaluer le statut du scellement de tubage :

1. La première a mesuré la conductivité hydraulique (K) autour du puits et permet de vérifier si l'eau s'infiltre plus facilement autour du puits que dans les surfaces environnantes. Un test statistique compare les valeurs mesurées. Si la valeur de

K autour du puits est significativement plus grande que celles des alentours, le scellement de tubage est potentiellement fautif.

2. La seconde méthode consiste à injecter une solution saline (NaCl) lors des essais d'infiltration au puits. Un suivi quotidien de la conductivité électrique dans la colonne d'eau du puits est effectué pour déceler la présence du traceur, laquelle démontrerait, le cas échéant, la présence d'un court-circuit hydraulique, ce qui signifie que les eaux de surface peuvent s'infiltrer en ruisselant sur le tubage du puits.

Résultats

1. Comparaison des conductivités hydrauliques (K)

Les essais d'infiltration ont été effectués les 16 et 17 août 2008. La conductivité hydraulique (K) mesurée au puits est plus grande que celle mesurée dans les environs. En langage statistique, cette différence n'est que « marginalement significative », ce qui signifie un scellement potentiellement fautif. L'essai de traçage avait pour but de corroborer ou de démentir cette affirmation.

2. Essai de traçage

L'injection du traceur s'est effectuée le 16 août. L'essai s'est déroulé en trois étapes. Pour commencer, la zone autour du puits fut saturée par l'injection d'eau du puits Ensuite, un total de 40L de solution saline, avec une conductivité électrique (EC) d'environ 19 000 µS/cm, a été injecté autour du puits. Finalement, 40L d'eau de puits furent versés dans le but de pousser le traceur en profondeur. La figure suivante montre quelques profils de conductivité électrique jusqu'à 12 jours après l'injection. Aucun des profils ne démontre de variations importantes ce qui signifie que le traceur n'a pas été détecté.

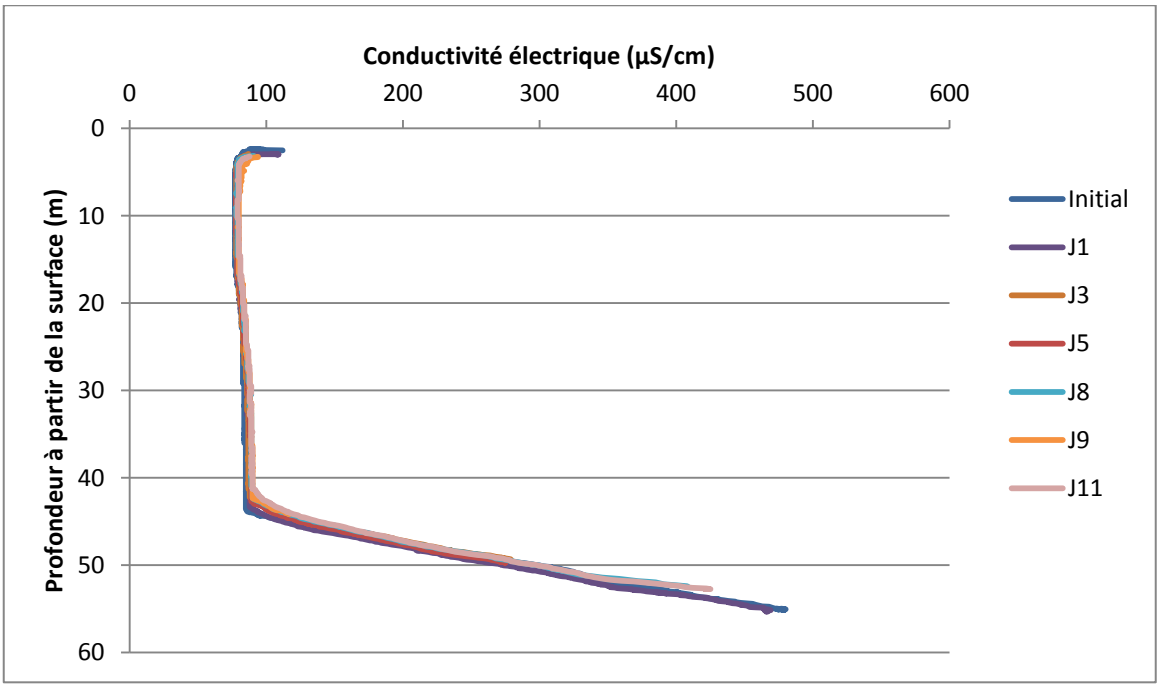


Figure 2 : Profils de conductivité électrique de la colonne d'eau avant et après l'injection de la solution saline.

Analyse bactériologique

Les bactéries sont naturellement présentes dans les eaux de surface et dans les sols. Elles sont transportées dans les eaux souterraines par le processus d'infiltration. Plusieurs facteurs affectent le mouvement des bactéries. Ces facteurs peuvent être reliés aux bactéries (type, taille, dynamique de la population) ou aux caractéristiques du sol (physique, chimique ou biologique). La plupart des bactéries sont filtrées dans le premier horizon du sol mais la présence de « macro-pores » peut contribuer au mouvement des bactéries en profondeur. Les macro-pores sont en fait des pores de grandes dimensions formées par l'activité biologique, les racines ou bien des fissures dans un milieu argileux. Ces macro-pores affectent la capacité du sol à filtrer les bactéries, ce qui leur permet de pénétrer plus profondément et rapidement.

La contamination bactérienne dans un puits peut provenir de plusieurs sources. Dans une municipalité comme Chelsea, où l'agriculture n'est que localisée et quasi-inexistante, la construction d'un puits (type, âge et profondeur), son emplacement, la distance au système septique ainsi que des facteurs reliés à la géologie sont les principales sources contribuant à la présence de bactéries dans un puits.

La figure ci-dessous présente les résultats de l'analyse bactériologique sous forme de graphique. On remarque deux dépassements aux cours de la période d'échantillonnage, soit le premier échantillon d'avril 2008 et en février 2009. Lors de l'échantillonnage, l'eau contenait beaucoup de particules d'argile.

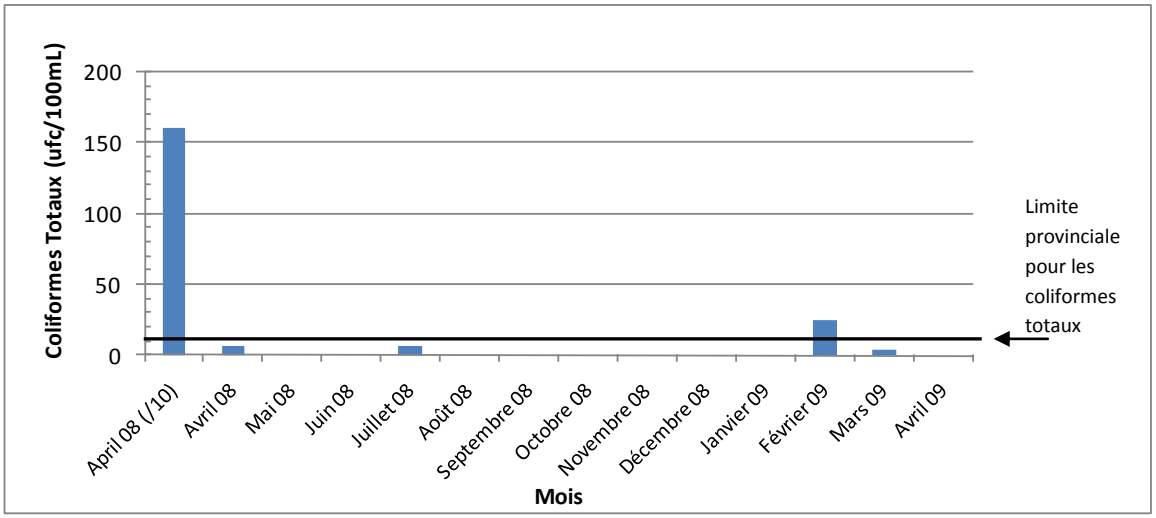


Figure 3: Résultats des analyses bactériologiques (coliformes totaux) des échantillons d'avril 2008 à mai 2009.

Analyse Chimique

Naturellement, l'eau dissout les minéraux lorsqu'elle s'écoule dans le sol. Le processus de dissolution est habituellement lent dans la roche Précambrienne comparativement aux jeunes roches sédimentaires telles le grès ou la calcite. Des sources anthropogéniques, telles l'épandage de sels routiers, les fertilisants et les systèmes septiques peuvent également contribuer à la teneur en minéraux dissouts dans les eaux souterraines.

Les échantillons d'eau furent analysés à l'université d'Ottawa pour identifier diverses composantes dissoutes. Les résultats sont présentés dans le tableau suivant. Ce tableau donne également la moyenne annuelle ainsi que les lignes directrices relatives à certains paramètres. Les concentrations sont mesurées en milligrammes par litre (mg/L).

Mois	pH	Fluorure (mg/L)	Chlorure (mg/L)	Nitrate -N (mg/L)	Sulfate (mg/L)	Calcium (mg/L)	Magnésium (mg/L)	Sodium (mg/L)	Dureté (mg/L de $CaCO_3$)
Avril 08	8.0	1.8	60.3	bdl	104.6	14.3	8.3	135.3	70.0
Mai 08	8.2	1.9	60.0	bdl	105.8	14.9	8.2	136.5	71.1
Juin 08	8.2	1.8	51.5	bdl	91.7	13.8	7.4	108.4	64.9
Juillet 08	7.7	1.9	51.8	bdl	97.4	15.0	8.3	129.9	71.4
Août 08	7.9	2.1	62.7	bdl	117.6	13.3	7.3	123.1	63.1
Septembre 08	8.5	1.3	22.3	bdl	39.8	7.8	7.7	128.7	51.1
Octobre 08	7.4	2.1	61.1	bdl	84.9	14.1	7.8	130.7	67.2
Novembre 08	7.6	1.0	23.7	bdl	41.6	13.4	7.4	121.2	63.9
Décembre 08	7.9	2.1	59.9	bdl	104.4	13.9	7.7	133.0	66.5
Janvier 09	7.4	2.1	63.3	bdl	113.3	12.8	7.2	126.4	61.6
Février 09	7.6	2.1	66.8	bdl	106.7	12.6	7.0	125.1	60.3
Mars 09	7.1	1.7	55.7	bdl	96.4	14.4	7.0	113.7	64.6
Avril 09	7.3	2.0	69.6	bdl	101.4	13.1	7.1	114.7	62.2
Mai09	7.4	2.0	60.5	bdl	105.5	11.9	7.0	107.7	58.6
Moyenne	7.7	1.9	54.9		93.7	13.2	7.5	123.9	64.0
Ligne directrice		1.5 CMP	250.0 OE	10.0 CMP	500.0 OE			20.0 OE	100 LDO

LDP = Ligne directrice opérationnelle
CMP= Concentration Maximale Permise
OE= Objectif Esthétique
Bdl= Sous limite de détection

Les paramètres mesurés lors de notre étude sont des indicateurs de la qualité de l'eau. Il est important de considérer que dans certain cas, leur présence n'a pas nécessairement un impact sur la santé. Le tableau décrit certain de ces paramètre ainsi que ce que les effets possible de leur présence.

Paramètres mesurés	Définitions/Sources	Effets possibles
pH	Mesure de l'acidité de l'eau	• Une eau acide (pH<6.5) peut avoir un effet corrosif
Fluorure	Présence naturelle	• Affecte la dentition des enfants • Des concentrations très élevées peuvent affecter le développement des os
Chlorure	Présence naturelle ou causée par l'activité humaine	• Effet corrosif sur la plomberie • Goût salé
Nitrates	Fertilisants, système septique	• Effets sur la santé
Sulfates	Présence naturelle ou causée par l'activité humaine	• L'eau à un effet laxatif
Sodium	Présence naturelle ou causée par l'activité humaine	• Hypertension (personne à risque)
Dureté	Causée par la présence de Calcium et Magnésium dans l'eau	• Aucun effet sur la santé • Réduit l'efficacité des savons • Effets sur la tuyauterie (dépôts et blocage) • Tache et salie le linge

Sources : Pratiques de gestion optimale-Les puits

Recommandations pour la qualité de l'eau potable au Canada

Catégorie	Concentration de carbonate de Calcium (mg/L)
Eau Douce	0 à <60
Eau modérément dure	60 à <120
Eau dure	120 à <180
Eau très dure	180 et plus

Source : Santé Canada

Sommaire et suggestions

Intégrité du scellement de tubage

Même si l'eau s'infiltre plus rapidement autour de puits que dans les surfaces avoisinantes, l'essai de traçage n'a pas démontré la présence d'une connexion hydraulique avec la surface, le scellement de tubage du puits serait donc efficace pour prévenir l'infiltration d'eau à la tête du puits.

Source possible de contamination

Il semblerait que les coliformes totaux soient présents en nombre plus important lors de la période de fonte des neiges. Il y aurait donc infiltration d'eau de surface dans le puits. Des fissures potentielles dans la couche d'argile peuvent en être la cause.

Analyse chimique

Tous les paramètres respectent les lignes directrices à l'exception des concentrations de fluorure et de sodium. Pour le fluorure, la moyenne annuelle est 1.9 mg/L alors que la concentration maximale permise est de 1.5 mg/L. Alors que pour le sodium, la moyenne annuelle est de 124 mg/L ce qui est plus élevé que l'objectif esthétique.

Suggestions

- La construction de votre puits est problématique. Le tubage d'acier devrait dépasser la surface d'au moins 20 cm et le sol autour du puits devrait être surélevé. Ceci préviendrait l'infiltration directe d'eau de surface lors de fortes périodes de pluies. Vous devriez faire appel à un puisatier qualifié pour remédier à la situation.
- Un bon couvercle devrait garder les insectes hors du puits. Même si aucun insecte ne fut détecté à l'intérieur, il est donc recommandé de vérifier l'intérieur et de s'assurer que le couvercle soit assez étanche pour ne pas laisser entrer les insectes, mais assez dégagé pour laisser passer l'air. Ceci pourrait prévenir le nombre de coliformes totaux dans le puits.

- Il est important de faire un suivi continu sur l'état de votre puits. Une fois l'an, vous devriez regarder dans le puits avec une lampe de poche. Recherchez la présence de fissures et de trous dans le cuvelage et près de l'embranchement des tuyaux vers la maison. Prenez des notes et comparez au fil des ans. Des mesures correctives peuvent être entreprises, par un puisatier, si un problème est détecté.
- Il est recommandé de faire une analyse bactériologique au moins 1 fois par année, et à l'occasion, notamment après une pluie importante et la fonte des neiges.
- Finalement, il serait impératif de faire installer un système de stérilisation de l'eau, tel les systèmes aux rayons ultra-violets.

L'information présentée dans ce rapport provient des sources suivantes :

*****Ces sources sont également excellentes pour en savoir plus sur les puits, les sources de contamination ainsi que sur la qualité de l'eau**

Conboy M.J, Smith S., 2005. A comprehensive consumer's guide for private water wells ISBN 0-9780387-0-3
www.wellwise.ca

Recommandations pour la qualité de l'eau potable au Canada -La dureté
http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/hardness-durete/index-fra.php

Ministère du développement durable, environnement et parcs- *La qualité de l'eau de mon puits*
http://www.mddep.gouv.qc.ca/eau/potable/depliant/index.htm

Publications : Ministère de l'agriculture, de l'alimentation et des affaires rurales (Ontario)
http://www.omafra.gov.on.ca/french/environment/water/publications.htm

Ministère de la santé et des soins de longue durée
http://www.health.gov.on.ca/english/public/pub/watersafe/watersafe_wellknow.html

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Université d'Ottawa • University of Ottawa
Faculté des sciences Faculty of Science
Sciences de la Terre Earth Sciences

Étude sur la contamination des puits domestiques
Municipalité de Chelsea, Québec



Rapport présenté à :
W20
Chelsea, QC

Rapport préparé par :
Pascale St-Germain
Candidate au doctorat
Université d'Ottawa

Mai 2010

Remerciements

Merci d'avoir participé à cette étude. Vos efforts furent importants dans l'avancement de notre compréhension sur les voies préférentielles de contamination des puits. Nous sommes très reconnaissants pour nous avoir donné l'accès à votre propriété, pour votre hospitalité ainsi que votre aide dans le prélèvement mensuel des échantillons.

Notes importantes

Les idées présentées dans ce rapport sont des suggestions qui pourraient améliorer la qualité de l'eau de votre puits. Elles pourraient possiblement être utiles dans la réduction du nombre de coliformes mais ne résoudront pas nécessairement le problème général. Nous avons fait notre possible pour évaluer la source probable de contamination, mais plusieurs facteurs peuvent affecter la qualité de l'eau d'un puits. Ce rapport a pour but de vous aider à comprendre votre puits et n'inclut pas toutes les conclusions de l'étude. Ces suggestions doivent être considérées avec prudence.

Avant d'investir dans votre puits (amélioration du puits ou système de traitement de l'eau) il serait important de demander l'avis d'un professionnel certifié et de faire analyser votre eau par un laboratoire indépendant.

Merci beaucoup pour votre compréhension.

Pascale St-Germain
Candidate au doctorat
Université d'Ottawa
Département des Sciences de la Terre

Glossaire

Roc Précambrien : Socle rocheux composé de roches ignées et métamorphiques datant de plus de 542 Millions d'années

Dépôts meubles : Sédiments non consolidés recouvrant le socle rocheux

Mer de Champlain : Mer créée lors de la fonte du Glacier *Inlandsis laurentidien*, il y a environ 10 000 ans, submergeant principalement la région de Montréal et une partie du sud-est ontarien.

Voies préférentielles : Présence de macro pores favorisant l'écoulement de l'eau sans le potentiel atténuant du sol, permettant aux contaminants de se faire transporter plus rapidement et plus profondément

Puits foré : Puits creusé dans le socle rocheux à l'aide d'une foreuse

Aquifère : Unité géologique capable de contenir et de transmettre de l'eau en quantité suffisante

Aquifère captif : Aquifère recouvert d'une couche imperméable isolant l'aquifère de la surface du sol

Aquifère libre : Aquifère non recouvert d'une couche imperméable et exposé à la pression atmosphérique

Aquitard : Unité géologique imperméable capable de contenir de l'eau mais incapable de la transmettre en quantité suffisante

Infiltration : Mouvement de l'eau de la surface jusque dans le sol

Conductivité hydraulique : Capacité d'un milieu poreux à transmettre l'eau

Conductivité électrique (EC) : Capacité de l'eau à transmettre un courant électrique; donne une mesure du montant total des composantes dissoutes dans l'eau. L'unité de mesure de la conductivitéélectrique est le Siemens par cm (S/cm) ou microsiemens par cm (µS/cm = 10^{-6} S/cm). A titre comparatif, la EC varie de quelques dizaines de µS/cm dans le cas des eaux de pluie à quelques centaines de millier de µS/cm dans le cas des eaux salées. Dans la région de Chelsea, elle varie entre environ 80 et 1600 µS/cm.

Coliformes totaux : Groupe de bactéries fermentant le lactose à 38°C. Ces bactéries sont présentes dans les matières fécales des humains et des animaux ainsi que dans le sol et la végétation.

Coliformes fécaux : Bactéries provenant du système digestif des humains et animaux. Indique une présence possible de pathogènes dans l'eau.

Macro-pores : Pores de grandes dimensions formées par l'activité biologique, les racines ou bien les fissures dans un milieu argileux.

Représentation schématique d'un puits domestique

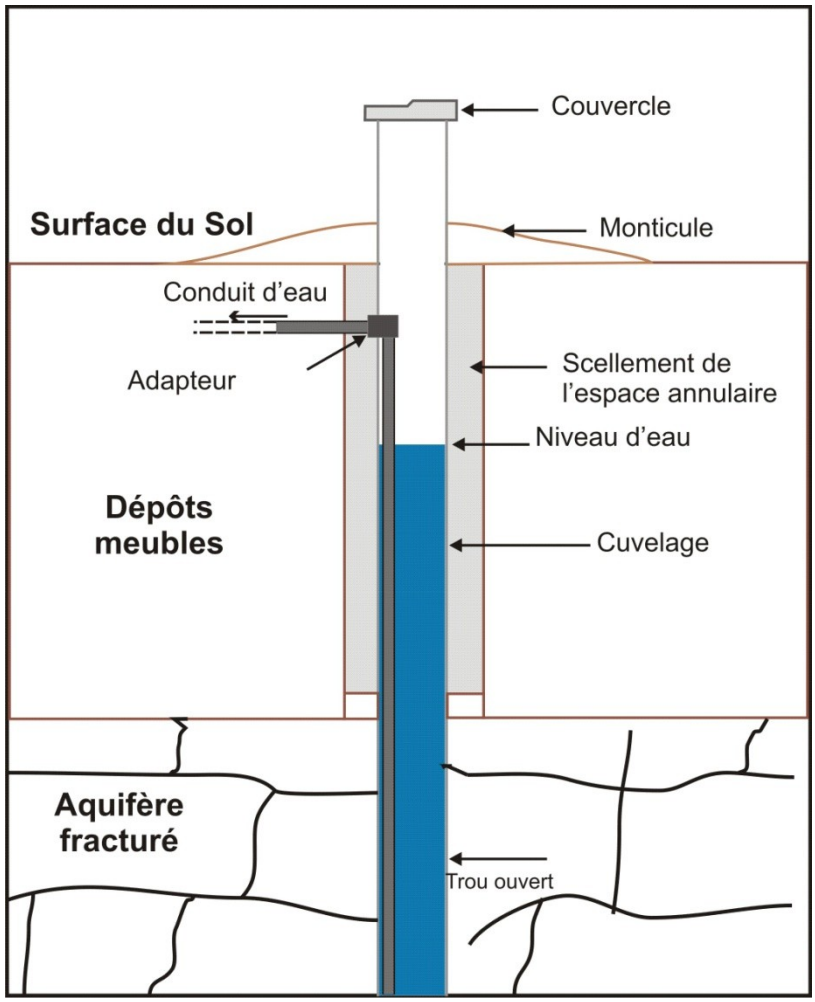


Image modifiée de : *Pratiques de gestion optimale-Les puits*

Introduction

L'objectif de ce projet est d'améliorer nos connaissances en ce qui a trait à la contamination des puits d'eau potable résultant de l'infiltration des eaux de surfaces. Notre but est d'évaluer le risque de contamination des puits forés en se basant sur les caractéristiques du site et sur la construction du puits.

En effectuant une analyse bactériologique mensuelle, il fut possible d'avoir une meilleure idée sur la saisonnalité de la contamination. L'analyse chimique de l'eau fût utilisée pour comprendre l'évolution des eaux souterraines et pour effectuer un lien avec une source possible de contamination.

L'objectif de ce rapport est de vous sensibiliser à la qualité de l'eau de votre puits et aux mesures existantes pour préserver ou améliorer sa qualité. Ce rapport présente un sommaire des travaux effectués, les principaux résultats ainsi que quelques suggestions, si nécessaire.

Description du site

Votre puits est foré dans le roc précambrien sur lequel repose une épaisse couche d'argile. Cette couche que l'on nomme couche de confinement, d'une dizaine de mètre d'épaisseur ou plus, s'est déposée lors de la dernière glaciation (environ 10 000 ans), lorsque la Mer de Champlain recouvrait partiellement la région. La profondeur du puits est d'environ 37 mètres et le niveau de l'eau est situé à 30 mètres de la surface du sol.

L'eau de votre puits provient d'un aquifère. Un aquifère peut être défini comme une unité géologique capable de contenir et de transmettre de l'eau. Cet aquifère est également considéré comme étant « captif » car il est recouvert d'une couche imperméable. Ce type d'aquifère est généralement moins vulnérable à la contamination car la couche de confinement (l'argile) est imperméable et protège naturellement l'aquifère des contaminants de surface.

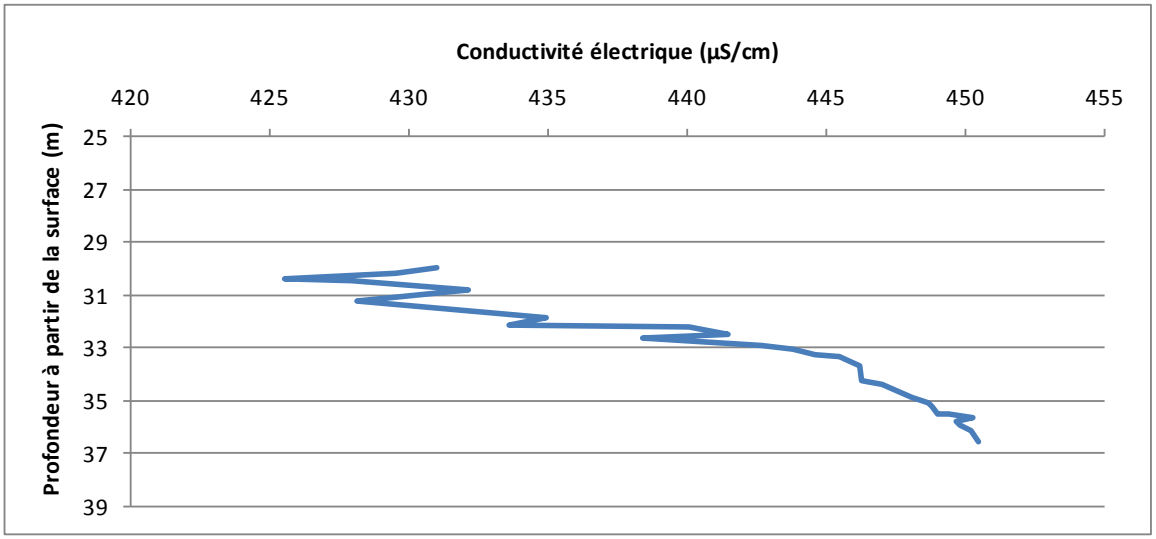


Figure 1: Profil de conductivité électrique de la colonne d'eau dans le puits

La figure ci-dessus représente un profil de conductivité électrique de la colonne d'eau de votre puits. La conductivité électrique est une mesure des composantes dissoutes dans l'eau. Le niveau d'eau est situé à environ 30 mètres sous la surface du sol. La conductivité électrique varie entre 425 et 450 µS/cm. Il semble que la conductivité électrique augmente en profondeur. Cependant, il est à noter que l'écart de conductivité électrique de l'eau entre la surface et la profondeur est du même ordre de grandeur que l'incertitude sur la mesure.

Analyse bactériologique

Les bactéries sont naturellement présentes dans les eaux de surface et dans les sols. Elles sont transportées dans les eaux souterraines par le processus d'infiltration. Plusieurs facteurs affectent le mouvement des bactéries. Ces facteurs peuvent être reliés aux bactéries (type, taille, dynamique de la population) ou aux caractéristiques du sol (physique, chimique ou biologique). La plupart des bactéries sont filtrées dans le premier horizon du sol mais la présence de « macro-pores » peut contribuer au mouvement des bactéries en profondeur. Les macro-pores sont en fait des pores de grandes dimensions formées par l'activité biologique, les racines ou bien des fissures dans un milieu argileux.

Ces macro-pores affectent la capacité du sol à filtrer les bactéries, ce qui leur permet de pénétrer plus profondément et rapidement.

La contamination bactérienne dans un puits peut provenir de plusieurs sources. Dans une municipalité comme Chelsea, où l'agriculture n'est que localisée et quasi-inexistante, la construction d'un puits (type, âge et profondeur), son emplacement, la distance au système septique ainsi que des facteurs reliés à la géologie sont les principales sources contribuant à la présence de bactéries dans un puits.

La présence de coliformes totaux a été détectée à une reprise, soit en avril 2008. Les coliformes totaux étaient présents en très grand nombre (OG). La collecte de l'échantillon s'étant fait dans la cuisine, il est possible qu'une contamination à partir du robinet soit la cause de ce nombre élevé. La présence de coliformes fécaux n'a jamais été détectée dans les échantillons prélevés.

Analyse Chimique

Naturellement, l'eau dissout les minéraux lorsqu'elle s'écoule dans le sol. Le processus de dissolution est habituellement lent dans la roche Précambrienne comparativement aux jeunes roches sédimentaires telles le grès ou la calcite. Des sources anthropogéniques, telles l'épandage de sels routiers, les fertilisants et les systèmes septiques peuvent également contribuer à la teneur en minéraux dissouts dans les eaux souterraines.

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Août 08	7.6	bdl	68.5	bdl	27.7	54.3	13.7	28.4	191.9
Septembre 08	8.6	bdl	7.7	bdl	5.6	10.7	1.9	3.9	34.5
Octobre 08	7.4	bdl	64.8	bdl	30.3	51.7	12.5	27.3	180.7
Novembre 08	7.4	bdl	66.0	bdl	29.8	53.6	12.8	27.7	186.5
Décembre 08	7.2	bdl	63.0	bdl	29.7	51.8	12.6	27.2	181.5
Janvier 09	7.9	bdl	66.9	bdl	30.0	51.3	12.4	27.0	179.4
Février 09	7.2	bdl	74.4	bdl	30.5	49.5	12.2	26.8	174.2
Mars 09	6.8	bdl	66.0	bdl	30.2	53.7	12.7	28.3	186.4
Avril 09	7.2	bdl	71.8	bdl	31.3	50.4	12.7	26.5	178.2
Moyenne	7.6		61.6		27.7	49.1	11.9	26.0	171.8
Ligne directrice		1.5 CMP	250.0 OE	10.0 CMP	500.0 OE			20.0 OE	100.0 LDO

LDP = Ligne directrice opérationnelle
CMP= Concentration Maximale Permise
OE= Objectif Esthétique
Bdl= Sous limite de détection

Les paramètres mesurés lors de notre étude sont des indicateurs de la qualité de l'eau. Il est important de considérer que dans certain cas, leur présence n'a pas nécessairement un impact sur la santé. Le tableau décrit certain de ces paramètre ainsi que ce que les effets possible de leur présence.

Paramètres mesurés	Définitions/Sources	Effets possibles
pH	Mesure de l'acidité de l'eau	• Une eau acide (pH<6.5) peut avoir un effet corrosif
Fluorure	Présence naturelle	• Affecte la dentition des enfants • Des concentrations très élevées peuvent affecter le développement des os
Chlorure	Présence naturelle ou causée par l'activité humaine	• Effet corrosif sur la plomberie • Goût salé
Nitrates	Fertilisants, système septique	• Effets sur la santé
Sulfates	Présence naturelle ou causée par l'activité humaine	• L'eau à un effet laxatif
Sodium	Présence naturelle ou causée par l'activité humaine	• Hypertension (personne à risque)
Dureté	Causée par la présence de Calcium et Magnésium dans l'eau	• Aucun effet sur la santé • Réduit l'efficacité des savons • Effets sur la tuyauterie (dépôts et blocage) • Tache et salie le linge

Sources : Pratiques de gestion optimale-Les puits

Recommandations pour la qualité de l'eau potable au Canada

Catégorie	Concentration de carbonate de Calcium (mg/L)
Eau Douce	0 à <60
Eau modérément dure	60 à <120
Eau dure	120 à <180
Eau très dure	180 et plus

Source : Santé Canada

Sommaire et suggestions

Source possible de contamination

L'analyse bactériologique de l'eau de votre puits est relativement bonne. Dans la majorité des analyses, le nombre de coliformes totaux est sous la limite provinciale et, dans tous les cas, les coliformes fécaux ne sont pas détectés. Il est possible que le dépassement pour les coliformes totaux résulte d'une contamination lors de l'échantillonnage.

Analyse chimique

Tous les paramètres respectent les lignes directrices à l'exception du sodium qui est légèrement plus élevé que l'objectif esthétique. Pour la dureté, la moyenne annuelle est de 172 mg/L de $CaCO_3$ alors que ligne directrice opérationnelle est de 100 mg/L de $CaCO_3$. L'eau est donc considérée comme dure. Par contre, un adoucisseur d'eau est déjà en place.

Suggestions

- Un bon couvercle devrait garder les insectes hors du puits. Des évidences d'insectes furent détectées à l'intérieur, il est donc recommandé d'installer un couvercle étanche aux insectes (mais non à l'air). Ceci pourrait réduire le nombre de coliformes totaux dans le puits.
- Il est important de faire un suivi continu sur l'état de votre puits. Une fois l'an, vous devriez regarder dans le puits avec une lampe de poche. Recherchez la présence de fissures et de trous dans le cuvelage et près de l'embranchement des tuyaux vers la maison. Prenez des notes et comparez au fil des ans. Des mesures correctives peuvent être entreprises, par un puisatier, si un problème est détecté.
- Il est recommandé de faire une analyse bactériologique au moins 1 fois par année, et à l'occasion, notamment après une pluie importante et la fonte des neiges.

L'information présentée dans ce rapport provient des sources suivantes :

*****Ces sources sont également excellentes pour en savoir plus sur les puits, les sources de contamination ainsi que sur la qualité de l'eau**

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Faculté des sciences Faculty of Science
Sciences de la Terre Earth Sciences

Étude sur la contamination des puits domestiques Municipalité de Chelsea, Québec



Rapport présenté à :
W21
Chelsea, QC

Rapport préparé par :
Pascale St-Germain
Candidate au doctorat
Université d'Ottawa

Mai 2010

Remerciements

Merci d'avoir participé à cette étude. Vos efforts furent importants dans l'avancement de notre compréhension sur les voies préférentielles de contamination des puits. Nous sommes très reconnaissants pour nous avoir donné l'accès à votre propriété, pour votre hospitalité ainsi que votre aide dans le prélèvement mensuel des échantillons.

Notes importantes

Les idées présentées dans ce rapport sont des suggestions qui pourraient améliorer la qualité de l'eau de votre puits. Elles pourraient possiblement être utiles dans la réduction du nombre de coliformes mais ne résoudront pas nécessairement le problème général. Nous avons fait notre possible pour évaluer la source probable de contamination, mais plusieurs facteurs peuvent affecter la qualité de l'eau d'un puits. Ce rapport a pour but de vous aider à comprendre votre puits et n'inclut pas toutes les conclusions de l'étude. Ces suggestions doivent être considérées avec prudence.

Avant d'investir dans votre puits (amélioration du puits ou système de traitement de l'eau) il serait important de demander l'avis d'un professionnel certifié et de faire analyser votre eau par un laboratoire indépendant.

Merci beaucoup pour votre compréhension.

Pascale St-Germain
Candidate au doctorat
Université d'Ottawa
Département des Sciences de la Terre

Glossaire

Roc Précambrien : Socle rocheux composé de roches ignées et métamorphiques datant de plus de 542 Millions d'années

Dépôts meubles : Sédiments non consolidés recouvrant le socle rocheux

Mer de Champlain : Mer créée lors de la fonte du Glacier *Inlandsis laurentidien*, il y a environ 10 000 ans, submergeant principalement la région de Montréal et une partie du sud-est ontarien.

Voies préférentielles : Présence de macro pores favorisant l'écoulement de l'eau sans le potentiel atténuant du sol, permettant aux contaminants de se faire transporter plus rapidement et plus profondément

Puits foré : Puits creusé dans le socle rocheux à l'aide d'une foreuse

Aquifère : Unité géologique capable de contenir et de transmettre de l'eau en quantité suffisante

Aquifère captif : Aquifère recouvert d'une couche imperméable isolant l'aquifère de la surface du sol

Aquifère libre : Aquifère non recouvert d'une couche imperméable et exposé à la pression atmosphérique

Aquitard : Unité géologique imperméable capable de contenir de l'eau mais incapable de la transmettre en quantité suffisante

Infiltration : Mouvement de l'eau de la surface jusque dans le sol

Conductivité hydraulique : Capacité d'un milieu poreux à transmettre l'eau

Conductivité électrique (EC) : Capacité de l'eau à transmettre un courant électrique; donne une mesure du montant total des composantes dissoutes dans l'eau. L'unité de mesure de la conductivitéélectrique est le Siemens par cm (S/cm) ou microsiemens par cm (µS/cm = 10^{-6} S/cm). A titre comparatif, la EC varie de quelques dizaines de µS/cm dans le cas des eaux de pluie à quelques centaines de millier de µS/cm dans le cas des eaux salées. Dans la région de Chelsea, elle varie entre environ 80 et 1600 µS/cm.

Coliformes totaux : Groupe de bactéries fermentant le lactose à 38°C. Ces bactéries sont présentes dans les matières fécales des humains et des animaux ainsi que dans le sol et la végétation

Coliformes fécaux : Bactéries provenant du système digestif des humains et animaux. Indique une présence possible de pathogènes dans l'eau

Macro-pores : Pores de grandes dimensions formées par l'activité biologique, les racines ou bien les fissures dans un milieu argileux

Représentation schématique d'un puits domestique

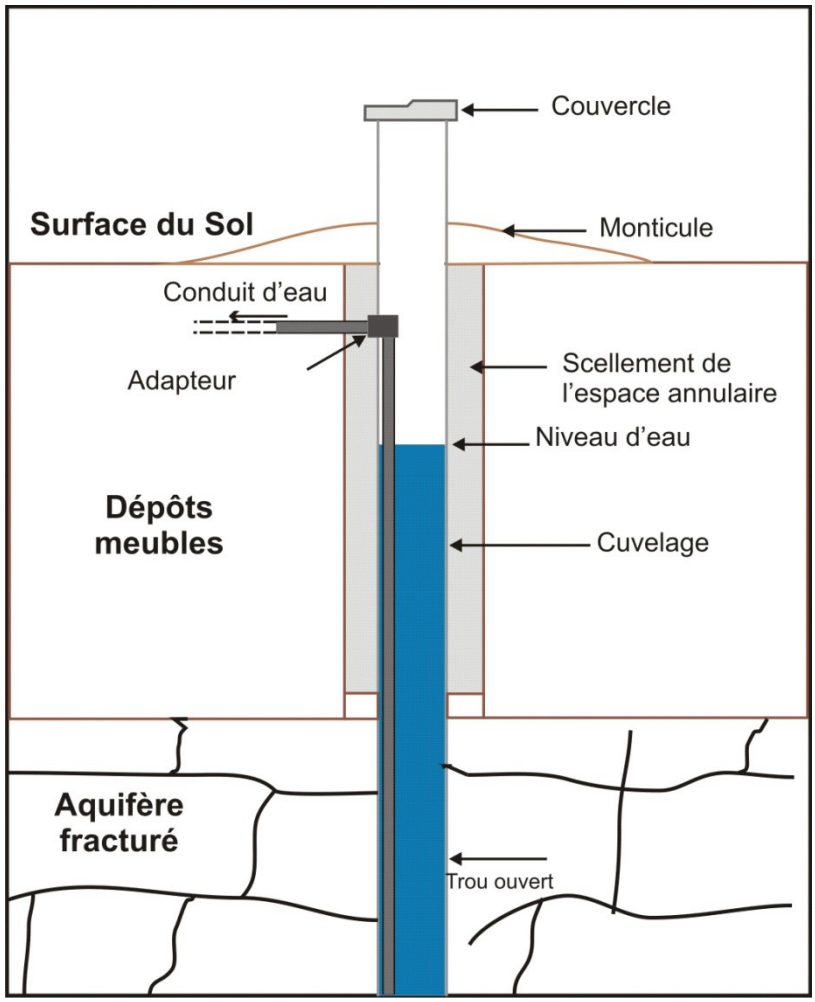


Image modifiée de : *Pratiques de gestion optimale-Les puits*

Introduction

L'objectif de ce projet est d'améliorer nos connaissances en ce qui a trait à la contamination des puits d'eau potable résultant de l'infiltration des eaux de surfaces. Notre but est d'évaluer le risque de contamination des puits forés en se basant sur les caractéristiques du site et sur la construction du puits.

En effectuant une analyse bactériologique mensuelle, il fut possible d'avoir une meilleure idée sur la saisonnalité de la contamination. L'analyse chimique de l'eau fût utilisée pour comprendre l'évolution des eaux souterraines et pour effectuer un lien avec une source possible de contamination.

L'objectif de ce rapport est de vous sensibiliser à la qualité de l'eau de votre puits et aux mesures existantes pour préserver ou améliorer sa qualité. Ce rapport présente un sommaire des travaux effectués, les principaux résultats ainsi que quelques suggestions, si nécessaire.

Description du site

Votre puits est foré dans le roc précambrien sur lequel repose une épaisse couche d'argile. Cette couche que l'on nomme couche de confinement, d'une dizaine de mètre d'épaisseur ou plus, s'est déposée lors de la dernière glaciation (environ 10 000 ans), lorsque la Mer de Champlain recouvrait partiellement la région. La profondeur du puits est d'environ 84 mètres et le niveau de l'eau est situé à 11 mètres de la surface du sol.

L'eau de votre puits provient d'un aquifère. Un aquifère peut être défini comme une unité géologique capable de contenir et de transmettre de l'eau. Cet aquifère est également considéré comme étant « captif » car il est recouvert d'une couche imperméable. Ce type d'aquifère est généralement moins vulnérable à la contamination car la couche de confinement (l'argile) est imperméable et protège naturellement l'aquifère des contaminants de surface.

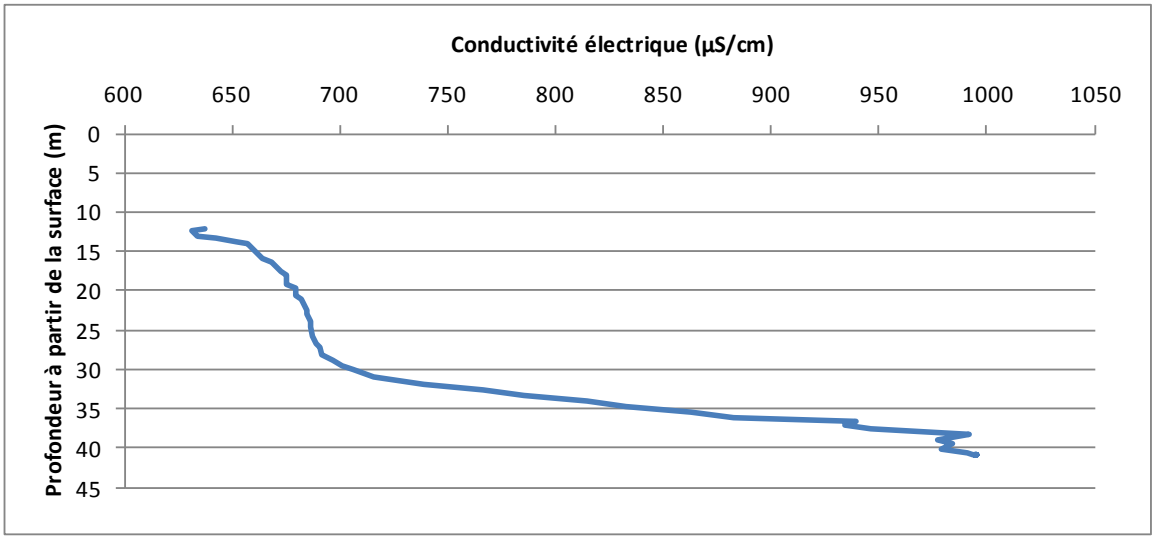


Figure 1: Profil de conductivité électrique de la colonne d'eau dans le puits

La figure ci-dessus représente un profil de conductivité électrique de la colonne d'eau de votre puits. La conductivité électrique est une mesure des composantes dissoutes dans l'eau. Le niveau d'eau est situé à environ 30 mètres sous la surface du sol. La conductivité électrique varie entre 625 et 1000 µS/cm. Il semble que la conductivité électrique augmente en profondeur, avec un changement important à environ 35 mètres. À cette profondeur, il est possible que des fractures alimentent votre puits avec de l'eau à condutivité électrique plus élevée. La présence de tuyeau dans le puits nous a empêché de descendre la sonde de conductivité après 40 mètres.

Analyse bactériologique

Les bactéries sont naturellement présentes dans les eaux de surface et dans les sols. Elles sont transportées dans les eaux souterraines par le processus d'infiltration. Plusieurs facteurs affectent le mouvement des bactéries. Ces facteurs peuvent être reliés aux bactéries (type, taille, dynamique de la population) ou aux caractéristiques du sol (physique, chimique ou biologique). La plupart des bactéries sont filtrées dans le premier horizon du sol mais la présence de « macro-pores » peut contribuer au mouvement des bactéries en profondeur. Les macro-pores sont en fait des pores de grandes dimensions formées par l'activité biologique, les racines ou bien des fissures dans un milieu argileux.

Ces macro-pores affectent la capacité du sol à filtrer les bactéries, ce qui leur permet de pénétrer plus profondément et rapidement.

La contamination bactérienne dans un puits peut provenir de plusieurs sources. Dans une municipalité comme Chelsea, où l'agriculture n'est que localisée et quasi-inexistante, la construction d'un puits (type, âge et profondeur), son emplacement, la distance au système septique ainsi que des facteurs reliés à la géologie sont les principales sources contribuant à la présence de bactéries dans un puits.

La figure ci-dessous présente les résultats de l'analyse bactériologique sous forme de graphique. La limite provinciale pour les coliformes totaux (10 ufc/100 mL) a été dépassée à deux reprises, soit en août et septembre 2008. Lorsque l'on compare le nombre de coliformes totaux aux précipitations, on remarque une certaine tendance. Il est donc possible que ces dépassements soient liés aux précipitations ayant eu lieu une semaine avant la collecte de l'échantillon. La présence de coliformes fécaux n'a jamais été détectée dans les échantillons prélevés.

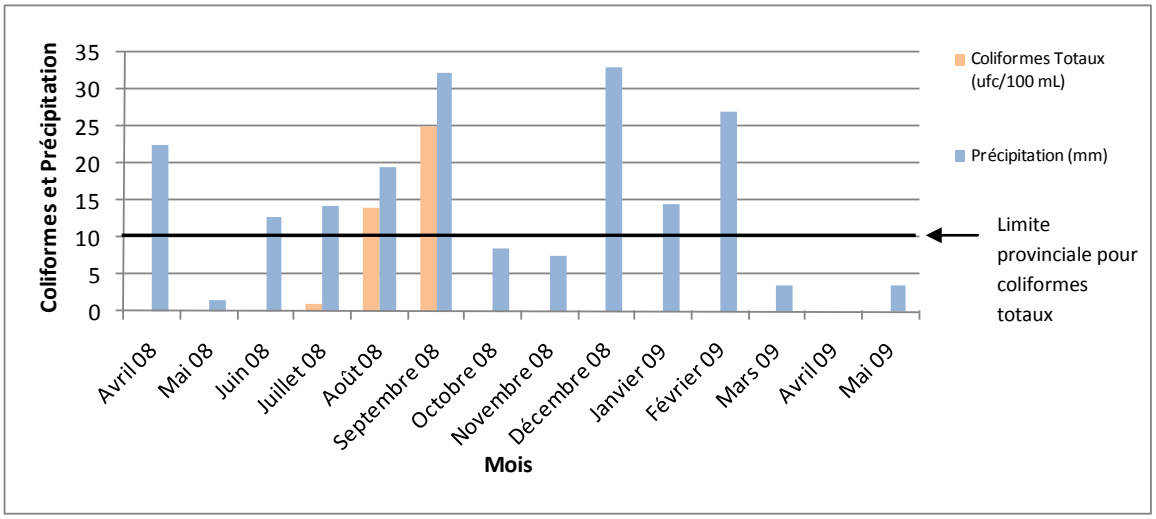


Figure 2: Résultats des analyses bactériologiques (coliformes totaux) des échantillons d'avril 2008 à mai 2009.

Analyse Chimique

Naturellement, l'eau dissout les minéraux lorsqu'elle s'écoule dans le sol. Le processus de dissolution est habituellement lent dans la roche Précambrienne comparativement aux jeunes roches sédimentaires telles le grès ou la calcite. Des sources anthropogéniques, telles l'épandage de sels routiers, les fertilisants et les systèmes septiques peuvent également contribuer à la teneur en minéraux dissouts dans les eaux souterraines.

Les échantillons d'eau furent analysés à l'université d'Ottawa pour identifier diverses composantes dissoutes. Les résultats sont présentés dans le tableau suivant. Ce tableau donne également la moyenne annuelle ainsi que les lignes directrices relatives à certains paramètres. Les concentrations sont mesurées en milligrammes par litre (mg/L).

Mois	pH	Fluorure (mg/L)	Chlorure (mg/L)	Nitrate -N (mg/L)	Sulfate (mg/L)	Calcium (mg/L)	Magnésium (mg/L)	Sodium (mg/L)
Avril 08	7.3	3.1	295.9	bdl	bdl	6.7	3.5	269.9
Mai 08	7.4	1.4	93.5	bdl	bdl	3.1	1.0	72.9
Juin 08	7.6	3.3	184.5	bdl	bdl	5.6	3.1	255.2
Juillet 08	7.5	3.5	215.8	bdl	0.1	5.2	2.7	232.0
Août 08	7.2	3.5	237.8	bdl	0.1	5.8	2.7	230.6
Septembre 08	7.3	1.5	35.4	bdl	bdl	6.4	3.5	260.1
Octobre 08	7.0	3.1	320.6	bdl	0.2	3.7	2.4	277.2
Novembre 08	7.7	2.0	52.4	bdl	0.1	5.6	3.5	267.8
Décembre 08	7.6	3.4	201.5	bdl	bdl	5.8	3.4	263.1
Janvier 09	6.7	1.5	323.1	bdl	0.5	6.0	3.2	253.0
Février 09	6.9	3.2	388.4	bdl	bdl	6.3	3.4	258.0
Mars 09	7.5	3.4	199.1	bdl	0.4	6.6	3.5	256.3
Avril 09	7.6	3.6	136.2	bdl	0.4	5.9	3.3	228.0
Mai09	7.4	3.5	190.0	bdl	bdl	5.6	3.2	230.2
Moyenne	7.3	2.8	205.3		0.2	5.6	3.0	239.6
Ligne directrice		1.5 CMP	250.0 OE	10.0 CMP	500.0 OE			20.0 OE

LDP = Ligne directrice opérationnelle
CMP= Concentration Maximale Permise
OE= Objectif Esthétique
Bdl= Sous limite de détection

Note : la dureté n'a pas été mesurée ici car les échantillons ont été prélevés après l'adoucisseur

Les paramètres mesurés lors de notre étude sont des indicateurs de la qualité de l'eau. Il est important de considérer que dans certain cas, leur présence n'a pas nécessairement un impact sur la santé. Le tableau décrit certain de ces paramètre ainsi que ce que les effets possible de leur présence.

Paramètres mesurés	Définitions/Sources	Effets possibles
pH	Mesure de l'acidité de l'eau	• Une eau acide (pH<6.5) peut avoir un effet corrosif
Fluorure	Présence naturelle	• Affecte la dentition des enfants • Des concentrations très élevées peuvent affecter le développement des os
Chlorure	Présence naturelle ou causée par l'activité humaine	• Effet corrosif sur la plomberie • Goût salé
Nitrates	Fertilisants, système septique	• Effets sur la santé
Sulfates	Présence naturelle ou causée par l'activité humaine	• L'eau à un effet laxatif
Sodium	Présence naturelle ou causée par l'activité humaine	• Hypertension (personne à risque)
Dureté	Causée par la présence de Calcium et Magnésium dans l'eau	• Aucun effet sur la santé • Réduit l'efficacité des savons • Effets sur la tuyauterie (dépôts et blocage) • Tache et salie le linge

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Eau très dure	180 et plus

Source : Santé Canada

Sommaire et suggestions

Source possible de contamination

L'analyse bactériologique de l'eau de votre puits est relativement bonne. Dans la majorité des analyses, le nombre de coliformes totaux est sous la limite provinciale et, dans tous les cas, les coliformes fécaux ne sont pas détectés. Il semble que la présence de bactéries soit corrélée avec les précipitations, Si c'est le cas, il existerait donc une voie préférentielle à d'infiltration d'eau de surface et je suspecte que la construction du puits en soit responsable. Si vous regardez autour du puits, vous remarquerez une légère dépression. Si l'eau s'accumule à cet endroit lors de fortes pluies, elle risque de s'infiltrer dans l'espace annulaire (créé lors de la construction et rempli avec un matériel techniquement imperméable). Si l'eau s'infiltre trop rapidement, le sol ne filtre pas les bactéries et il y a un risque de contamination. Aussi comme votre puits est situé dans une pente, le ruissellement de surface s'effectue vers le puits, ce qui accroît ce risque de contamination.

Analyse chimique

Tous les paramètres respectent les lignes directrices à l'exception de la concentration de fluorure et de la dureté. Pour la concentration en fluorure, la moyenne annuelle est 2.8 mg/L alors que la concentration maximale permise est de 1.5 mg/L. La moyenne est légèrement au dessus de la limite. Le chlorure dépasse également l'objectif esthétique.

Provenances possibles de Na et Cl :

Votre système d'adoucisseur contribue à l'apport de sodium (Na) dans votre eau. La dureté est causée pas une haute teneur en Calcium (Ca) et Magnésium (Mg). L'adoucisseur remplace les ions Ca et Mg par l'ion Na, ce qui augmente la concentration de ce dernier.

Une autre proportion du Na proviendrait directement de l'eau présente dans l'aquifère car la haute teneur en sodium est également associée à de grandes

concentrations de Cl: votre puits est creusé dans de l'argile déposée lors de la dernière fonte glaciaire et la présence de la Mer de Champlain (il y a environ 10 000 ans). Il est également assez profond. L'eau salée de la Mer de Champlain s'est infiltrée dans les aquifères rocheux. Il est donc possible qu'une certaine proportion de l'eau de votre puits proviennent de ces aquifères. Si c'est le cas, l'eau de votre puits serait assez « âgée » comme on dit. Par contre, cette dernière explication reste une hypothèse.

Finalement, il est possible que la présence du NaCl provienne de l'épandage de sels routiers. Ces derniers pourraient atteindre l'aquifère par des fractures présentes dans l'argile.

Suggestions

- L'espace annulaire étant possiblement une voie préférentielle à la contamination, il est important de réduire le ruissellement vers le puits. Pour ce faire, il est recommandé d'élever le sol à la tête du puits, ce qui évitera l'eau de ruissellement de s'accumuler et s'infiltrer à cet endroit.
- Un bon couvercle devrait garder les insectes hors du puits. Même si aucun insecte ne fut détecté à l'intérieur, il est donc recommandé de vérifier l'intérieur et de s'assurer que le couvercle soit assez étanche pour ne pas laisser entrer les insectes, mais assez dégagé pour laisser passer l'air. Ceci pourrait prévenir le nombre de coliformes totaux dans le puits.
- Il est important de faire un suivi continu sur l'état de votre puits. Une fois l'an, vous devriez regarder dans le puits avec une lampe de poche. Recherchez la présence de fissures et de trous dans le cuvelage et près de l'embranchement des tuyaux vers la maison. Prenez des notes et comparez au fil des ans. Des mesures correctives peuvent être entreprises, par un puisatier, si un problème est détecté.
- Il est recommandé de faire une analyse bactériologique au moins 1 fois par année, et à l'occasion, notamment après une pluie importante et la fonte des neiges.
- Finalement, si la contamination bactérienne persiste, il serait impératif de faire installer un système de stérilisation de l'eau, tel les systèmes aux rayons ultra-violets.

L’information présentée dans ce rapport provient des sources suivantes :

*****Ces sources sont également excellentes pour en savoir plus sur les puits, les sources de contamination ainsi que sur la qualité de l’eau**

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Notes importantes

Les idées présentées dans ce rapport sont des suggestions qui pourraient améliorer la qualité de l'eau de votre puits. Elles pourraient possiblement être utiles dans la réduction du nombre de coliformes mais ne résoudront pas nécessairement le problème général. Nous avons fait notre possible pour évaluer la source probable de contamination, mais plusieurs facteurs peuvent affecter la qualité de l'eau d'un puits. Ce rapport a pour but de vous aider à comprendre votre puits et n'inclut pas toutes les conclusions de l'étude. Ces suggestions doivent être considérées avec prudence.

Avant d'investir dans votre puits (amélioration du puits ou système de traitement de l'eau) il serait important de demander l'avis d'un professionnel certifié et de faire analyser votre eau par un laboratoire indépendant.

Merci beaucoup pour votre compréhension.

Pascale St-Germain
Candidate au doctorat
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Glossaire

Roc Précambrien : Socle rocheux composé de roches ignées et métamorphiques datant de plus de 542 Millions d'années

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Représentation schématique d'un puits domestique

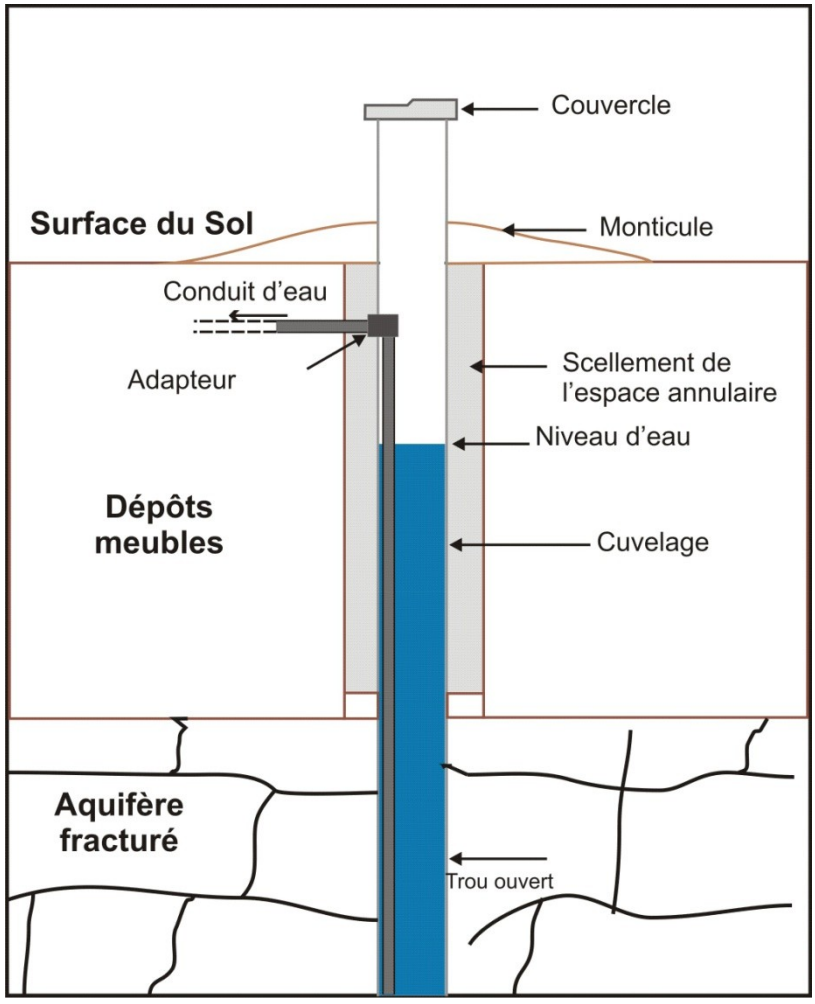


Image modifiée de : *Pratiques de gestion optimale-Les puits*

Introduction

L'objectif de ce projet est d'améliorer nos connaissances en ce qui a trait à la contamination des puits d'eau potable résultant de l'infiltration des eaux de surfaces. Notre but est d'évaluer le risque de contamination des puits forés en se basant sur les caractéristiques du site et sur la construction du puits.

En effectuant une analyse bactériologique mensuelle, il fut possible d'avoir une meilleure idée sur la saisonnalité de la contamination. L'analyse chimique de l'eau fût utilisée pour comprendre l'évolution des eaux souterraines et pour effectuer un lien avec une source possible de contamination.

L'objectif de ce rapport est de vous sensibiliser à la qualité de l'eau de votre puits et aux mesures existantes pour préserver ou améliorer sa qualité. Ce rapport présente un sommaire des travaux effectués, les principaux résultats ainsi que quelques suggestions, si nécessaire.

Description du site

Votre puits est foré dans le roc précambrien sur lequel repose une mince couche de dépôts meubles, principalement composés de sable, silt et argile déposés lors de la dernière glaciation, il y a environ 10 000 ans. La profondeur du puits est d'environ 36 mètres et le niveau de l'eau est situé à 5 mètres de la surface du sol.

L'eau de votre puits provient d'un aquifère. Un aquifère peut être défini comme une unité géologique capable de contenir et de transmettre de l'eau. Cet aquifère est également considéré comme étant « libre » car il n'est pas recouvert d'une couche imperméable. Ce type d'aquifère est généralement plus vulnérable à la contamination car il n'y a pas de couche imperméable protégeant naturellement l'aquifère des contaminants de surface.

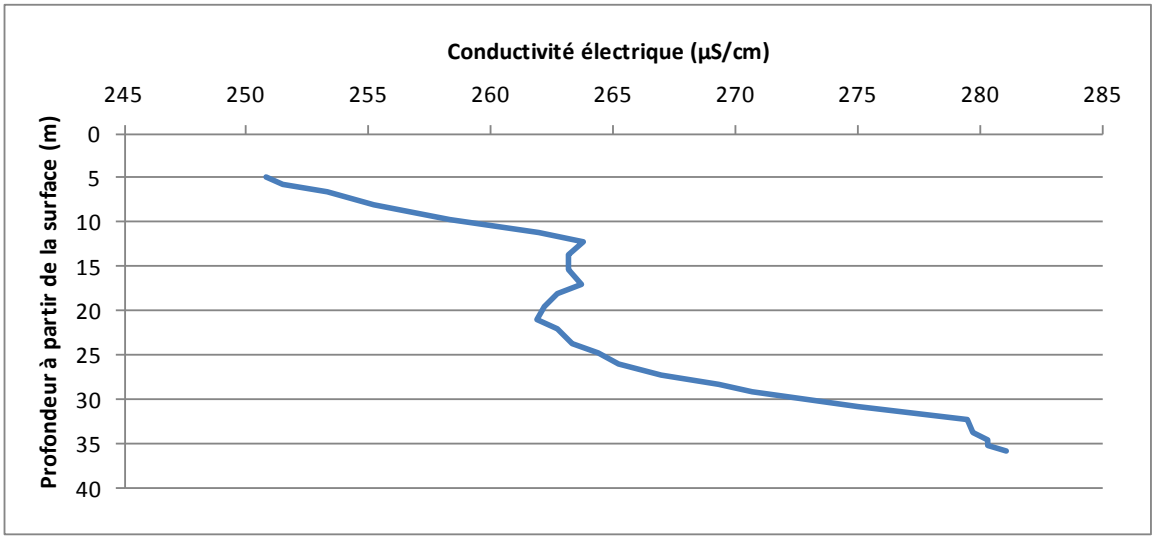


Figure 1: Profil de conductivité électrique de la colonne d'eau dans le puits

La figure ci-dessus représente un profil de conductivité électrique de la colonne d'eau de votre puits. La conductivité électrique est une mesure des composantes dissoutes dans l'eau. Le niveau d'eau est situé à environ 5 mètres sous la surface du sol. La conductivité électrique varie entre 250 et 280 µS/cm, ce qui indique une qualité de l'eau excellente. Il semble que la conductivité électrique augmente en profondeur. Cependant, il est à noter que l'écart de conductivité électrique de l'eau entre la surface et la profondeur est du même ordre de grandeur que l'incertitude sur la mesure.

Analyse bactériologique

Les bactéries sont naturellement présentes dans les eaux de surface et dans les sols. Elles sont transportées dans les eaux souterraines par le processus d'infiltration. Plusieurs facteurs affectent le mouvement des bactéries. Ces facteurs peuvent être reliés aux bactéries (type, taille, dynamique de la population) ou aux caractéristiques du sol (physique, chimique ou biologique). La plupart des bactéries sont filtrées dans le premier horizon du sol mais la présence de « macro-pores » peut contribuer au mouvement des bactéries en profondeur. Les macro-pores sont en fait des pores de grandes dimensions formées par l'activité biologique, les racines ou bien des fissures dans un milieu argileux.

Ces macro-pores affectent la capacité du sol à filtrer les bactéries, ce qui leur permet de pénétrer plus profondément et rapidement.

La contamination bactérienne dans un puits peut provenir de plusieurs sources. Dans une municipalité comme Chelsea, où l'agriculture n'est que localisée et quasi-inexistante, la construction d'un puits (type, âge et profondeur), son emplacement, la distance au système septique ainsi que des facteurs reliés à la géologie sont les principales sources contribuant à la présence de bactéries dans un puits.

La présence de coliformes totaux n'a pas été détectée lors de la période de collecte. La présence de coliformes fécaux n'a pas été détectée dans les échantillons prélevés.

Vous avez observé la présence d'un certain résidu noir dans le tuyau de la laveuse. Si le résidu est gélatineux, il est possible qu'il indique la présence de bactéries oxydantes de fer/manganèse dans le puits (*thiobacillus ferrooxydans)*. Ce type de bactéries ne faisait pas partie de l'analyse bactériologique. La présence de résidus rougeâtres dans le réservoir de la toilette confirmerait cette hypothèse. Si c'est le cas il est possible que la communauté de bactéries soit bien installée dans le puits et l'aquifère. Un traitement sous pression au chlore est alors une solution à envisager. Par contre, cette solution n'est que temporaire. Ce traitement est effectué par des professionnels car le chlore doit être injecté sous pression pour désinfecter le puits et l'aquifère. Ce problème s'appelle « biofouling » (désolée je ne connais pas le terme francophone). Il peut être le résultat d'un puits sous l'influence d'eau de surface ou bien le résultat d'un rabattement important (le rabattement est la diminution du niveau de l'eau lors du pompage). Un rabattement important introduit de l'air dans le puits favorisant la précipitation du fer/manganèse et la formation de substances gélatineuses sur la pompe et les tuyaux.

Il est important de noter que le résidu que vous avez observé n'indique pas nécessairement la présence de bactérie. Il est possible que le résidu soit le résultat de la précipitation du fer/manganèse provenant de la corrosion du cuvelage. Les analyses chimiques ont démontré des concentrations d'environ 0.08 mg/L de manganèse alors que les concentrations de fer étaient sous les limites de détection (ces concentrations ne sont qu'approximatives car les échantillons n'ont pas été acidifiés sur place. Il est possible que ces minéraux aient précipités réduisant ainsi leurs concentrations). Donc le résidu noir

pourrait être le résultat d'accumulation de précipités de manganèse sur le filtre. La couleur orange proviendrait alors de l'oxydation du précipité par l'exposition à l'air.

Analyse Chimique

Naturellement, l'eau dissout les minéraux lorsqu'elle s'écoule dans le sol. Le processus de dissolution est habituellement lent dans la roche Précambrienne comparativement aux jeunes roches sédimentaires telles le grès ou la calcite. Des sources anthropogéniques, telles l'épandage de sels routiers, les fertilisants et les systèmes septiques peuvent également contribuer à la teneur en minéraux dissouts dans les eaux souterraines.

Les échantillons d'eau furent analysés à l'université d'Ottawa pour identifier diverses composantes dissoutes. Les résultats sont présentés dans le tableau suivant. Ce tableau donne également la moyenne annuelle ainsi que les lignes directrices relatives à certains paramètres. Les concentrations sont mesurées en milligrammes par litre (mg/L).

Mois	pH	Fluorure (mg/L)	Chlorure (mg/L)	Nitrate -N (mg/L)	Sulfate (mg/L)	Calcium (mg/L)	Magnésium (mg/L)	Sodium (mg/L)	Dureté (mg/L de $CacO_3$)
Avril 08	7.3	1.2	17.4	bdl	23.6	67.1	8.8	6.6	204.0
Mai 08	7.5	1.1	23.2	bdl	25.6	70.9	9.2	6.7	215.3
Juin 08	7.5	1.1	30.0	bdl	29.1	69.0	8.7	6.9	208.5
Juillet 08	7.1	1.1	23.6	bdl	24.6	64.9	8.7	7.0	198.1
Août 08	7.3	1.0	27.8	bdl	27.6	36.3	9.1	6.3	128.2
Septembre 08	7.5	0.8	5.4	bdl	8.3	19.9	3.1	3.6	62.7
Octobre 08	7.2	1.2	22.4	bdl	27.5	65.4	8.5	7.9	198.3
Novembre 08	7.1	1.3	27.9	bdl	26.3	66.5	8.7	12.7	201.9
Décembre 08	7.2	1.3	16.2	bdl	25.1	64.7	8.6	7.3	197.2
Janvier 09	7.1	1.3	15.3	bdl	24.8	61.3	8.3	6.5	187.6
Février 09	6.9	1.3	17.8	bdl	28.3	63.9	8.6	7.8	195.2
Mars 09	7.1	1.3	14.6	bdl	23.9	61.5	8.2	6.5	187.7
Avril 09	6.9	1.3	16.6	bdl	24.2	56.9	8.2	7.5	175.9
Mai 09	6.9	1.3	21.2	bdl	24.2	60.8	8.7	6.3	188.0
Moyenne	7.2	1.2	20.0		24.5	59.2	8.3	7.1	182.0
Ligne directrice		1.5 CMP	250.0 OE	10.0 CMP	500.0 OE			20.0 OE	100 LDO

LDP = Ligne directrice opérationnelle
CMP= Concentration Maximale Permise
OE= Objectif Esthétique
Bdl= Sous limite de détection

Les paramètres mesurés lors de notre étude sont des indicateurs de la qualité de l'eau. Il est important de considérer que dans certain cas, leur présence n'a pas nécessairement un impact sur la santé. Le tableau décrit certain de ces paramètre ainsi que ce que les effets possible de leur présence.

Paramètres mesurés	Définitions/Sources	Effets possibles
pH	Mesure de l'acidité de l'eau	• Une eau acide (pH<6.5) peut avoir un effet corrosif
Fluorure	Présence naturelle	• Affecte la dentition des enfants • Des concentrations très élevées peuvent affecter le développement des os
Chlorure	Présence naturelle ou causée par l'activité humaine	• Effet corrosif sur la plomberie • Goût salé
Nitrates	Fertilisants, système septique	• Effets sur la santé
Sulfates	Présence naturelle ou causée par l'activité humaine	• L'eau à un effet laxatif
Sodium	Présence naturelle ou causée par l'activité humaine	• Hypertension (personne à risque)
Dureté	Causée par la présence de Calcium et Magnésium dans l'eau	• Aucun effet sur la santé • Réduit l'efficacité des savons • Effets sur la tuyauterie (dépôts et blocage) • Tache et salie le linge

Sources : Pratiques de gestion optimale-Les puits

Recommandations pour la qualité de l'eau potable au Canada

Catégorie	Concentration de carbonate de Calcium (mg/L)
Eau Douce	0 à <60
Eau modérément dure	60 à <120
Eau dure	120 à <180
Eau très dure	180 et plus

Source : Santé Canada

Sommaire et suggestions

Source possible de contamination

L'analyse bactériologique de l'eau de votre puits est bonne en ce qui concerne les coliformes totaux et fécaux. Il est possible que la présence des bactéries causant les résidus noirs résulte d'infiltration d'eau de surface dans l'aquifère. Les caractéristiques du site (mince couche de sol) ainsi que la construction du puits (absence possible de matériel imperméable dans l'espace annulaire, corrosion du cuvelage) peuvent être des facteurs affectant l'infiltration d'eau de surface.

Analyse chimique

Tous les paramètres respectent les lignes directrices à l'exception de la concentration de la dureté. La moyenne annuelle est de 186 mg/L de $CaCO_3$ alors que ligne directrice opérationnelle est de 100 mg/L de $CaCO_3$. L'eau est donc considérée comme dure.

Suggestions

- Un bon couvercle devrait garder les insectes hors du puits. Lors de notre dernière visite, il nous fut impossible de vérifier la présence d'insectes dans le couvercle. Il est donc recommandé de vérifier l'intérieur et de s'assurer que le couvercle soit étanche aux insectes mains non à l'air.
- L'espace annulaire pourrait être une voie préférentielle à la l'infiltration d'eau de surface. Il est donc important de réduire le ruissellement vers le puits. Pour ce faire, il est recommandé d'élever le sol à la tête du puits, ce qui évitera l'eau de ruissellement de s'accumuler et s'infiltrer à cet endroit.
- Il est important de faire un suivi continu sur l'état de votre puits. Une fois l'an, vous devriez regarder dans le puits avec une lampe de poche. Recherchez la présence de fissures et de trous dans le cuvelage et près de l'embranchement des tuyaux vers la maison. Prenez des notes et comparez au fil des ans. Des mesures correctives peuvent être entreprises, par un puisatier, si un problème est détecté.

- L'installation d'un système de traitement du fer à l'air (et non au permanganate) pourrait être une solution pour atténuer la présence de manganèse. Comme les systèmes de traitement de l'eau sont assez dispendieux, il serait important d'effectuer une analyse chimique de l'eau par un laboratoire indépendant et de consulter un professionnel avant d'investir dans un système.
- Il est recommandé de faire une analyse bactériologique au moins 1 fois par année, et à l'occasion, notamment après une pluie importante et la fonte des neiges.

L'information présentée dans ce rapport provient des sources suivantes :

*****Ces sources sont également excellentes pour en savoir plus sur les puits, les sources de contamination ainsi que sur la qualité de l'eau**

Conboy M.J, Smith S., 2005. A comprehensive consumer's guide for private water wells ISBN 0-9780387-0-3
www.wellwise.ca

Recommandations pour la qualité de l'eau potable au Canada -La dureté
http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/hardness-durete/index-fra.php

Ministère du développement durable, environnement et parcs- *La qualité de l'eau de mon puits*
http://www.mddep.gouv.qc.ca/eau/potable/depliant/index.htm

Publications : Ministère de l'agriculture, de l'alimentation et des affaires rurales (Ontario)
http://www.omafra.gov.on.ca/french/environment/water/publications.htm

Ministère de la santé et des soins de longue durée
http://www.health.gov.on.ca/english/public/pub/watersafe/watersafe_wellknow.html

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Sciences de la Terre Earth Sciences

Étude sur la contamination des puits domestiques
Municipalité de Chelsea, Québec



Rapport présenté à :
W23
Chelsea, QC

Rapport préparé par :
Pascale St-Germain
Candidate au doctorat
Université d'Ottawa

Mai 2010

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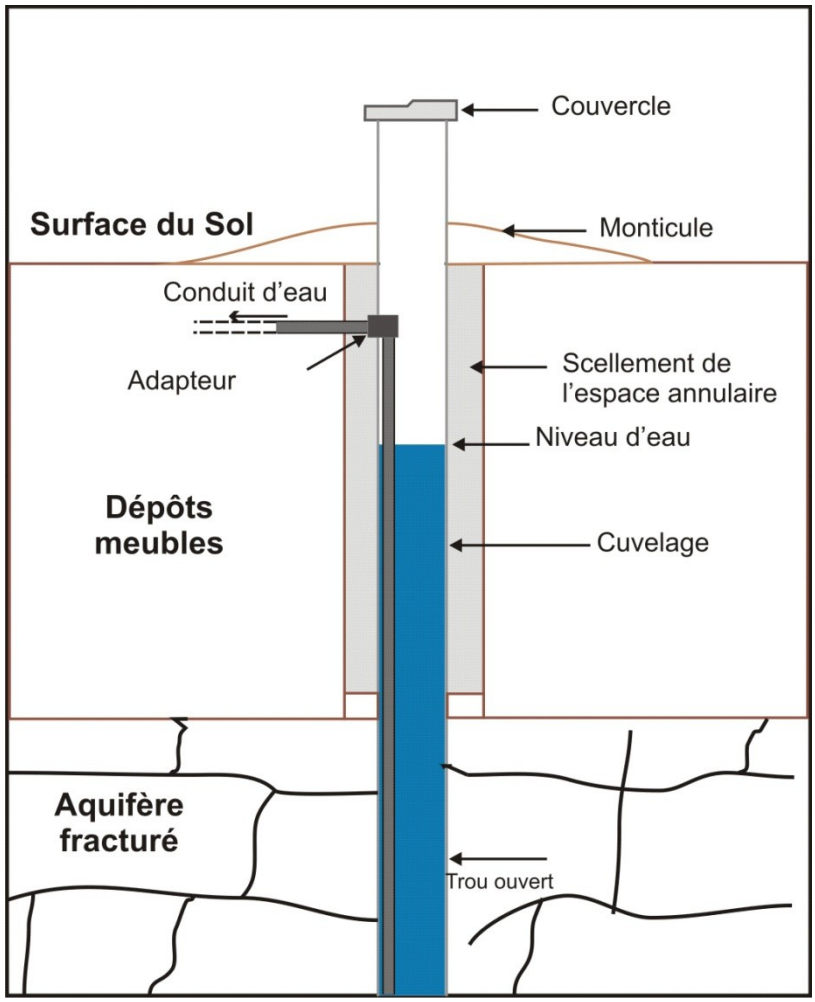


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L'objectif de ce rapport est de vous sensibiliser à la qualité de l'eau de votre puits et aux mesures existantes pour préserver ou améliorer sa qualité. Ce rapport présente un sommaire des travaux effectués, les principaux résultats ainsi que quelques suggestions, si nécessaire.

Description du site

Votre puits est foré dans le roc précambrien sur lequel repose une épaisse couche d'argile. Cette couche que l'on nomme couche de confinement, d'une dizaine de mètre d'épaisseur ou plus, s'est déposée lors de la dernière glaciation (environ 10 000 ans), lorsque la Mer de Champlain recouvrait partiellement la région. La profondeur du puits est d'environ 54 mètres et le niveau de l'eau est situé à 34 mètres de la surface du sol.

L'eau de votre puits provient d'un aquifère. Un aquifère peut être défini comme une unité géologique capable de contenir et de transmettre de l'eau. Cet aquifère est également considéré comme étant « captif » car il est recouvert d'une couche imperméable. Ce type d'aquifère est généralement moins vulnérable à la contamination car la couche de confinement (l'argile) est imperméable et protège naturellement l'aquifère des contaminants de surface.

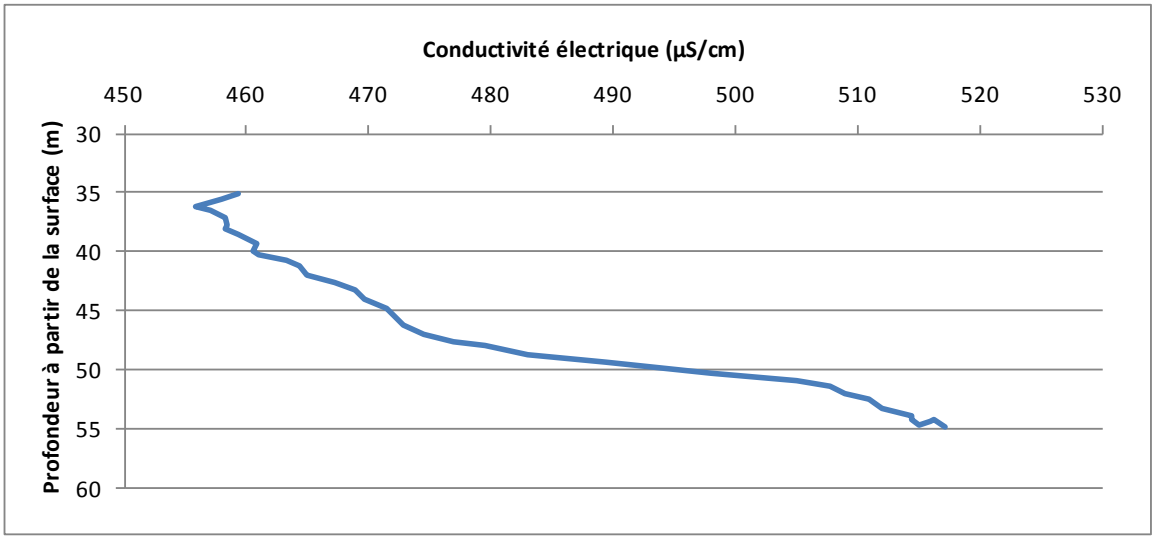


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Sommaire de la technique

Deux méthodes sont utilisées pour évaluer le statut du scellement de tubage :

1. La première a mesuré la conductivité hydraulique (K) autour du puits et permet de vérifier si l'eau s'infiltre plus facilement autour du puits que dans les surfaces environnantes. Un test statistique compare les valeurs mesurées. Si la valeur de K autour du puits est significativement plus grande que celles des alentours, le scellement de tubage est potentiellement fautif.

2. La seconde méthode consiste à injecter une solution saline (NaCl) lors des essais d'infiltration au puits. Un suivi quotidien de la conductivité électrique dans la colonne d'eau du puits est effectué pour déceler la présence du traceur, laquelle démontrerait, le cas échéant, la présence d'un court-circuit hydraulique, ce qui signifie que les eaux de surface peuvent s'infiltrer en ruisselant sur le tubage du puits.

Résultats

1. Comparaison des conductivités hydrauliques (K)

Les essais d'infiltration ont été effectués les 29 et 30 juin 2008. La conductivité hydraulique (K) mesurée au puits est plus grande que celle mesurée dans les environs. En langage statistique, cette différence n'est que « marginalement significative », ce qui signifie que cette technique démontre un scellement potentiellement fautif. L'essai de traçage avait pour but de corroborer ou de démentir cette affirmation.

2. Essai de traçage

L'injection du traceur s'est effectuée le 30 juin. L'essai n'est pas concluant dû à un léger malfonctionnement du système d'injection du traceur : une faible quantité de traceur s'est infiltrée directement par la tête du puits, ce qui fausse les résultats. Il est donc impossible de vérifier les résultats de la comparaison des conductivités hydrauliques à l'aide de l'essai de traçage.

Analyse bactériologique

Les bactéries sont naturellement présentes dans les eaux de surface et dans les sols. Elles sont transportées dans les eaux souterraines par le processus d'infiltration. Plusieurs facteurs affectent le mouvement des bactéries. Ces facteurs peuvent être reliés aux bactéries (type, taille, dynamique de la population) ou aux caractéristiques du sol

(physique, chimique ou biologique). La plupart des bactéries sont filtrées dans le premier horizon du sol mais la présence de « macro-pores » peut contribuer au mouvement des bactéries en profondeur. Les macro-pores sont en fait des pores de grandes dimensions formées par l'activité biologique, les racines ou bien des fissures dans un milieu argileux. Ces macro-pores affectent la capacité du sol à filtrer les bactéries, ce qui leur permet de pénétrer plus profondément et rapidement.

La contamination bactérienne dans un puits peut provenir de plusieurs sources. Dans une municipalité comme Chelsea, où l'agriculture n'est que localisée et quasi-inexistante, la construction d'un puits (type, âge et profondeur), son emplacement, la distance au système septique ainsi que des facteurs reliés à la géologie sont les principales sources contribuant à la présence de bactéries dans un puits.

La figure ci-dessous présente les résultats de l'analyse bactériologique sous forme de graphique. On remarque trois dépassements, pour les coliformes totaux, au cours de la période d'échantillonnage. La présence de coliformes fécaux n'a jamais été détectée dans les échantillons prélevés.

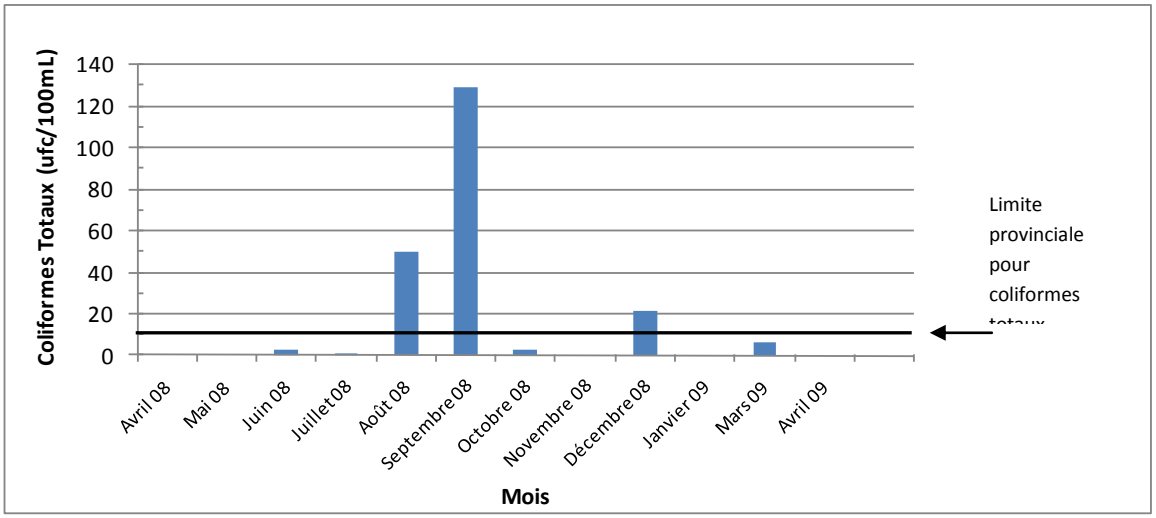


Figure 2: Résultats des analyses bactériologiques (coliformes totaux) des échantillons d'avril 2008 à mai 2009.

Analyse Chimique

Naturellement, l'eau dissout les minéraux lorsqu'elle s'écoule dans le sol. Le processus de dissolution est habituellement lent dans la roche Précambrienne comparativement aux jeunes roches sédimentaires telles le grès ou la calcite. Des sources anthropogéniques, telles l'épandage de sels routiers, les fertilisants et les systèmes septiques peuvent également contribuer à la teneur en minéraux dissouts dans les eaux souterraines.

Les échantillons d'eau furent analysés à l'université d'Ottawa pour identifier diverses composantes dissoutes. Les résultats sont présentés dans le tableau suivant. Ce tableau donne également la moyenne annuelle ainsi que les lignes directrices relatives à certains paramètres. Les concentrations sont mesurées en milligrammes par litre (mg/L).

Mois	pH	Fluorure (mg/L)	Chlorure (mg/L)	Nitrate -N (mg/L)	Sulfate (mg/L)	Calcium (mg/L)	Magnésium (mg/L)	Sodium (mg/L)	Dureté (mg/L de $CaCO_3$)
Avril 08	8.3	2.4	11.8	bdl	23.6	9.2	8.0	123.9	56.1
Mai 08	8.4	2.0	10.1	bdl	19.7	9.6	8.8	122.2	59.9
Juin 08	8.4	2.5	12.3	bdl	24.7	8.7	6.9	105.7	50.2
Juillet 08	8.1	2.7	12.2	bdl	24.9	8.2	7.4	119.2	51.0
Août 08	8.4	2.4	7.0	bdl	13.2	8.1	7.1	113.2	49.2
Septembre 08	8.3	1.3	1.0	bdl	2.4	7.0	5.1	83.3	38.4
Octobre 08	8.0	2.7	12.5	bdl	24.9	8.9	7.6	128.3	53.6
Novembre 08	8.0	1.5	6.7	bdl	11.3	8.6	7.4	120.0	51.9
Décembre 08	8.0	2.7	12.7	bdl	25.3	9.0	7.7	125.4	54.1
Janvier 09	8.1	2.6	13.9	bdl	24.8	8.8	7.8	117.7	54.1
Mars 09	7.3	2.6	12.5	bdl	25.7	9.2	7.6	117.7	54.5
Avril 09	7.7	2.7	13.1	bdl	26.7	8.6	7.4	109.8	51.9
Mai 09	7.8	2.8	13.3	bdl	26.6	8.1	7.3	111.9	50.5
Moyenne	8.1	2.4	10.7		21.1	8.6	7.4	115.3	52.0
Ligne directrice		1.5 CMP	250.0 OE	10.0 CMP	500.0 OE			20.0 OE	100.0 LDO

LDP = Ligne directrice opérationnelle
CMP= Concentration Maximale Permise
OE= Objectif Esthétique
Bdl= Sous limite de détection

Les paramètres mesurés lors de notre étude sont des indicateurs de la qualité de l'eau. Il est important de considérer que dans certain cas, leur présence n'a pas nécessairement un impact sur la santé. Le tableau décrit certain de ces paramètre ainsi que ce que les effets possible de leur présence.

Paramètres mesurés	Définitions/Sources	Effets possibles
pH	Mesure de l'acidité de l'eau	• Une eau acide (pH<6.5) peut avoir un effet corrosif
Fluorure	Présence naturelle	• Affecte la dentition des enfants • Des concentrations très élevées peuvent affecter le développement des os
Chlorure	Présence naturelle ou causée par l'activité humaine	• Effet corrosif sur la plomberie • Goût salé
Nitrates	Fertilisants, système septique	• Effets sur la santé
Sulfates	Présence naturelle ou causée par l'activité humaine	• L'eau à un effet laxatif
Sodium	Présence naturelle ou causée par l'activité humaine	• Hypertension (personne à risque)
Dureté	Causée par la présence de Calcium et Magnésium dans l'eau	• Aucun effet sur la santé • Réduit l'efficacité des savons • Effets sur la tuyauterie (dépôts et blocage) • Tache et salie le linge

Sources : Pratiques de gestion optimale-Les puits

Recommandations pour la qualité de l'eau potable au Canada

Catégorie	Concentration de carbonate de Calcium (mg/L)
Eau Douce	0 à <60
Eau modérément dure	60 à <120
Eau dure	120 à <180
Eau très dure	180 et plus

Source : Santé Canada

Sommaire et suggestions

Intégrité du scellement de tubage

L'eau s'infiltre un peu plus rapidement autour de puits que dans les surfaces avoisinantes. Il est donc possible que l'espace annulaire soit une voie préférentielle à l'infiltration d'eau de surface. Par contre, il s'avère impossible d'utiliser les résultats de l'essai de traçage dans l'analyse du statu du scellement de tubage.

Source possible de contamination

Il semblerait que les coliformes totaux soient présents en nombre plus important lors de période de fortes précipitations. Il est possible que des fissures soient présentes dans l'argile. Ces fissures peuvent être un facteur à l'infiltration d'eau de surface.

Analyse chimique

Tous les paramètres respectent les lignes directrices à l'exception des concentrations de fluorure et de sodium. Pour le fluorure, la moyenne annuelle est 2.4 mg/L alors que la concentration maximale permise est de 1.5 mg/L. Alors que pour le sodium, la moyenne annuelle est de 115 mg/L ce qui est plus élevé que l'objectif esthétique.

Suggestions

- L'espace annulaire étant une voie préférentielle à la contamination, il est important de réduire le ruissellement vers le puits. Pour ce faire, il est recommandé d'élever le sol à la tête du puits, ce qui évitera l'eau de ruissellement de s'accumuler et s'infiltrer à cet endroit.
- Un bon couvercle devrait garder les insectes hors du puits. Même si aucun insecte ne fut détecté à l'intérieur, il est donc recommandé de vérifier l'intérieur et de s'assurer que le couvercle soit assez étanche pour ne pas laisser entrer les insectes, mais assez dégagé pour laisser passer l'air. Ceci pourrait prévenir le nombre de coliformes totaux dans le puits.

- Il est important de faire un suivi continu sur l'état de votre puits. Une fois l'an, vous devriez regarder dans le puits avec une lampe de poche. Recherchez la présence de fissures et de trous dans le cuvelage et près de l'embranchement des tuyaux vers la maison. Prenez des notes et comparez au fil des ans. Des mesures correctives peuvent être entreprises, par un puisatier, si un problème est détecté.
- Il est recommandé de faire une analyse bactériologique au moins 1 fois par année, et à l'occasion, notamment après une pluie importante et la fonte des neiges.
- Finalement, il serait impératif de faire installer un système de stérilisation de l'eau, tel les systèmes aux rayons ultra-violets.

L'information présentée dans ce rapport provient des sources suivantes :

*****Ces sources sont également excellentes pour en savoir plus sur les puits, les sources de contamination ainsi que sur la qualité de l'eau**

Conboy M.J, Smith S., 2005. A comprehensive consumer's guide for private water wells ISBN 0-9780387-0-3
www.wellwise.ca

Recommandations pour la qualité de l'eau potable au Canada -La dureté
http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/hardness-durete/index-fra.php

Ministère du développement durable, environnement et parcs- *La qualité de l'eau de mon puits*
http://www.mddep.gouv.qc.ca/eau/potable/depliant/index.htm

Publications : Ministère de l'agriculture, de l'alimentation et des affaires rurales (Ontario)
http://www.omafra.gov.on.ca/french/environment/water/publications.htm

Ministère de la santé et des soins de longue durée
http://www.health.gov.on.ca/english/public/pub/watersafe/watersafe_wellknow.html

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Faculté des sciences Faculty of Science
Sciences de la Terre Earth Sciences

Étude sur la contamination des puits domestiques Municipalité de Chelsea, Québec



Rapport présenté à :
W24
Chelsea, QC

Rapport préparé par :
Pascale St-Germain
Candidate au doctorat
Université d'Ottawa

Mai 2010

Remerciements

Merci d'avoir participé à cette étude. Vos efforts furent importants dans l'avancement de notre compréhension sur les voies préférentielles de contamination des puits. Nous sommes très reconnaissants pour nous avoir donné l'accès à votre propriété, pour votre hospitalité ainsi que votre aide dans le prélèvement mensuel des échantillons.

Notes importantes

Les idées présentées dans ce rapport sont des suggestions qui pourraient améliorer la qualité de l'eau de votre puits. Elles pourraient possiblement être utiles dans la réduction du nombre de coliformes mais ne résoudront pas nécessairement le problème général. Nous avons fait notre possible pour évaluer la source probable de contamination, mais plusieurs facteurs peuvent affecter la qualité de l'eau d'un puits. Ce rapport a pour but de vous aider à comprendre votre puits et n'inclut pas toutes les conclusions de l'étude. Ces suggestions doivent être considérées avec prudence.

Avant d'investir dans votre puits (amélioration du puits ou système de traitement de l'eau) il serait important de demander l'avis d'un professionnel certifié et de faire analyser votre eau par un laboratoire indépendant.

Merci beaucoup pour votre compréhension.

Pascale St-Germain
Candidate au doctorat
Université d'Ottawa
Département des Sciences de la Terre

Glossaire

Roc Précambrien :	Socle rocheux composé de roches ignées et métamorphiques datant de plus de 542 Millions d'années
Dépôts meubles :	Sédiments non consolidés recouvrant le socle rocheux
Mer de Champlain :	Mer créée lors de la fonte du Glacier *Inlandsis laurentidien*, il y a environ 10 000 ans, submergeant principalement la région de Montréal et une partie du sud-est ontarien.
Voies préférentielles :	Présence de macro pores favorisant l'écoulement de l'eau sans le potentiel atténuant du sol, permettant aux contaminants de se faire transporter plus rapidement et plus profondément
Puits foré :	Puits creusé dans le socle rocheux à l'aide d'une foreuse
Aquifère :	Unité géologique capable de contenir et de transmettre de l'eau en quantité suffisante
Aquifère captif :	Aquifère recouvert d'une couche imperméable isolant l'aquifère de la surface du sol
Aquifère libre :	Aquifère non recouvert d'une couche imperméable et exposé à la pression atmosphérique
Aquitard :	Unité géologique imperméable capable de contenir de l'eau mais incapable de la transmettre en quantité suffisante
Infiltration :	Mouvement de l'eau de la surface jusque dans le sol
Conductivité hydraulique :	Capacité d'un milieu poreux à transmettre l'eau
Conductivité électrique (EC) :	Capacité de l'eau à transmettre un courant électrique; donne une mesure du montant total des composantes dissoutes dans l'eau. L'unité de mesure de la conductivitéélectrique est le Siemens par cm (S/cm) ou microsiemens par cm (µS/cm = 10^{-6} S/cm). A titre comparatif, la EC varie de quelques dizaines de µS/cm dans le cas des eaux de pluie à quelques centaines de millier de µS/cm dans le cas des eaux salées. Dans la région de Chelsea, elle varie entre environ 80 et 1600 µS/cm.
Coliformes totaux :	Groupe de bactéries fermentant le lactose à 38°C. Ces bactéries sont présentes dans les matières fécales des humains et des animaux ainsi que dans le sol et la végétation

Coliformes fécaux :	Bactéries provenant du système digestif des humains et animaux. Indique une présence possible de pathogènes dans l'eau
Macro-pores :	Pores de grandes dimensions formées par l'activité biologique, les racines ou bien les fissures dans un milieu argileux

Représentation schématique d'un puits domestique

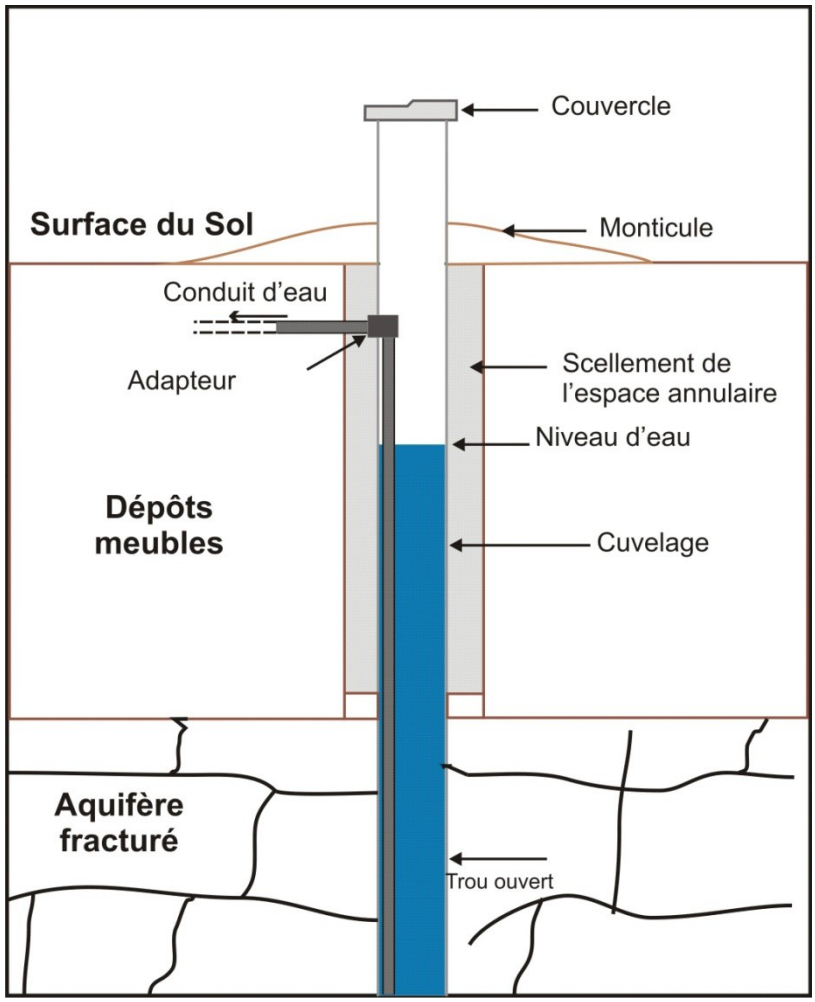


Image modifiée de : *Pratiques de gestion optimale-Les puits*

Introduction

L'objectif de ce projet est d'améliorer nos connaissances en ce qui a trait à la contamination des puits d'eau potable résultant de l'infiltration des eaux de surfaces. Notre but est d'évaluer le risque de contamination des puits forés en se basant sur les caractéristiques du site et sur la construction du puits.

En effectuant une analyse bactériologique mensuelle, il fut possible d'avoir une meilleure idée sur la saisonnalité de la contamination. L'analyse chimique de l'eau fût utilisée pour comprendre l'évolution des eaux souterraines et pour effectuer un lien avec une source possible de contamination.

L'objectif de ce rapport est de vous sensibiliser à la qualité de l'eau de votre puits et aux mesures existantes pour préserver ou améliorer sa qualité. Ce rapport présente un sommaire des travaux effectués, les principaux résultats ainsi que quelques suggestions, si nécessaire.

Description du site

Votre puits est foré dans le roc précambrien sur lequel repose une mince couche de dépôts meubles, principalement composés de sable, silt et argile déposés lors de la dernière glaciation, il y a environ 10 000 ans. La profondeur du puits est d'environ 60 mètres et le niveau de l'eau est situé à 0,5 mètres de la surface du sol.

L'eau de votre puits provient d'un aquifère. Un aquifère peut être défini comme une unité géologique capable de contenir et de transmettre de l'eau. Cet aquifère est également considéré comme étant « libre » car il n'est pas recouvert d'une couche imperméable. Ce type d'aquifère est généralement plus vulnérable à la contamination car il n'y a pas de couche imperméable protégeant naturellement l'aquifère des contaminants de surface.

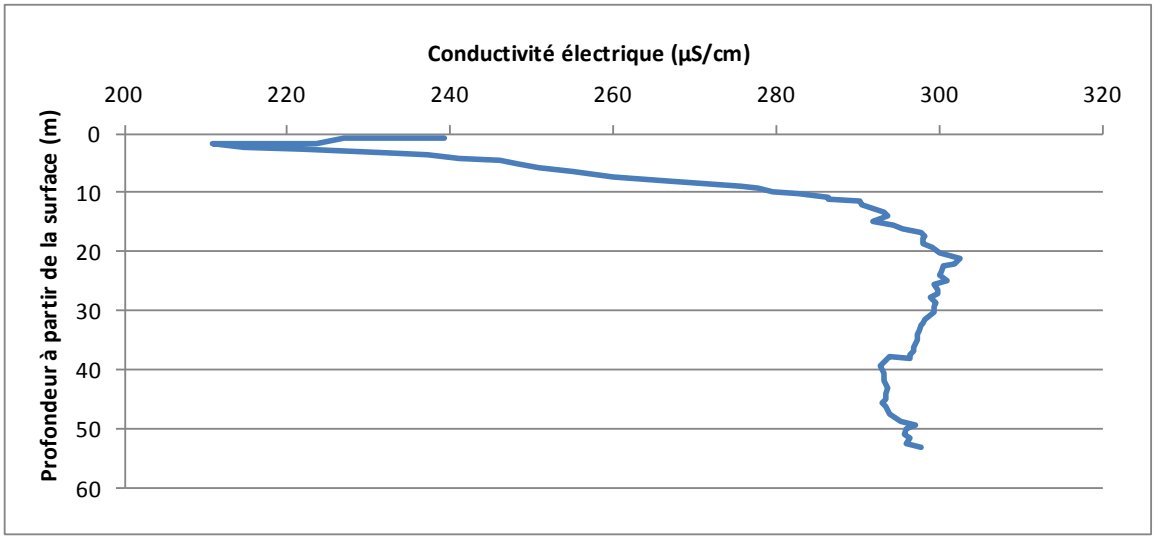


Figure 1: Profil de conductivité électrique de la colonne d'eau dans le puits

La figure ci-dessus représente un profil de conductivité électrique de la colonne d'eau de votre puits. La conductivité électrique est une mesure des composantes dissoutes dans l'eau. Le niveau d'eau est situé à environ 0.5 mètres sous la surface du sol. La conductivité électrique varie entre 210 et 300 µS/cm. Les petites variations dans le profil sont reliées aux différentes fractures alimentant le puits.

Sommaire de la méthode

Deux méthodes sont utilisées pour évaluer le statut du scellement de tubage :

1. La première a mesuré la conductivité hydraulique (K) autour du puits et permet de vérifier si l'eau s'infiltre plus facilement autour du puits que dans les surfaces environnantes. Un test statistique compare les valeurs mesurées. Si la valeur de K autour du puits est significativement plus grande que celles des alentours, le scellement de tubage est potentiellement fautif.

2. La seconde méthode consiste à injecter une solution saline (NaCl) lors des essais d'infiltration au puits. Un suivi quotidien de la conductivité électrique dans la colonne d'eau du puits est effectué pour déceler la présence du traceur,

laquelle démontrerait, le cas échéant, la présence d'un court-circuit hydraulique, ce qui signifie que les eaux de surface peuvent s'infiltrer en ruisselant sur le tubage du puits.

Résultats

1. Comparaison des conductivités hydrauliques (K)

Les essais d'infiltration ont été effectués du 23 au 25 août 2008. Le suivi s'est effectué jusqu'au 3 septembre. La conductivité hydraulique (K) mesurée au puits est plus grande que celle mesurée dans les environs. Il est donc impossible de démontrer l'existence d'un scellement efficace (au quel cas la conductivité hydraulique serait significativement plus faible au puits). Par contre, la conductivité hydraulique au puits n'est pas significativement plus grande (p=0.61) ce qui indique que cette technique démontre pas un scellement potentiellement fautif. L'essai de traçage avait pour but de corroborer ou de démentir cette affirmation.

2. Essai de traçage

L'injection du traceur s'est effectuée le 20 août. L'essai s'est déroulé en trois étapes. Pour commencer, la zone autour du puits fut saturée par l'injection d'eau du puits (environ 360L). Ensuite, un total de 360L de solution saline, avec une conductivité électrique(EC) d'environ 16 000 µS/cm, a été injecté autour du puits. Finalement, 180L d'eau de puits furent versés dans le but de pousser le traceur en profondeur. La figure suivante montre certains profils de conductivité électrique jusqu'à 9 jours après l'injection. L'arrivée du traceur, dans la colonne d'eau, commencerait quatre jours (*J4*) après son injection. Dans ce profil, la conductivité électrique augmente légèrement à une profondeur de 5.6 mètres, ce qui correspond au sabot du cuvelage (là où le tubage se termine). Cette augmentation de conductivité électrique est un peu plus évidente dans le profil représentant la colonne d'eau après cinq jours (*J5*). Finalement après neuf jours (J9) la conductivité électrique de la colonne d'eau est un peu plus élevée comparativement à celle du profil initial.

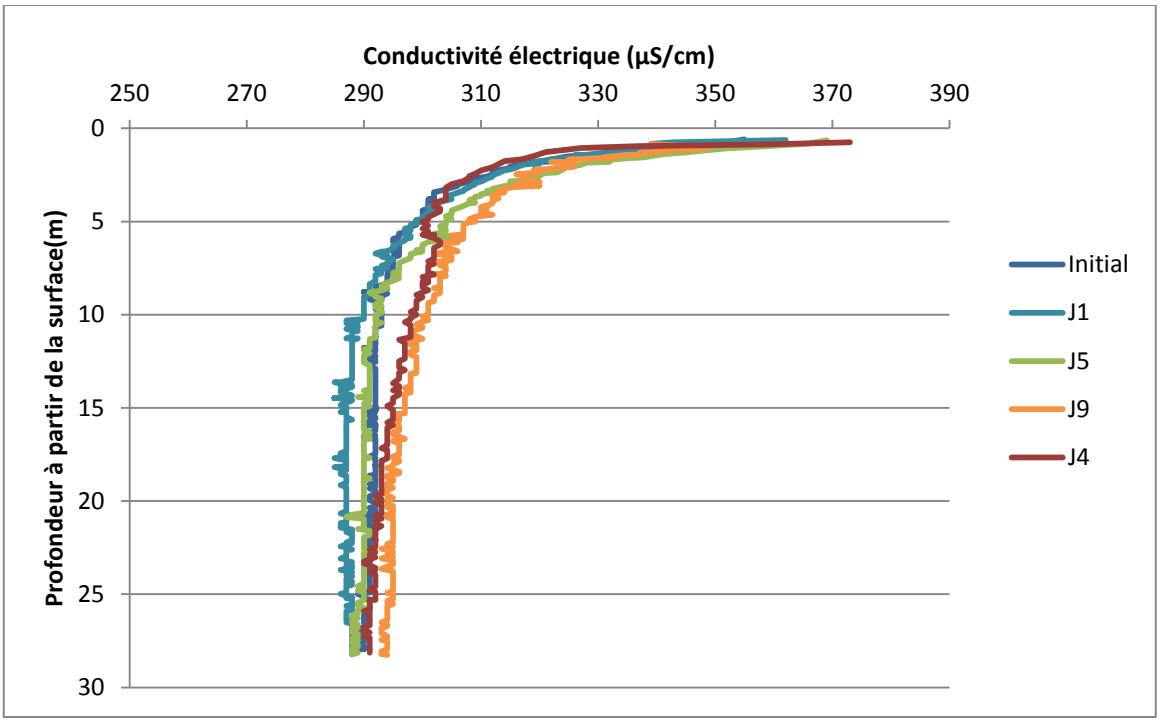


Figure 2 : Profils de conductivité électrique de la colonne d'eau jusqu'à neuf jours après l'injection de la solution saline.

Analyse bactériologique

Les bactéries sont naturellement présentes dans les eaux de surface et dans les sols. Elles sont transportées dans les eaux souterraines par le processus d'infiltration. Plusieurs facteurs affectent le mouvement des bactéries. Ces facteurs peuvent être reliés aux bactéries (type, taille, dynamique de la population) ou aux caractéristiques du sol (physique, chimique ou biologique). La plupart des bactéries sont filtrées dans le premier horizon du sol mais la présence de « macro-pores » peut contribuer au mouvement des bactéries en profondeur. Les macro-pores sont en fait des pores de grandes dimensions formées par l'activité biologique, les racines ou bien des fissures dans un milieu argileux. Ces macro-pores affectent la capacité du sol à filtrer les bactéries, ce qui leur permet de pénétrer plus profondément et rapidement.

La contamination bactérienne dans un puits peut provenir de plusieurs sources. Dans une municipalité comme Chelsea, où l'agriculture n'est que localisée et quasi-inexistante, la construction d'un puits (type, âge et profondeur), son emplacement, la distance au système septique ainsi que des facteurs reliés à la géologie sont les principales sources contribuant à la présence de bactéries dans un puits.

La figure ci-dessous présente les résultats de l'analyse bactériologique sous forme de graphique. On remarque que la présence de coliformes totaux a été détectée à quelques reprises, mais en aucun cas, n'a dépassée la limite provinciale de 10 ufc/100 mL.

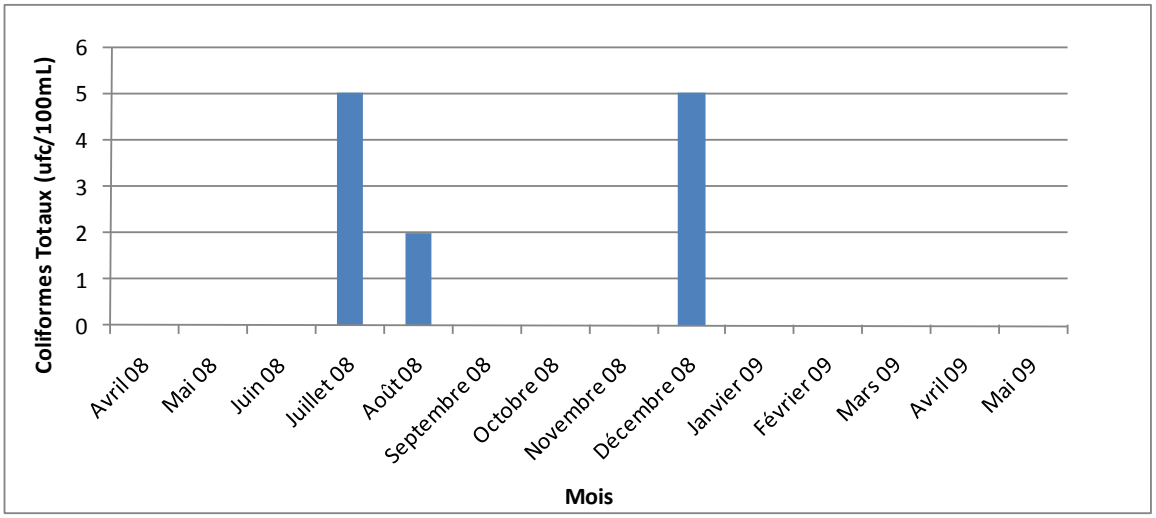


Figure 3: Résultats des analyses bactériologiques (coliformes totaux et fécaux) des échantillons d'avril 2008 à mai 2009.

Analyse Chimique

Naturellement, l'eau dissout les minéraux lorsqu'elle s'écoule dans le sol. Le processus de dissolution est habituellement lent dans la roche Précambrienne comparativement aux jeunes roches sédimentaires telles le grès ou la calcite. Des sources anthropogéniques, telles l'épandage de sels routiers, les fertilisants et les systèmes septiques peuvent également contribuer à la teneur en minéraux dissouts dans les eaux souterraines.

Les échantillons d'eau furent analysés à l'université d'Ottawa pour identifier diverses composantes dissoutes. Les résultats sont présentés dans le tableau suivant. Ce tableau donne également la moyenne annuelle ainsi que les lignes directrices relatives à certains paramètres. Les concentrations sont mesurées en milligrammes par litre (mg/L).

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Avril 08	7.0	0.6	30.6	0.4	15.4	61.8	10.8	12.4	199.1
Mai 08	6.9	bdl	30.6	bdl	15.1	60.7	10.6	12.3	195.3
Juin 08	6.9	0.7	30.1	bdl	16.1	56.6	9.5	17.7	180.8
Juillet 08	6.6	bdl	32.4	0.2	15.6	57.3	10.2	12.3	185.2
Août 08	7.1	0.5	32.1	0.1	13.6	50.1	9.7	12.6	165.3
Septembre 08	7.1	0.8	43.5	bdl	11.8	56.1	10.9	10.4	185.2
Octobre 08	9.3	bdl	6.6	bdl	2.2	7.6	2.0	1.9	27.3
Novembre 08	6.9	bdl	13.2	bdl	8.4	64.8	11.3	12.3	208.5
Décembre 08	6.9	0.8	31.4	bdl	14.9	60.2	10.9	11.5	195.0
Janvier 09	6.9	0.8	22.5	bdl	16.2	55.1	10.3	10.7	180.4
Février 09	6.8	0.8	39.5	bdl	13.1	60.2	10.9	10.1	195.6
Mars 09	6.8	0.8	34.1	bdl	16.0	58.9	10.7	10.6	191.3
Avril 09	7.0	0.8	35.0	bdl	20.7	54.8	10.5	12.0	180.3
Mai09	7.1	0.8	32.8	bdl	19.3	52.5	10.3	9.7	173.7
Moyenne	7.1	0.7	29.6	0.2	14.2	54.1	9.9	11.2	175.9
Ligne directrice		1.5 CMP	250.0 OE	10.0 CMP	500.0 OE			20.0 OE	100.0 LDO

LDP = Ligne directrice opérationnelle
CMP= Concentration Maximale Permise
OE= Objectif Esthétique
Bdl= Sous limite de détection

Les paramètres mesurés lors de notre étude sont des indicateurs de la qualité de l'eau. Il est important de considérer que dans certain cas, leur présence n'a pas nécessairement un impact sur la santé. Le tableau décrit certain de ces paramètre ainsi que ce que les effets possible de leur présence.

Paramètres mesurés	Définitions/Sources	Effets possibles
pH	Mesure de l'acidité de l'eau	• Une eau acide (pH<6.5) peut avoir un effet corrosif
Fluorure	Présence naturelle	• Affecte la dentition des enfants • Des concentrations très élevées peuvent affecter le développement des os
Chlorure	Présence naturelle ou causée par l'activité humaine	• Effet corrosif sur la plomberie • Goût salé
Nitrates	Fertilisants, système septique	• Effets sur la santé
Sulfates	Présence naturelle ou causée par l'activité humaine	• L'eau à un effet laxatif
Sodium	Présence naturelle ou causée par l'activité humaine	• Hypertension (personne à risque)
Dureté	Causée par la présence de Calcium et Magnésium dans l'eau	• Aucun effet sur la santé • Réduit l'efficacité des savons • Effets sur la tuyauterie (dépôts et blocage) • Tache et salie le linge

Sources : Pratiques de gestion optimale-Les puits

Recommandations pour la qualité de l'eau potable au Canada

Catégorie	Concentration de carbonate de Calcium (mg/L)
Eau Douce	0 à <60
Eau modérément dure	60 à <120
Eau dure	120 à <180
Eau très dure	180 et plus

Source : Santé Canada

Sommaire et suggestions

Intégrité du scellement de tubage

Malgré le fait que le taux d'infiltration autour du puits soit semblable aux surfaces avoisinantes, il semblerait qu'une connexion hydraulique, entre la surface et la colonne d'eau, existe au puits. L'essai de traçage ayant démontré cette connexion, l'espace annulaire du puits serait donc une voie préférentielle à l'infiltration des eaux de surface. Les analyses bactériologiques indiquent aussi une connexion possible.

Source de Coliformes totaux

Lors de notre passage, on a trouvé des insectes dans le couvercle. Il est possible que les coliformes totaux proviennent de la présence d'insectes dans le puits.

Analyse chimique

Tous les paramètres respectent les lignes directrices à l'exception de la dureté. La moyenne annuelle est de 176 mg/L de $CaCO_3$ alors que ligne directrice opérationnelle est de 100 mg/L de $CaCO_3$. L'eau est donc considérée comme dure.

Comme les échantillons n'ont pas été acidifiés sur place, les concentrations de fer n'ont pas été mesurées.

Recommandations

- L'espace annulaire étant une voie préférentielle à la contamination, il est important de réduire le ruissellement vers le puits. Pour ce faire, il est recommandé d'élever le sol à la tête du puits, ce qui évitera l'eau de ruissellement de s'accumuler et s'infiltrer à cet endroit.
- Un bon couvercle devrait garder les insectes hors du puits. Des évidences d'insectes furent détectées à l'intérieur, il est donc recommandé d'installé un couvercle étanche pour les insectes (mais non à l'air). Ceci pourrait réduire le nombre de coliformes totaux dans le puits.

- Il est important de faire un suivi continu sur l'état de votre puits. Une fois l'an, vous devriez regarder dans le puits avec une lampe de poche. Recherchez la présence de fissures et de trous dans le cuvelage et près de l'embranchement des tuyaux vers la maison. Prenez des notes et comparez au fil des ans. Des mesures correctives peuvent être entreprises, par un puisatier, si un problème est détecté.
- Même si la présence de coliformes dans votre puits n'est pas problématique, il est recommandé de faire une analyse bactériologique au moins 1 fois par année, et à l'occasion, notamment après une pluie importante et la fonte des neiges.

L'information présentée dans ce rapport provient des sources suivantes :

*****Ces sources sont également excellentes pour en savoir plus sur les puits, les sources de contamination ainsi que sur la qualité de l'eau**

Conboy M.J, Smith S., 2005. A comprehensive consumer's guide for private water wells ISBN 0-9780387-0-3
www.wellwise.ca

Recommandations pour la qualité de l'eau potable au Canada -La dureté
http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/hardness-durete/index-fra.php

Ministère du développement durable, environnement et parcs- *La qualité de l'eau de mon puits*
http://www.mddep.gouv.qc.ca/eau/potable/depliant/index.htm

Publications : Ministère de l'agriculture, de l'alimentation et des affaires rurales (Ontario)
http://www.omafra.gov.on.ca/french/environment/water/publications.htm

Ministère de la santé et des soins de longue durée
http://www.health.gov.on.ca/english/public/pub/watersafe/watersafe_wellknow.html

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Université d'Ottawa • University of Ottawa
Faculté des sciences Faculty of Science
Sciences de la Terre Earth Sciences

Étude sur la contamination des puits domestiques
Municipalité de Chelsea, Québec



Rapport présenté à :
W25
Chelsea, QC

Rapport préparé par :
Pascale St-Germain
Candidate au doctorat
Université d'Ottawa

Mai 2010

Remerciements

Merci d'avoir participé à cette étude. Vos efforts furent importants dans l'avancement de notre compréhension sur les voies préférentielles de contamination des puits. Nous sommes très reconnaissants pour nous avoir donné l'accès à votre propriété, pour votre hospitalité ainsi que votre aide dans le prélèvement mensuel des échantillons.

Notes importantes

Les idées présentées dans ce rapport sont des suggestions qui pourraient améliorer la qualité de l'eau de votre puits. Elles pourraient possiblement être utiles dans la réduction du nombre de coliformes mais ne résoudront pas nécessairement le problème général. Nous avons fait notre possible pour évaluer la source probable de contamination, mais plusieurs facteurs peuvent affecter la qualité de l'eau d'un puits. Ce rapport a pour but de vous aider à comprendre votre puits et n'inclut pas toutes les conclusions de l'étude. Ces suggestions doivent être considérées avec prudence.

Avant d'investir dans votre puits (amélioration du puits ou système de traitement de l'eau) il serait important de demander l'avis d'un professionnel certifié et de faire analyser votre eau par un laboratoire indépendant.

Merci beaucoup pour votre compréhension.

Pascale St-Germain
Candidate au doctorat
Université d'Ottawa
Département des Sciences de la Terre

Glossaire

Roc Précambrien : Socle rocheux composé de roches ignées et métamorphiques datant de plus de 542 Millions d'années

Dépôts meubles : Sédiments non consolidés recouvrant le socle rocheux

Mer de Champlain : Mer créée lors de la fonte du Glacier *Inlandsis laurentidien*, il y a environ 10 000 ans, submergeant principalement la région de Montréal et une partie du sud-est ontarien.

Voies préférentielles : Présence de macro pores favorisant l'écoulement de l'eau sans le potentiel atténuant du sol, permettant aux contaminants de se faire transporter plus rapidement et plus profondément

Puits foré : Puits creusé dans le socle rocheux à l'aide d'une foreuse

Aquifère : Unité géologique capable de contenir et de transmettre de l'eau en quantité suffisante

Aquifère captif : Aquifère recouvert d'une couche imperméable isolant l'aquifère de la surface du sol

Aquifère libre : Aquifère non recouvert d'une couche imperméable et exposé à la pression atmosphérique

Aquitard : Unité géologique imperméable capable de contenir de l'eau mais incapable de la transmettre en quantité suffisante

Infiltration : Mouvement de l'eau de la surface jusque dans le sol

Conductivité hydraulique : Capacité d'un milieu poreux à transmettre l'eau

Conductivité électrique (EC) : Capacité de l'eau à transmettre un courant électrique; donne une mesure du montant total des composantes dissoutes dans l'eau. L'unité de mesure de la conductivitéélectrique est le Siemens par cm (S/cm) ou microsiemens par cm (µS/cm = 10^{-6} S/cm). A titre comparatif, la EC varie de quelques dizaines de µS/cm dans le cas des eaux de pluie à quelques centaines de millier de µS/cm dans le cas des eaux salées. Dans la région de Chelsea, elle varie entre environ 80 et 1600 µS/cm.

Coliformes totaux : Groupe de bactéries fermentant le lactose à 38°C. Ces bactéries sont présentes dans les matières fécales des humains et des animaux ainsi que dans le sol et la végétation

Coliformes fécaux :	Bactéries provenant du système digestif des humains et animaux. Indique une présence possible de pathogènes dans l'eau
Macro-pores :	Pores de grandes dimensions formées par l'activité biologique, les racines ou bien les fissures dans un milieu argileux

Représentation schématique d'un puits domestique

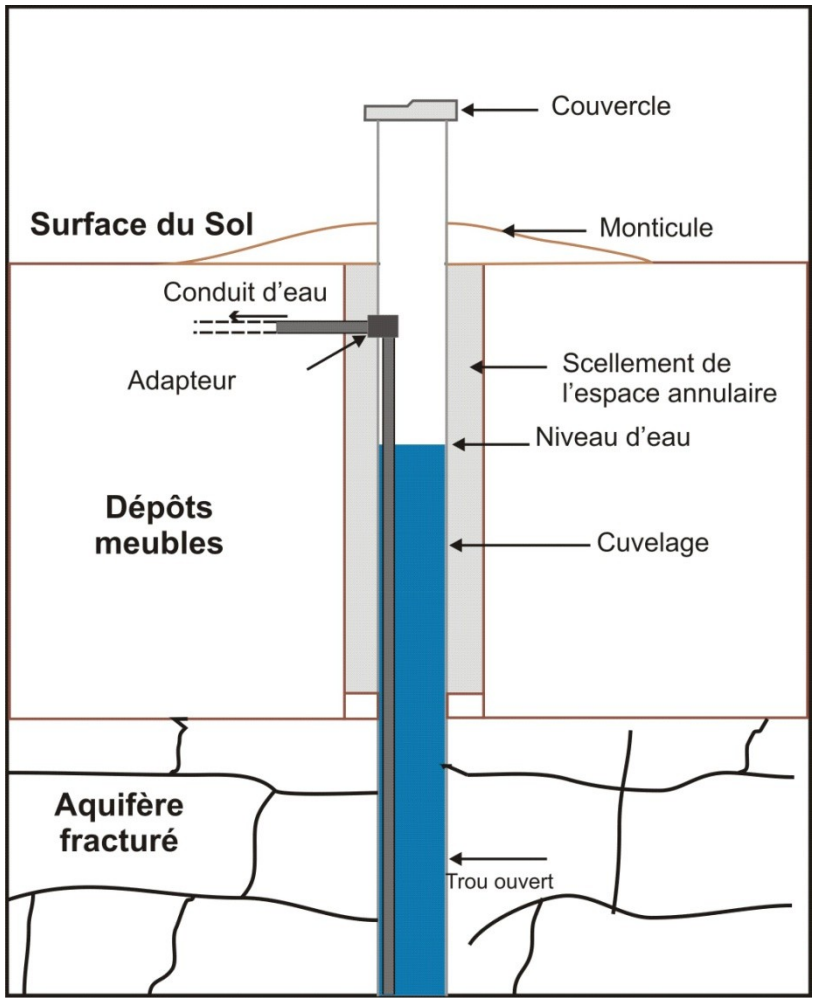


Image modifiée de : *Pratiques de gestion optimale-Les puits*

Introduction

L'objectif de ce projet est d'améliorer nos connaissances en ce qui a trait à la contamination des puits d'eau potable résultant de l'infiltration des eaux de surfaces. Notre but est d'évaluer le risque de contamination des puits forés en se basant sur les caractéristiques du site et sur la construction du puits.

En effectuant une analyse bactériologique mensuelle, il fut possible d'avoir une meilleure idée sur la saisonnalité de la contamination. L'analyse chimique de l'eau fût utilisée pour comprendre l'évolution des eaux souterraines et pour effectuer un lien avec une source possible de contamination.

L'objectif de ce rapport est de vous sensibiliser à la qualité de l'eau de votre puits et aux mesures existantes pour préserver ou améliorer sa qualité. Ce rapport présente un sommaire des travaux effectués, les principaux résultats ainsi que quelques suggestions, si nécessaire.

Description du site

Votre puits est foré dans le roc précambrien sur lequel repose une mince couche de dépôts meubles, principalement composés de sable, silt et argile déposés lors de la dernière glaciation, il y a environ 10 000 ans. La profondeur du puits est d'environ 80 mètres et le niveau de l'eau est situé à 0,5 mètres de la surface du sol.

L'eau de votre puits provient d'un aquifère. Un aquifère peut être défini comme une unité géologique capable de contenir et de transmettre de l'eau. Cet aquifère est également considéré comme étant « libre » car il n'est pas recouvert d'une couche imperméable. Ce type d'aquifère est généralement plus vulnérable à la contamination car il n'y a pas de couche imperméable protégeant naturellement l'aquifère des contaminants de surface.

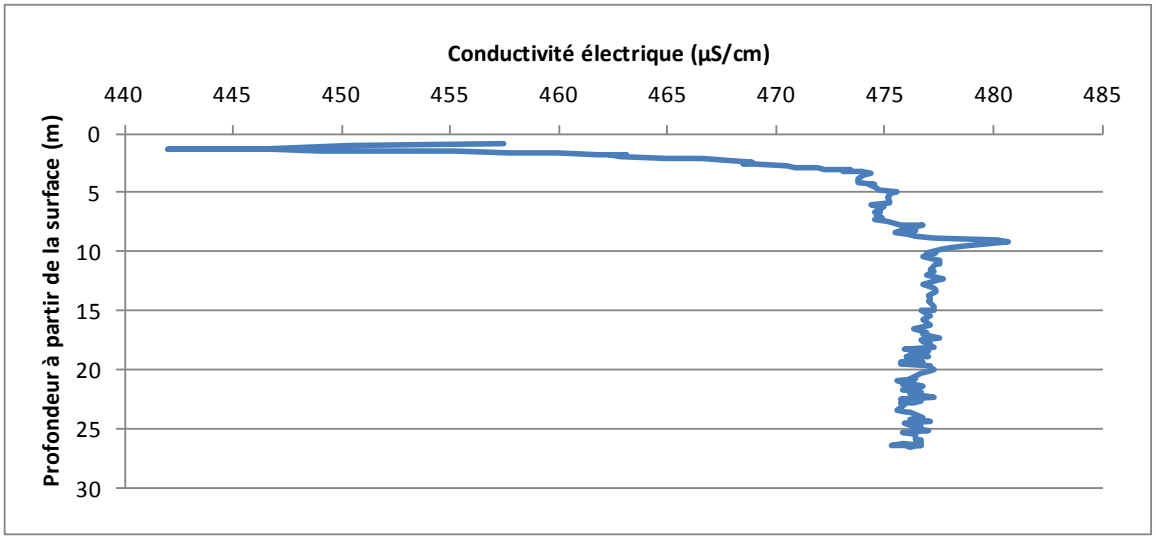


Figure 1: Profil de conductivité électrique de la colonne d'eau dans le puits

La figure ci-dessus représente un profil de conductivité électrique de la colonne d'eau de votre puits. La conductivité électrique est une mesure des composantes dissoutes dans l'eau. Le niveau d'eau est situé à environ 0.5 mètres sous la surface du sol. La conductivité électrique varie entre 440 et 480 µS/cm. Les petites variations dans le profil sont reliées aux différentes fractures alimentant le puits. Cependant, il est à noter que l'écart de conductivité électrique de l'eau entre la surface et la profondeur est du même ordre de grandeur que l'incertitude sur la mesure.

Méthode

Deux méthodes sont utilisées pour évaluer le statut du scellement de tubage :

1. La première a mesuré la conductivité hydraulique (K) autour du puits et permet de vérifier si l'eau s'infiltre plus facilement autour du puits que dans les surfaces environnantes. Un test statistique compare les valeurs mesurées. Si la valeur de K autour du puits est significativement plus grande que celles des alentours, le scellement de tubage est potentiellement fautif.

2. La seconde méthode consiste à injecter une solution saline (NaCl) lors des essais d'infiltration au puits. Un suivi quotidien de la conductivité électrique dans la colonne d'eau du puits est effectué pour déceler la présence du traceur, laquelle démontrerait, le cas échéant, la présence d'un court-circuit hydraulique, ce qui signifie que les eaux de surface peuvent s'infiltrer en ruisselant sur le tubage du puits.

Résultats

1. Comparaison des conductivités hydrauliques (K)

Les essais d'infiltration ont été effectués du 20 au 21 juillet 2008. Le suivi s'est effectué jusqu'au 30 juillet.

La conductivité hydraulique (K) mesurée au puits est plus grande que celle mesurée dans les environs. En langage statistique, cette différence est «significative », ce qui signifie que cette technique démontre un scellement potentiellement fautif. L'essai de traçage avait pour but de corroborer ou de démentir cette affirmation.

2. Essai de traçage

L'injection du traceur s'est effectuée le 21 août. L'essai s'est déroulé en trois étapes. Pour commencer, la zone autour du puits fut saturée par l'injection d'eau du puits (environ 360L). Ensuite, un total de 360L de solution saline, avec une conductivité électrique (EC) d'environ 12 000 µS/cm, a été injecté autour du puits. Finalement, 360L d'eau de puits furent versés dans le but de pousser le traceur en profondeur. La figure suivante montre certains profils de conductivité électrique jusqu'à 9 jours après l'injection. L'arrivée du traceur, dans la colonne d'eau, commencerait cinq jours (*J5*) après son injection. Dans ce profil, des instabilités dans la colonne d'eau sont observées. Ces instabilités sont présentes jusqu'au huitième jour après l'injection (*J8*) et serait le résultat de l'arrivé du traceur dans la colonne d'eau du puits.

Lors de la période du suivi, un évènement de précipitation assez important a eu lieu quatre jours après l'injection du traceur. Il est possible que le profil du jour 9 (*J9*) soit représentatif de cet évènement car la conductivité électrique de la colonne d'eau est légèrement plus faible comparativement aux autres profils. Il y aurait donc un délai possible de cinq jours entre un évènement de précipitation et la recharge au puits.

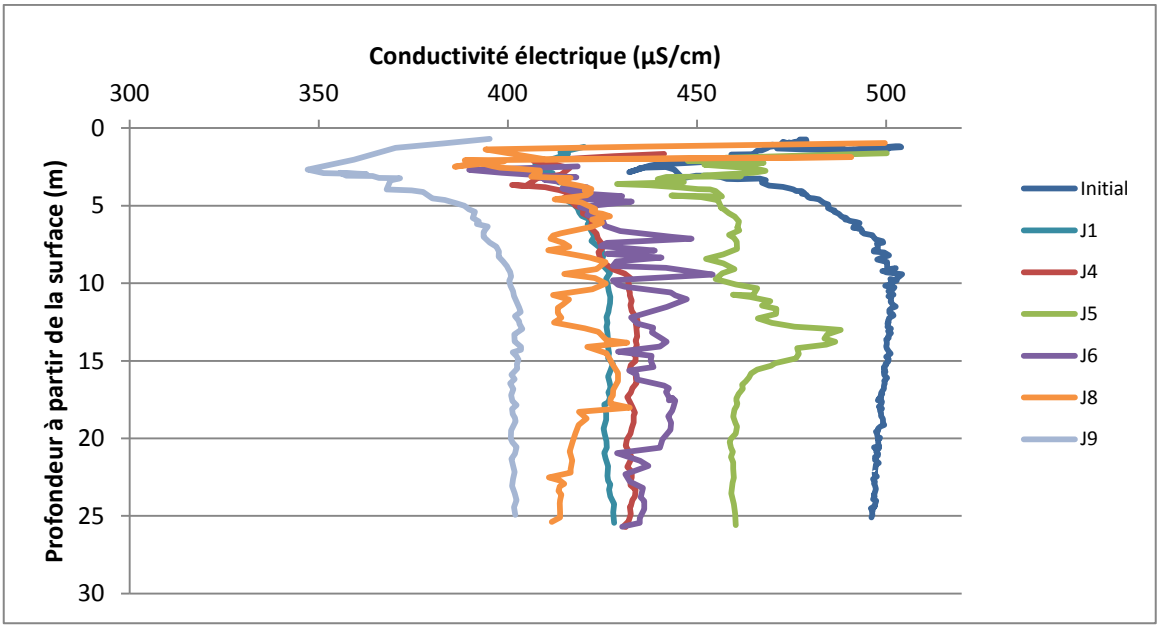


Figure 2 : Profils de conductivité électrique de la colonne d'eau jusqu'à neuf jours après l'injection de la solution saline.

Analyse bactériologique

Les bactéries sont naturellement présentes dans les eaux de surface et dans les sols. Elles sont transportées dans les eaux souterraines par le processus d'infiltration. Plusieurs facteurs affectent le mouvement des bactéries. Ces facteurs peuvent être reliés aux bactéries (type, taille, dynamique de la population) ou aux caractéristiques du sol (physique, chimique ou biologique). La plupart des bactéries sont filtrées dans le premier horizon du sol mais la présence de « macro-pores » peut contribuer au mouvement des bactéries en profondeur. Les macro-pores sont en fait des pores de grandes dimensions formées par l'activité biologique, les racines ou bien des fissures dans un milieu argileux.

Ces macro-pores affectent la capacité du sol à filtrer les bactéries, ce qui leur permet de pénétrer plus profondément et rapidement.

La contamination bactérienne dans un puits peut provenir de plusieurs sources. Dans une municipalité comme Chelsea, où l'agriculture n'est que localisée et quasi-inexistante, la construction d'un puits (type, âge et profondeur), son emplacement, la distance au système septique ainsi que des facteurs reliés à la géologie sont les principales sources contribuant à la présence de bactéries dans un puits.

La figure ci-dessous présente les résultats de l'analyse bactériologique sous forme de graphique. On remarque une présence constante de coliformes totaux de mai à octobre. Le nombre de coliformes totaux dépasse la limite provinciale de 10 ufc/100mL à deux reprises, soit en mai et juillet. La présence de coliformes fécaux a été détectée en juillet 08, où le nombre de coliformes totaux était le plus important.

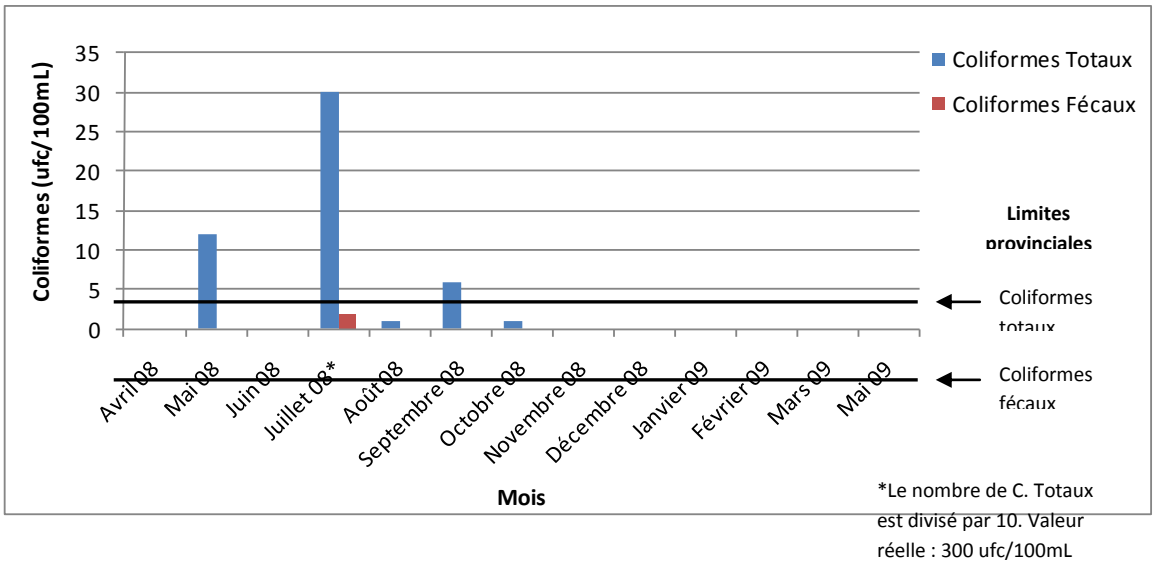


Figure 3: Résultats des analyses bactériologiques (coliformes totaux et fécaux) des échantillons d'avril 2008 à mai 2009.

Analyse Chimique

Naturellement, l'eau dissout les minéraux lorsqu'elle s'écoule dans le sol. Le processus de dissolution est habituellement lent dans la roche Précambrienne comparativement aux jeunes roches sédimentaires telles le grès ou la calcite. Des sources anthropogéniques, telles l'épandage de sels routiers, les fertilisants et les systèmes septiques peuvent également contribuer à la teneur en minéraux dissouts dans les eaux souterraines.

Les échantillons d'eau furent analysés à l'université d'Ottawa pour identifier diverses composantes dissoutes. Les résultats sont présentés dans le tableau suivant. Ce tableau donne également la moyenne annuelle ainsi que les lignes directrices relatives à certains paramètres. Les concentrations sont mesurées en milligrammes par litre (mg/L).

Mois	pH	Fluorure (mg/L)	Chlorure (mg/L)	Nitrate -N (mg/L)	Sulfate (mg/L)	Calcium (mg/L)	Magnésium (mg/L)	Sodium (mg/L)	Dureté (mg/L de $CaCO_3$)
Avril 08	7.7	1.2	28.4	bdl	78.3	49.2	7.8	61.5	155.2
Mai 08	7.9	1.2	27.8	bdl	77.0	48.6	7.6	58.8	152.6
Juin 08	7.6	1.3	26.7	bdl	75.1	45.7	6.9	50.9	142.5
Juillet 08	7.6	1.2	30.3	bdl	85.1	45.4	7.3	60.4	143.4
Août 08	7.5	1.3	28.7	bdl	80.6	38.7	6.8	68.5	124.8
Septembre 08	7.7	1.2	32.3	bdl	77.1	30.2	7.0	54.0	104.2
Octobre 08	7.4	1.4	29.7	bdl	82.5	43.5	7.1	55.9	137.8
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Décembre 08	7.2	1.4	30.7	bdl	85.1	45.0	7.3	59.9	142.5
Janvier 09	7.7	1.4	24.8	bdl	68.4	41.8	6.9	55.6	132.9
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Mai09	7.1	1.4	30.6	bdl	84.1	39.5	6.8	49.8	127.0
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Ligne directrice		1.5 CMP	250.0 OE	10.0 CMP	500.0 OE			20.0 OE	100.0 LDO

LDP = Ligne directrice opérationnelle
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Les paramètres mesurés lors de notre étude sont des indicateurs de la qualité de l'eau. Il est important de considérer que dans certain cas, leur présence n'a pas nécessairement un impact sur la santé. Le tableau décrit certain de ces paramètre ainsi que ce que les effets possible de leur présence.

Paramètres mesurés	Définitions/Sources	Effets possibles
pH	Mesure de l'acidité de l'eau	• Une eau acide (pH<6.5) peut avoir un effet corrosif
Fluorure	Présence naturelle	• Affecte la dentition des enfants • Des concentrations très élevées peuvent affecter le développement des os
Chlorure	Présence naturelle ou causée par l'activité humaine	• Effet corrosif sur la plomberie • Goût salé
Nitrates	Fertilisants, système septique	• Effets sur la santé
Sulfates	Présence naturelle ou causée par l'activité humaine	• L'eau à un effet laxatif
Sodium	Présence naturelle ou causée par l'activité humaine	• Hypertension (personne à risque)
Dureté	Causée par la présence de calcium et magnésium dans l'eau	• Aucun effet sur la santé • Réduit l'efficacité des savons • Effets sur la tuyauterie (dépôts et blocage) • Tache et salie le linge

Sources : Pratiques de gestion optimale-Les puits

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Catégorie	Concentration de carbonate de Calcium (mg/L)
Eau Douce	0 à <60
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Eau dure	120 à <180
Eau très dure	180 et plus

Source : Santé Canada

Sommaire et suggestions

Intégrité du scellement de tubage

La conductivité hydraulique au puits est plus élevée que celle des surfaces avoisinantes. Il semblerait qu'une connexion hydraulique, entre la surface et la colonne d'eau, existe au puits. L'essai de traçage ayant démontré cette connexion, l'espace annulaire du puits serait donc une voie préférentielle à l'infiltration des eaux de surface. Les analyses bactériologiques indiquent aussi une connexion possible.

Source de contamination

Comme la contamination est plus importante lors des mois estivaux, il est possible que l'infiltration d'eaux de surface soit la principale cause de la présence de bactéries. La construction du puits et les caractéristiques du site (mince couche de sol et drainage vers le puits) sont probablement les facteurs responsables.

Analyse chimique

Tous les paramètres respectent les lignes directrices à l'exception du sodium qui est légèrement plus élevé que l'objectif esthétique.

La dureté est également plus élevée que la ligne directrice opérationnelle, mais un adoucisseur est déjà en place.

Suggestions

- L'espace annulaire étant une voie préférentielle à la contamination, il est important de réduire le ruissellement vers le puits. Pour ce faire, il est recommandé d'élever le sol à la tête du puits, ce qui évitera l'eau de ruissellement de s'accumuler et s'infiltrer à cet endroit.

- Un bon couvercle devrait garder les insectes hors du puits. Même si aucun insecte ne fut détecté à l'intérieur, il est donc recommandé de vérifier l'intérieur et de s'assurer que le couvercle soit assez étanche pour ne pas laisser entrer les insectes, mais assez dégagé pour laisser passer l'air. Ceci pourrait prévenir le nombre de coliformes totaux dans le puits.
- Il est important de faire un suivi continu sur l'état de votre puits. Une fois l'an, vous devriez regarder dans le puits avec une lampe de poche. Recherchez la présence de fissures et de trous dans le cuvelage et près de l'embranchement des tuyaux vers la maison. Prenez des notes et comparez au fil des ans. Des mesures correctives peuvent être entreprises, par un puisatier, si un problème est détecté.
- Il est recommandé de faire une analyse bactériologique au 1 fois par année, et à l'occasion, notamment après une pluie importante et la fonte des neiges.
- Finalement, il serait impératif de faire installer un système de stérilisation de l'eau, tel les systèmes aux rayons ultra-violets.

L'information présentée dans ce rapport provient des sources suivantes :

*****Ces sources sont également excellentes pour en savoir plus sur les puits, les sources de contamination ainsi que sur la qualité de l'eau**

Conboy M.J, Smith S., 2005. A comprehensive consumer's guide for private water wells ISBN 0-9780387-0-3
www.wellwise.ca

Recommandations pour la qualité de l'eau potable au Canada -La dureté
http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/hardness-durete/index-fra.php

Ministère du développement durable, environnement et parcs- *La qualité de l'eau de mon puits*
http://www.mddep.gouv.qc.ca/eau/potable/depliant/index.htm

Publications : Ministère de l'agriculture, de l'alimentation et des affaires rurales (Ontario)
http://www.omafra.gov.on.ca/french/environment/water/publications.htm

Ministère de la santé et des soins de longue durée
http://www.health.gov.on.ca/english/public/pub/watersafe/watersafe_wellknow.html

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Sciences de la Terre Earth Sciences

Contamination of Private Well Study
Municipality of Chelsea, Québec



Report presented to:
W26
Chelsea, QC

Report prepared by:
Pascale St-Germain
PhD Candidate
University of Ottawa

May 2010

Acknowledgements

Thank you for your help with this study. Your assistance is valuable in our effort to better understand groundwater wells in fractured bedrock and potential contaminant pathways. We appreciate the access to your property, your hospitality and your collecting water samples for the purpose of this research.

Important note

The suggestions presented in this report are made to improve the quality of your well water. They may help reduce the number of coliforms in your well, but may not be the only solution to any problems. An attempt was made to find the most probable source of contamination; however, many factors can affect water quality. This report was prepared to give you a better understanding of your well and does not include all the conclusions found in the overall study. All suggestions should be treated with caution.

Before investing in your well (well upgrade or water treatment system) I would suggest seeking advice from professionals and getting your water tested independently by an accredited laboratory before future investment in a treatment system.

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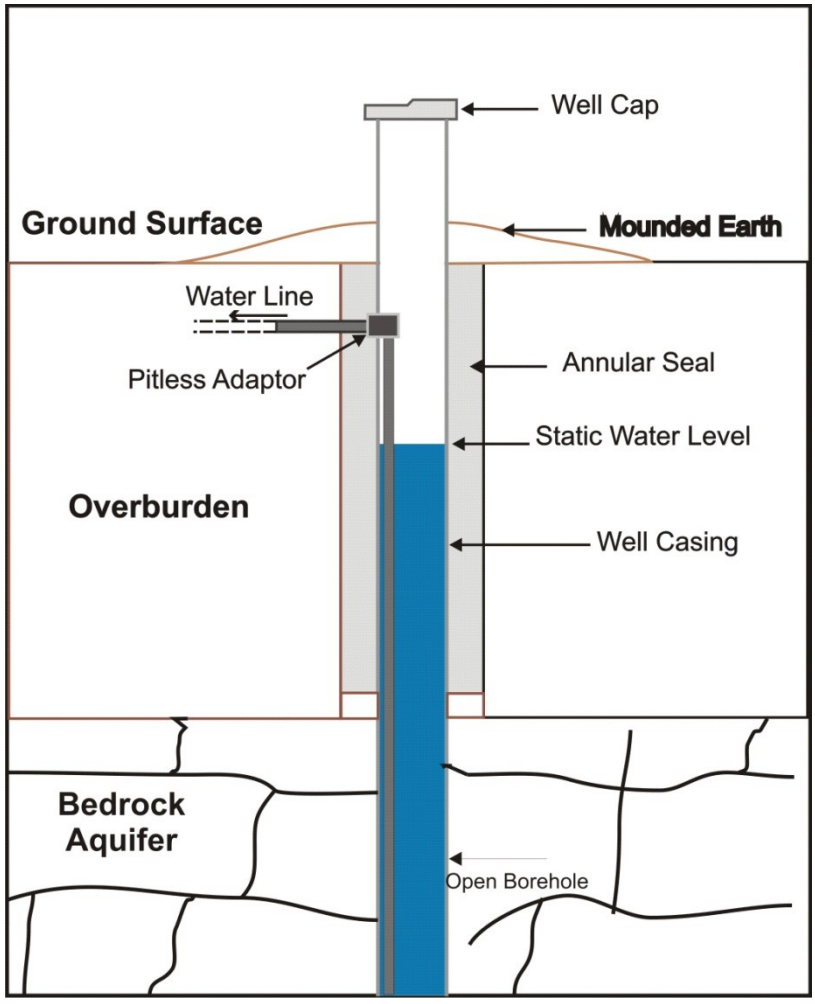
Pascale St-Germain
PhD candidate
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Glossary

Precambrian bedrock:	Fracture bedrock mainly composed of igneous and metamorphic rocks that are more than 542 million years old.
Overburden:	Unconsolidated sediments overlaying the bedrock and composed of grains of various sizes.
Champlain Sea:	Inland sea created about 10 000 year ago resulting from the melting of the *Inlandsis laurentidien* ice sheet. The sea principally covered the Montreal area but also some areas in south eastern Ontario.
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Drilled well:	Well drilled into the fractured bedrock
Aquifer:	Geological unit capable of storing and transmitting water in sufficient quantity.
Confined aquifer:	Aquifer overlain by an impermeable layer. This layer protects the aquifer from surficial contaminant.
Unconfined aquifer:	Aquifer not overlain by an impermeable layer and exposed to atmospheric pressure.
Aquitard:	Geological unit capable of storing water but incapable of transmitting water in sufficient quantities.
Infiltration:	Movement of water from ground surface into the soil.
Hydraulic conductivity:	Ability of a porous media to transmit water.
Electrical conductivity (EC):	Ability of the water to conduct an electrical current. It is a general indication of the amount of total dissolved solids (TDS) in the water. EC is measure in Siemens per cm (S/cm) or microSiemens per cm (µS/cm = 10^{-6} S/cm). It ranges from several tens of µS/cm for rain water to several thousands of µS/cm for sea water. In the Chelsea area, the EC values range from approximately 90 to 1600 µS/cm.
Total coliforms:	Bacteria present in human and animal feces but also in the soil and vegetation

Faecal coliforms:	Bacteria originating from digestive tracts of humans and animals. Their presence indicates faecal pollution and the potential for pathogens to be present into the water
Macropore:	Pore of greater dimension resulting from biological activity in the soil, from roots and cracks in clay

Drilled well



Source: Modified from Best Management Practice – Water Well

Introduction

The objective of the project was to improve the understanding of private well contamination resulting from the infiltration of surface water. The risk of contamination in drilled wells was evaluated based on site characteristics and well construction.

Your well was tested every month for bacteria in order to assess the seasonality of contamination. Chemical analysis of the well water was carried out to understand the groundwater pathways and to establish possible links to potential contamination sources.

The objective of this report is to increase your awareness of possible water quality issues in your well and of the possible remedial actions that could taken preserve or improve the quality of your well water. It contains a summary of the work conducted, the data obtained, conclusions and some suggestions.

Site Description

Your well is drilled into the Precambrian bedrock, which is overlain by less than 1 metre of fine-grained sediments like sand and silt. The well is approximately 45 metres deep and the static water level is located 3 metres below ground surface.

Your well draws water from an unconfined aquifer. An aquifer is defined as a geologic unit capable of storing and transmitting water. This aquifer is also considered unconfined because there is no impermeable protective layer overlaying it. Usually, these types of aquifer are more vulnerable to contamination since there is no confining layer. The confining layer provides an impermeable barrier, thereby naturally protecting the well against surface contamination.

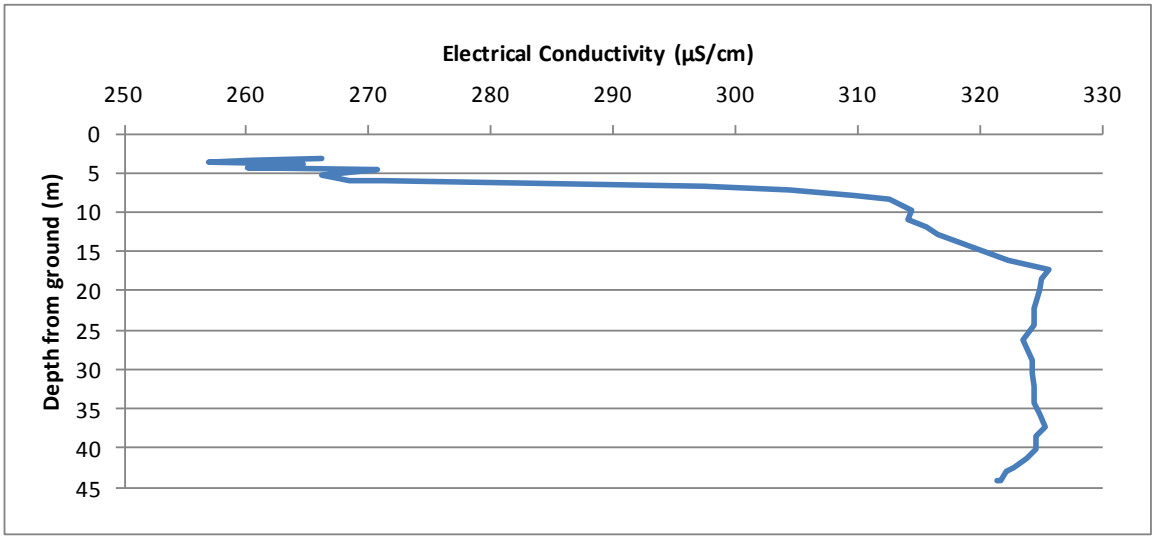


Figure 1: Electrical conductivity profile of the water column

The figure above displays the electrical conductivity (EC) profile of the well water column. The electrical conductivity is the ability of the water to conduct an electric current and it is a measure of the amount of dissolved solids in the well. For this well, the values range from 260 to 325 µS/cm, which is relatively low. The EC gradually increases towards a depth of 17 metres and then stays constant. While testing the well for a faulty seal, multiple EC profiles were collected when monitoring for the tracer arrival. It was possible to hear water dripping at a approximate depth of 6 metres. Therefore, there is potential for highly fractured bedrock at this depth. This could contribute to infiltration of surface water into the well and help explain the EC profile in your well.

Analytical Techniques

To evaluate the status of the well seal, two techniques were employed:

1. Hydraulic Conductivity

   The first technique measures the hydraulic conductivity (K) around the well to see if water infiltrates into the ground more easily than in the surrounding area. A statistical test was done to compare the K values resulting from the infiltration

tests. If the K value at the well was found to be relatively greater than the K values of the surrounding, then there is a potential for a faulty seal.

2. Tracer Test

   The second technique involves injecting a tracer (a solution of NaCl or commonly, table salt) around the well casing and then measuring the electrical conductivity of the well water over time. If the tracer is detected in the well water, then surface water is likely capable of seeping down the sides of the well, indicating a hydraulic connection with the surface.

Results

1. Hydraulic conductivity comparison

The infiltration tests were done on August 6th and 7th 2008. The hydraulic conductivity value measured at the well was statistically significantly higher than the hydraulic conductivity measurements in the vicinity of the well.

2. Tracer test

The tracer was injected on August 7th and monitored until August 18th. Many rainfall events occurred during the tracer monitoring period which could have contributed to the tracer dilution.

A total of 380L of the tracer solution, with an EC of 14,000µS/cm, was injected following the infiltration of 380L of well water (EC around 300 µS/cm), which acted as the pre-tracer in this case. After the injection of the tracer, more well water was infiltrated as a "chaser" in order to help the infiltration of the tracer.

For comparison purposes, the EC profiles are plotted in the figure below. The variability in the water column appears to be the result of rain events since two different types of profiles were observed in the well. From the figure below, the *before tracer injection*

and the *after tracer injection* are typical profiles representing these two scenarios. The EC values of the *after tracer injection* profile are lower and could be the results of dilution from rain water reaching the water column. The EC values of the *initial* and *before injection* profiles potentially represent water from different sources entering the well in the upper section of the water column. The higher values indicate that these sources may have resulted from proximal anthropogenic activities. The daily variability between the EC profiles makes the tracer arrival difficult to detect. Therefore, it is not clear if the increase of the EC values observed in the *2 days* profile represent the tracer arrival or another source of water entering the well.

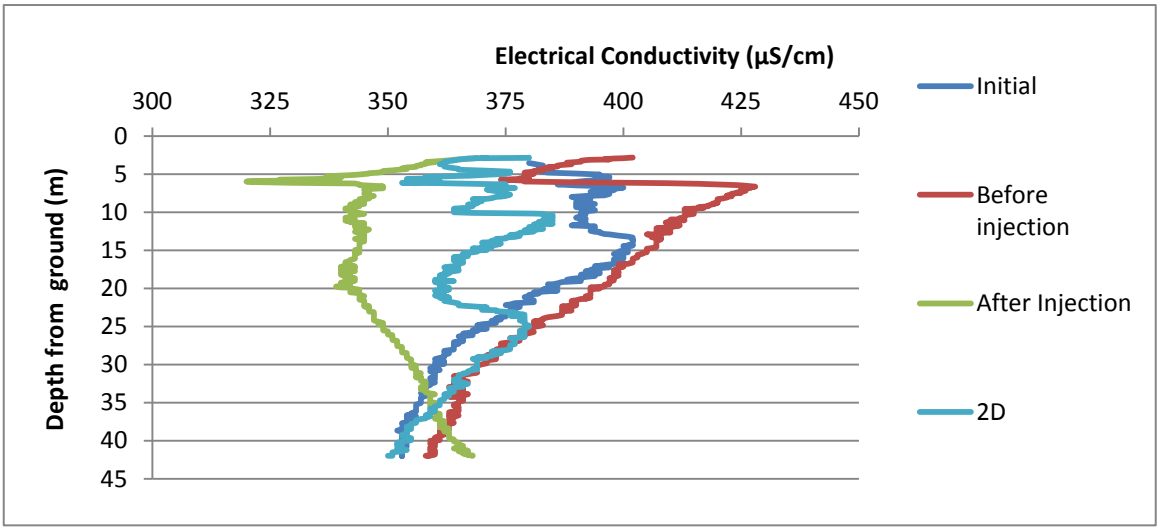


Figure 2: Electrical conductivity profiles of the water columns, before the tracer injection up to 2 days following the injection. The tracer can be noticed in the *2 days* profile.

Bacteria

Bacteria are naturally present in surface water and soil. They are carried to the groundwater system through the infiltration process. A number of factors may affect the movement of bacteria in soil. These are directly related to the bacteria (type, size and population dynamic) and the soil properties (chemical, biological and physical). Usually, most of the bacteria are filtered through the upper soil profile, but water can carry bacteria deeper using larger pore structures. These structures, called macropores, result from many things: earthworms, decayed roots and crack in clayey soil are some examples.

Macropores reduce the efficiency of the soil to filter bacteria allowing them to travel deeper and faster.

Bacterial contamination in a well is a product of many factors. In a municipality like Chelsea, where agriculture is not a common practice, well construction (type, age, depth), location, the presence of septic system and the geology (bedrock and surficial) would be the primary contributors to bacterial contamination.

One sample exceeded the regulation limits for total coliforms during the April 2008 to May 2009 sampling period. Total coliforms were also detected in five other samples, but the counts were below the provincial limit of 10 cfu/100mL (colony forming units / 100 millilitres). During the same period, one sample (August) exceeded the faecal coliforms regulation limit of 0 cfu/100mL.

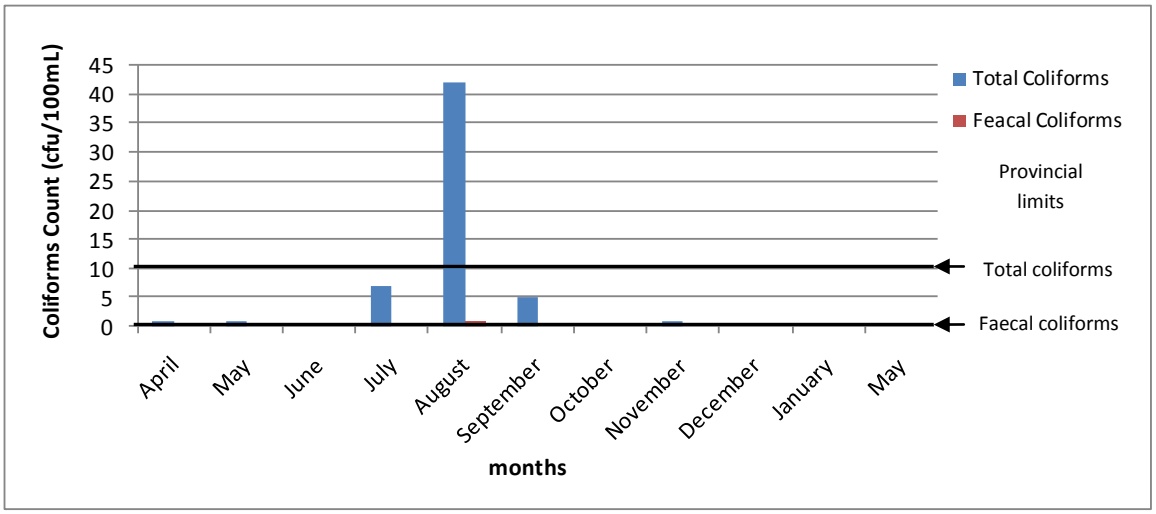


Figure 3: Results of the bacterial analysis (total and faecal coliforms) of the water samples, from April 2008 to May 2009.

Chemical analysis

As water naturally flows into the subsurface, it dissolves minerals along its pathway. The dissolution process is relatively slow in Precambrian bedrock compared to younger sedimentary rocks such as limestone or sandstone. However, other non natural sources may contribute to dissolved solids such as road salt application, septic systems or fertilizers.

Water samples were analysed for various dissolved species at the University of Ottawa. The results of the analyses are given in the following table. This table also shows the yearly average and the provincial guideline, if applicable. The concentrations are measured in milligrams per litre (mg/L).

Sampling date	pH	Fluoride (mg/L)	Chloride (mg/L)	Nitrate as N (mg/L)	Sulphate (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Hardness (mg/L as $CaCO_3$)
Apr-08	6.1	0.5	67.9	bdl	21.9	37.7	4.9	11.5	114.3
May-08	6.3	bdl	55.5	bdl	10.4	53.2	6.5	17.0	159.6
Jun-08	6.1	bdl	104.1	bdl	20.8	59.2	7.0	16.8	176.6
Jul-08	6.0	bdl	94.1	bdl	23.6	53.4	6.6	20.3	160.5
Aug-08	6.0	0.5	115.1	bdl	29.1	58.0	7.9	29.9	177.5
Sep-08	8.8	bdl	3.4	bdl	1.5	7.9	0.4	1.2	21.4
Oct-08	6.7	bdl	13.6	bdl	4.7	45.4	6.2	14.2	139.0
Nov-08	6.2	bdl	62.2	bdl	12.8	78.4	10.1	29.0	237.4
Dec-08	6.1	bdl	28.9	bdl	24.2	57.8	7.4	22.1	174.9
Jan-09	6.4	bdl	59.0	bdl	18.8	36.6	4.9	13.8	111.8
May-09	6.8	bdl	97.3	bdl	22.1	45.0	6.5	17.1	139.2
Average	6.5	0.5	63.7		17.2	48.4	6.2	17.5	146.6
Guideline		1.5 MAC	250.0 AO	10.0 MAC	500.0 AO			20.0 AO	100.0 AO

OG = Operational Guideline
MAC= Maximum Allowable Concentration
AO= Aesthetic Objective
Bdl= below detection limit

The dissolved solids measured during this study are water quality indicators. It is important to realize that their presence may not have an impact on health. The following table describes the parameters and their possible effects.

Parameters	Definition/sources	Possible effects/concerns
pH	Measure of the acidity of water	• An acid water (pH<6.5) can have a corrosive effect • Low pH increases metals in solution, which could yield health concerns
Fluoride	Natural occurrence	• Mottled teeth • Bone development (high concentrations)
Chloride	Natural occurrence or human related activities	• Corrosive effect on plumbing • Salty taste
Nitrates	Human related activities	• Health Concerns
Sulphates	Natural occurrence or human related activities	• Water has laxative effect
Sodium	Natural occurrence or human related activities	• Health concerns • Salty taste
Hardness	Caused by the presence of calcium and magnesium and occasionally iron in the water	• No health effect • Soap scum • Scale buildup on plumbing fixture and pipes • Stained and mottled laundry

Sources: Best Management Practices –Water Well

Guidelines for Hardness

Category	Concentration of calcium carbonate (mg/L)
Soft	0 to <60
Medium Hard	60 to <120
Hard	120 to <180
Very Hard	180 and more

Source : Health Canada

Summary and Suggestions

Seal testing

The infiltration tests demonstrated that surface water infiltrated easier at the wellhead compared to the area surrounding the well. It is not clear if the tracer was detected in the water column. The water column of this well is subject to daily variations which could have contributed to the dilution of the tracer. These variations are the result of rapid recharge from rainfall water and potentially, a contaminant plume entering the well. The plume could result from a nearby septic system which increases the concentrations of sodium, sulphate and chloride in the well. Even if the tracer detection is not obvious, there is still a high risk of having hydraulic connectivity between the surface and the well. This is explained by the rapid recharge observed after a rainfall event. Although a faulty seal is a potential pathway to contamination, other factors such as shallow soil thickness may lead to such contamination.

Possible sources of contamination

Your well is characterized by sporadic contamination events. While monitoring the tracer arrival in the well, we observed a short response time to rain events. This could result from the characteristics of the site, which may allow rapid infiltration of surface water. When rapid infiltration occurs, the soil may not have sufficient time to filter the bacteria and they can reach the water column. During the major contamination events, the total coliforms were associated with faecal coliforms. This could be resulting from natural causes near the well or in recharge area.

Chemical analysis

Most constituent concentrations are below guidelines/regulations with the exception of the hardness. The yearly average for this parameter is 147 mg/L as $CaCO_3$, while the aesthetic objective is 100 mg/L as $CaCO_3$. Your well water is therefore considered as hard.

Suggestions

- In your situation, the presence of bacteria is recurrent and extra care should be taken for any use of water related to human consumption. The installation of a filtration system that kills microorganisms should be considered. This system is already installed.
- It is recommended to get your water tested for bacteria at least 1 time a year, especially after important rainfall events and snowmelt.
- A potential preferential pathway to surface water infiltration is the well annular space. To diminish the infiltration at the wellhead, it is recommended that the soil be mounded around the casing, which will deviate the runoff away from the wellhead, allowing the natural soil process to attenuate the bacteria present in the water.
- It is important to consider activities around the wellhead, especially uphill from the well. For example: if the driveway is located uphill from the well and runoff water flow towards the well. Extra care should be taken to make sure there are no leaks from cars and salt should not be used as de-icing agent. To prevent nitrate contamination, no fertilizers should be used uphill or near the well recharge area.
- Every year, examine into the inside of the well with a flash light. You can look for cracks in the casing caused by corrosion. Also check for holes around the pitless adaptor (area where pipes are connected). A record should be kept and comparisons made year to year. Corrective action can be suggested a licensed well contractor if something wrong is detected.
- It is not recommended to plant flowers, shrubs or trees near the wellhead since their roots can affect the integrity of the annular seal protecting the well. The roots also increase the infiltration rate in the area.

The information presented in this report comes from the following sources:

*****These are also excellent sources for more information on water wells**

Conboy M.J, Smith S., 2005. A comprehensive consumer's guide for private water wells ISBN 0-9780387-0-3
www.wellwise.ca

Guidelines for Canadian Water Quality-Hardness
http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/hardness-durete/index-eng.php

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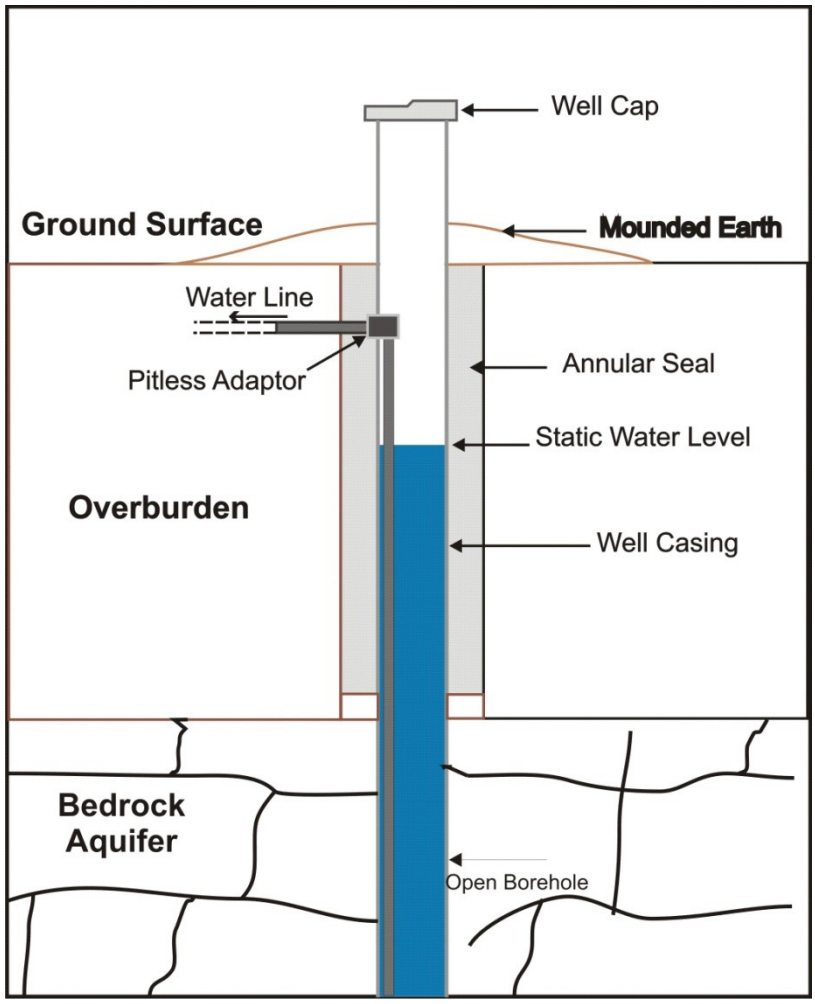
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Drilled well



Source: Modified from Best Management Practice – Water Well

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Site Description

Your well is drilled into the Precambrian bedrock, which is overlain by a thick layer of sand deposited during the last glaciation (about 10,000 years ago). The well is approximately 20 metres deep and the static water level is located 6 metres below ground surface.

Your well draws water from an unconfined aquifer. An aquifer is defined as a geologic unit capable of storing and transmitting water. This aquifer is also considered unconfined because there is no impermeable protective layer overlaying it. Usually, these types of aquifer are more vulnerable to contamination since there is no confining layer. The confining layer provides an impermeable barrier, thereby naturally protecting the well against surface contamination.

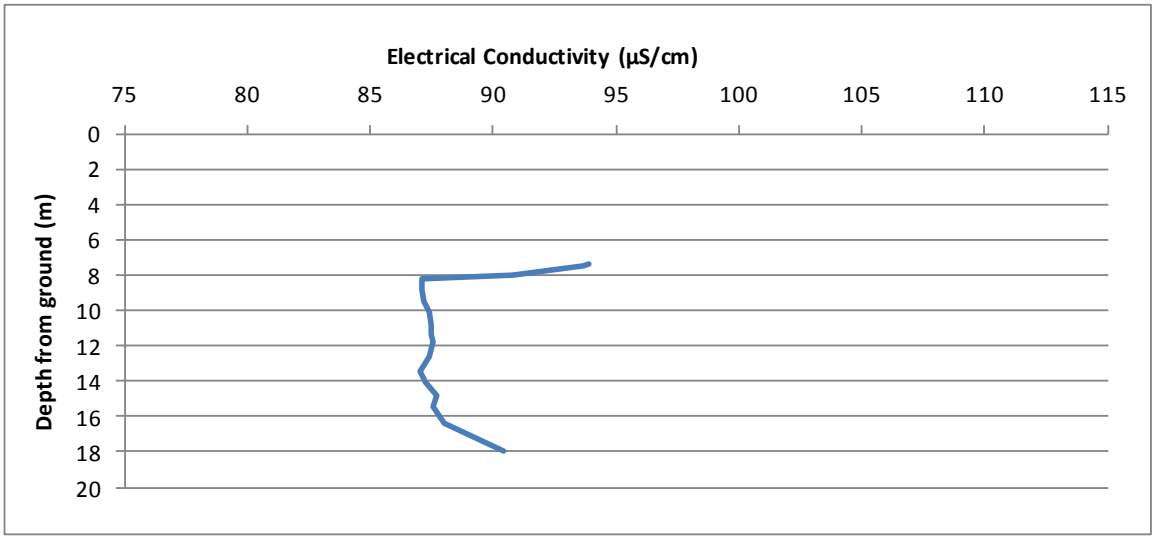


Figure 1: Electrical conductivity profile of the water column

The figure above displays the electrical conductivity (EC) profile of the well water column. The electrical conductivity is the ability of the water to conduct an electric current and it is a measure of the amount of dissolved solids in the well. For this well, the values range from 85 to 95 µS/cm. These values are extremely low for groundwater, indicating water of good quality but also indicating that the water may be mostly of surface water.

Analytical Techniques

To evaluate the status of the well seal, two techniques were employed:

1. Hydraulic Conductivity

   The first technique measures the hydraulic conductivity (K) around the well to see if water infiltrates into the ground more easily than in the surrounding area. A statistical test was done to compare the K values resulting from the infiltration tests. If the K value at the well was found to be relatively greater than the K values of the surrounding, then there is a potential for a faulty seal.

2. Tracer Test

The second technique involves injecting a tracer (a solution of NaCl or commonly, table salt) around the well casing and then measuring the electrical conductivity of the well water over time. If the tracer is detected in the well water, then surface water is likely capable of seeping down the sides of the well, indicating a hydraulic connection with the surface.

Results

1. Hydraulic conductivity comparison

The infiltration tests were done on July 17th and 18th 2008. The hydraulic conductivity value measured at the well was significantly higher than the hydraulic conductivity measurements in the vicinity of the well.

2. Tracer test

The tracer was injected on July 17th and monitored until July 30th. A total of 380L of the tracer solution, with an EC of 6000 µS/cm, was injected following the infiltration of 180L of well water (EC around 90 µS/cm), which acted as the pre-tracer in this case. After the injection of the tracer, more well water was infiltrated as a "chaser" in order to help the infiltration of the tracer. For comparison purposes, the EC profiles are plotted in the figure below. The tracer was detected 1 day following its injection, but it is more noticeable in the EC profiles 2 day after (*2 days* profile). It is clear that the tracer reached the well at a depth of 10 metres below ground, where the bottom of the casing located.

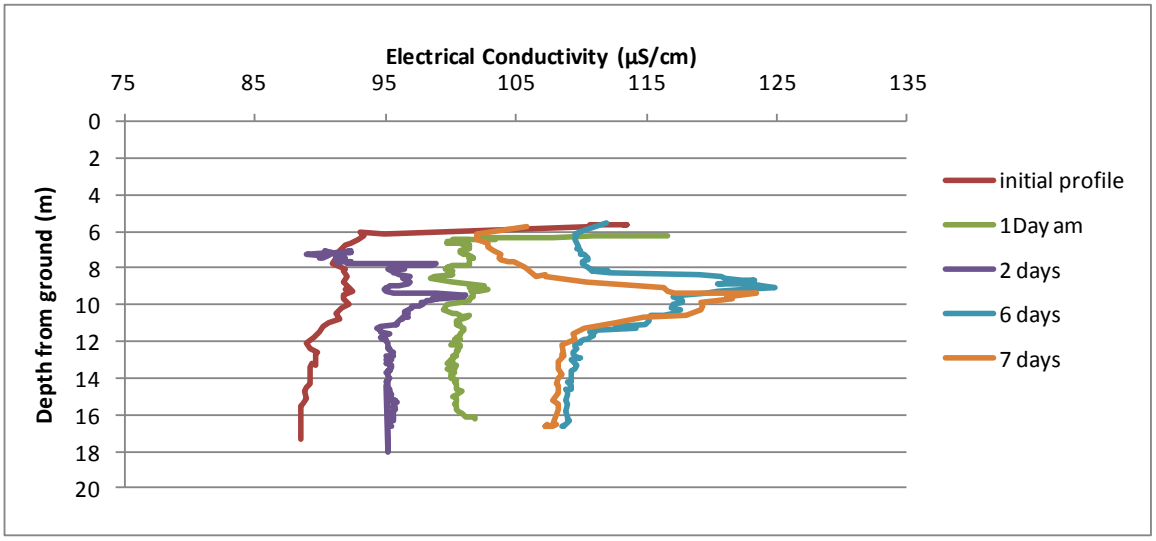


Figure 2: Electrical conductivity profiles of the water columns, from the initial profile up to 7 days following the injection. The tracer can be noticed in the *2 days* profile

Bacteria

Bacteria are naturally present in surface water and soil. They are carried to the groundwater system through the infiltration process. A number of factors may affect the movement of bacteria in soil. These are directly related to the bacteria (type, size and population dynamic) and the soil properties (chemical, biological and physical). Usually, most of the bacteria are filtered through the upper soil profile, but water can carry bacteria deeper using larger pore structures. These structures, called macropores, result from many things: earthworms, decayed roots and crack in clayey soil are some examples. Macropores reduce the efficiency of the soil to filter bacteria allowing them to travel deeper and faster.

Bacterial contamination in a well is a product of many factors. In a municipality like Chelsea, where agriculture is not a common practice, well construction (type, age, depth), location, the presence of septic system and the geology (bedrock and surficial) would be the primary contributors to bacterial contamination.

The well shows two contamination events during the April 2008 to May 2009 sampling period. Faecal coliforms were detected once. Neither total nor faecal coliforms were detected in the water samples taken after June 2008.

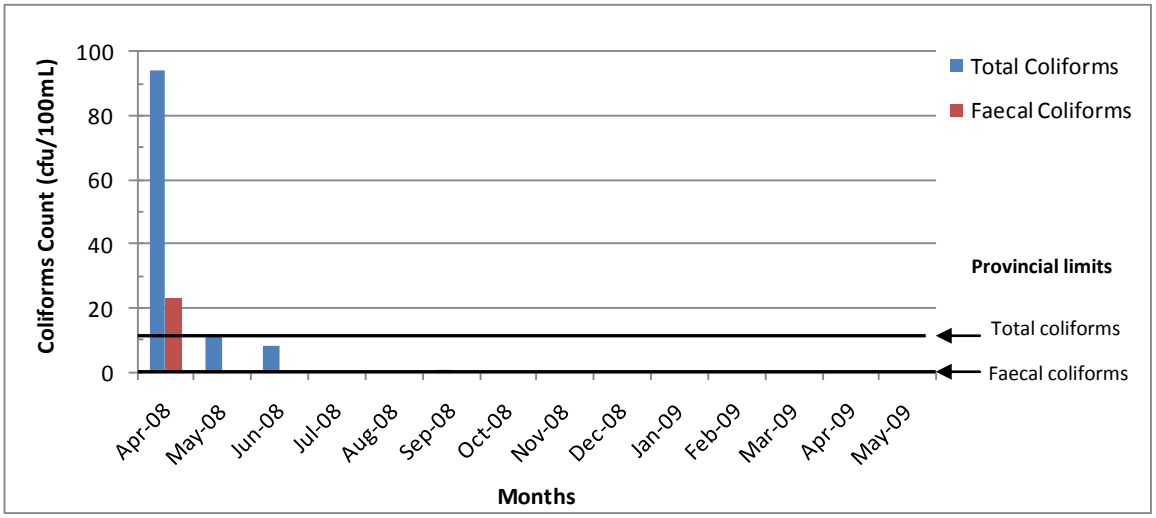


Figure 3: Results of the bacterial analysis (total and faecal coliforms) of the water samples, from April 2008 to May 2009.

Chemical analysis

As water naturally flows into the subsurface, it dissolves minerals along its pathway. The dissolution process is relatively slow in Precambrian bedrock compared to younger sedimentary rocks such as limestone or sandstone. However, other non natural sources may contribute to dissolved solids such as road salt application, septic systems or fertilizers.

Water samples were analysed for various dissolved species at the University of Ottawa. The results of the analyses are given in the following table. This table also shows the yearly average and the provincial guideline, if applicable. The concentrations are measured in milligrams per litre (mg/L)

Sampling date	pH	Fluoride (mg/L)	Chloride (mg/L)	Nitrate as N (mg/L)	Sulphate (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Hardness (mg/L as $CaCO_3$)
Apr-08	6.8	NA	NA	NA	NA	35.4	3.1	1.7	101.4
May-08	6.8	bdl	0.6	0.5	10.8	22.7	2.1	1.0	65.2
Jun-08	6.7	bdl	1.0	0.5	12.5	25.6	2.2	1.1	73.1
Jul-08	6.6	bdl	0.8	0.6	11.8	25.8	2.4	1.1	74.3
Aug-08	6.8	bdl	0.9	0.6	12.4	24.7	2.6	1.5	72.5
Sep-08	6.3	bdl	1.2	0.6	13.6	31.8	3.0	1.3	91.9
Oct-08	6.7	bdl	1.4	0.7	14.4	35.4	3.2	1.3	101.9
Nov-08	6.7	bdl	1.5	0.9	15.2	38.2	3.5	1.3	109.9
Dec-08	6.6	bdl	1.4	0.8	14.0	37.8	3.6	1.3	109.3
Jan-09	6.7	bdl	1.3	0.8	13.4	31.0	2.9	1.2	89.3
Feb-09	6.5	bdl	1.5	0.9	15.4	33.2	3.1	1.5	95.6
Mar-09	6.8	bdl	1.4	0.9	14.8	34.0	3.1	1.6	97.4
Apr-09	6.7	bdl	0.8	0.7	11.2	23.0	2.3	1.1	67.0
May-09	6.8	bdl	0.8	0.5	11.6	19.9	2.0	1.0	57.7
Average	6.6		1.2	0.7	13.4	30.4	2.9	1.3	87.9
Guideline		1.5 MAC	250.0 AO	10.0 MAC	500.0 AO			20.0 AO	100.0 AO

OG = Operational Guideline
MAC= Maximum Allowable Concentration
AO= Aesthetic Objective
Bdl= below detection limit

The dissolved solids measured during this study are water quality indicators. It is important to realize that their presence may not have an impact on health. The following table describes the parameters and their possible effects.

Parameters	Definition/sources	Possible effects/concerns
pH	Measure of the acidity of water	• An acid water (pH<6.5) can have a corrosive effect • Low pH increases metals in solution, which could yield health concerns
Fluoride	Natural occurrence	• Mottled teeth • Bone development (high concentrations)
Chloride	Natural occurrence or human related activities	• Corrosive effect on plumbing • Salty taste
Nitrates	Human related activities	• Health Concerns
Sulphates	Natural occurrence or human related activities	• Water has laxative effect
Sodium	Natural occurrence or human related activities	• Health concerns • Salty taste
Hardness	Caused by the presence of calcium and magnesium and occasionally iron in the water	• No health effect • Soap scum • Scale buildup on plumbing fixture and pipes • Stained and mottled laundry

Sources: Best Management Practices –Water Well

Guidelines for Hardness

Category	Concentration of calcium carbonate (mg/L)
Soft	0 to <60
Medium Hard	60 to <120
Hard	120 to <180
Very Hard	180 and more

Source : Health Canada

Summary and Suggestions

Seal testing

The infiltration tests demonstrated that surface water infiltrated easier at the wellhead compared to the area surrounding the well. The probable detection of the tracer in the well suggests the presence of a hydraulic connection between the wellhead and the water column. Although a faulty seal is a potential pathway to contamination, other factors such as the proximity to the Meech Lake may lead to such contamination.

Possible sources of contamination

The indication of a rapid infiltration rate at the wellhead suggests the presence of a preferential pathway for surface water to infiltrate the well. This could lead to a potential contamination problem in the well if a contaminant source was proximal to the wellhead.

The contamination pattern in the well appears to be related to the 2008 snowmelt. However, this was not reproduced during the 2009 snowmelt.

Chemical analysis

Concentrations of nitrate were detected in the well, but the levels are below the maximum allowed concentration. It would be important to monitor this parameter. It is recommended by the MDDEP to have this parameter analysed every few years. If the level gets above 5 mg-N/L, then yearly monitoring is recommended.

Suggestions

- In your situation, the presence of bacteria is recurrent and extra care should be taken for any use of water related to human consumption. The installation of a filtration system that kills microorganisms should be considered. However, this system is already in place.

- It is recommended to get your water tested for bacteria at least 1 time a year, especially after important rainfall events and snowmelt.
- A potential preferential pathway to surface water infiltration is the well annular space. To diminish the infiltration at the wellhead, it is recommended that the soil be mounded around the casing, which will deviate the runoff away from the wellhead, allowing the natural soil process to attenuate the bacteria present in the water.
- Every year, examine into the inside of the well with a flash light. You can look for cracks in the casing caused by corrosion. Also check for holes around the pitless adaptor (area where pipes are connected). A record should be kept and comparisons made year to year. Corrective action can be suggested a licensed well contractor if something wrong is detected.
- It is important to consider activities around the wellhead, especially uphill from the well. For example: if the driveway is located uphill from the well and runoff water flow towards the well. Extra care should be taken to make sure there are no leaks from cars and salt should not be used as de-icing agent. To prevent nitrate contamination, no fertilizers should be used uphill or near the well recharge area.

The information presented in this report comes from the following sources:

*****These are also excellent sources for more information on water wells**

Conboy M.J, Smith S., 2005. A comprehensive consumer's guide for private water wells ISBN 0-9780387-0-3
www.wellwise.ca

Guidelines for Canadian Water Quality-Hardness
http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/hardness-durete/index-eng.php

Ministère du développement durable, environnement et parcs (MDDEP) -*La qualité de l'eau de mon puits* (French only)
http://www.mddep.gouv.qc.ca/eau/potable/depliant/index.htm

Ontario Ministry of Agriculture Food and Rural Affairs/Agriculture and Agri-food Canada. 2003 *Best Management Practices –Water Well*
http://www.omafra.gov.on.ca/english/environment/water/publications.htm

Appendix D: Supporting data for Chapter 4

Monthly variation in coliform concentration

Monthly results for indicator micro-organisms total coliforms (TC) and faecal coliforms (FC) are summarized in Table 2. The number of samples collected each month varied from 19 to 27. TC concentrations range from 0 to 65 000 CFU/100 mL with individual well averages varying from <1 to 2432 CFU/100 mL, and median values from 0 to 4 CFU/100 mL. FC concentration ranges from 0 to 85 CFU/100 mL with individual well averages varying from 0 to ~4 CFU/100 mL, and a median value of 0 CFU/100mL. The coefficients of variation (CV), defined as the standard deviation divided by the mean (expressed as a percentage) range from 182 to 514% for TC and from 0 to 520% for FC. The lowest TC CV is observed in June 2008 whereas the highest is in September 2008. The large CV of September is explained by high concentration of TC in W1 (65 000 CFU/100mL). This outlier affects both the average and CV for this month. From July to October 2008, the median value for TC concentration is greater than 0. This corresponds to the highest relative frequency of samples contaminated by TC and FC. October 2008 shows the highest CV for FC during the sampling period. FC were not detected in May, June and November 2008 nor in January, March and April 2009.

Table D1: Descriptive statistics of indicator bacteria concentration during the sampling period.

Month Sampled	N	Total coliforms (CFU/100mL)							Faecal coliforms (CFU/100mL)					
		Mean	St.Dev	C.V (%)	Median	Range	R.F >0 (%)	R.F ≥10 (%)	Mean	St.Dev	C.V (%)	Median	Range	R.F >0 (%)
April 2008	25	76.0	319.1	419.9	0	0-1600	24.0	16.0	0.9	4.6	500.0	0	0-23	4.0
May 2008	27	2.0	6.1	311.0	0	0-28	14.8	11.1	0.0	0.0	0.0	0	0-0	0.0
June 2008	27	1.0	1.9	182.3	0	0-8	33.3	0.0	0.0	0.0	0.0	0	0-0	0.0
July 2008	27	24.7	67.8	274.3	2	0-300	66.7	25.9	3.5	16.3	469.2	0	0-85	14.8
August 2008	25	16.5	34.3	207.7	3	0-165	60.0	40.0	2.6	12.7	482.2	0	0-66	14.8
eptember 2008	27	2431.5	12504.5	514.3	4	0-65000	59.3	33.3	0.3	0.9	293.3	0	0-4	14.8
October 2008	27	19.6	46.6	237.2	1	0-214	55.6	29.6	2.0	10.4	519.6	0	0-54	3.7
November 2008	26	2.1	4.0	193.5	0	0-18	38.5	3.8	0.0	0.0	0.0	0	0-0	0.0
December 2008	25	3.5	9.1	258.4	0	0-42	48.0	8.0	0.1	0.3	346.1	0	0-1	8.0
January 2009	25	1.4	3.2	230.5	0	0-14	32.0	4.0	0.0	0.0	0.0	0	0-0	0.0
February 2009	21	1.2	3.3	266.5	0	0-12	23.8	9.5	0.0	0.2	458.3	0	0-1	4.8
March 2009	23	2.0	5.6	274.6	0	0-25	30.4	8.7	0.0	0.0	0.0	0	0-0	0.0
April 2009	19	0.3	0.9	354.7	0	0-4	10.5	0.0	0.0	0.0	0.0	0	0-0	0.0
May 2009	26	0.6	1.6	269.3	0	0-6	15.4	0.0	0.1	0.6	509.9	0	0-3	3.8

Seasonal variability as a function of water type

The month of April 2008 shows high concentrations of TC and FC for the Ca-Mg-HCO_3 and mixed-water types, despite a relatively low cumulated precipitation (Figs. 4a and 6a). For the Ca-Mg-HCO_3 and Na-HCO_3, the sum of concentration of TC is generally lower from December 2008 to March 2009 compared to warmer months (Figs. 4a and 5a). This period showed little liquid precipitation because temperatures are generally below freezing point. The sum of TC concentration and the relative frequency of contamination are higher from July to October 2008 for the Ca-Mg-HCO_3 water type, and FC are detected in August and September 2008 for some of the wells. The relative frequency of TC occurrence is >30% from June to December, and <30% during the remainder of the sampling period (Fig 4b). When comparing the Ca to the Ca-Mg subtype, the Ca-Mg subtype shows higher mean value for coliforms. From July to December 2008, FC are detected in only two wells (W5 and W11) from this water type and these wells are classified into the Ca-Mg subtype. TC are consistently detected from July to October 2008 in wells classified in the Na-HCO_3 water type, but do not always exceed the DWO (Appendix D). The relative frequency of coliform occurrence is somewhat higher from July to December for this water type (Fig. 5b). Lastly, in the mixed-water type, there are no strong trends observed when comparing relative frequency of positive samples for TC because the wells in this water type are consistently contaminated. Relatively higher sums of TC concentration are observed from July to October 2008, whereas the highest sum of TC concentration is found in September followed by October when the relative frequency of occurrence exceeds 60% (Fig. 6b).

Ca-CHO_3 water type

Figure D1 shows the mean TC concentration and the relative frequency of sample which tested positive for coliform bacteria for the wells classified in the Ca-Mg-HCO_3 water type. Some wells are consistently free of coliform bacteria (W13, W14, W15, W20 and W22) while coliform bacteria are consistently or sporadically detected in others. Average concentrations of TC and FC range from 0 to approximately 4500 CFU/100mL and from 0 to about 6 CFU/100mL, respectively. Well-site W1 shows the highest average concentration for TC followed by W27. Even if TC are consistently detected in some wells, the DWO is only exceeded in a few samples. The relative frequency of positive TC samples ranges

from 0 to ~80% while the relative frequency of TC contaminated (TC>DWO) samples ranges from 0 to 30%. FC are detected in well-sites W1, W5, W11 and W27 with average concentration usually less than 5 CFU/100mL and a relative frequency of contaminated sample less than 10%.

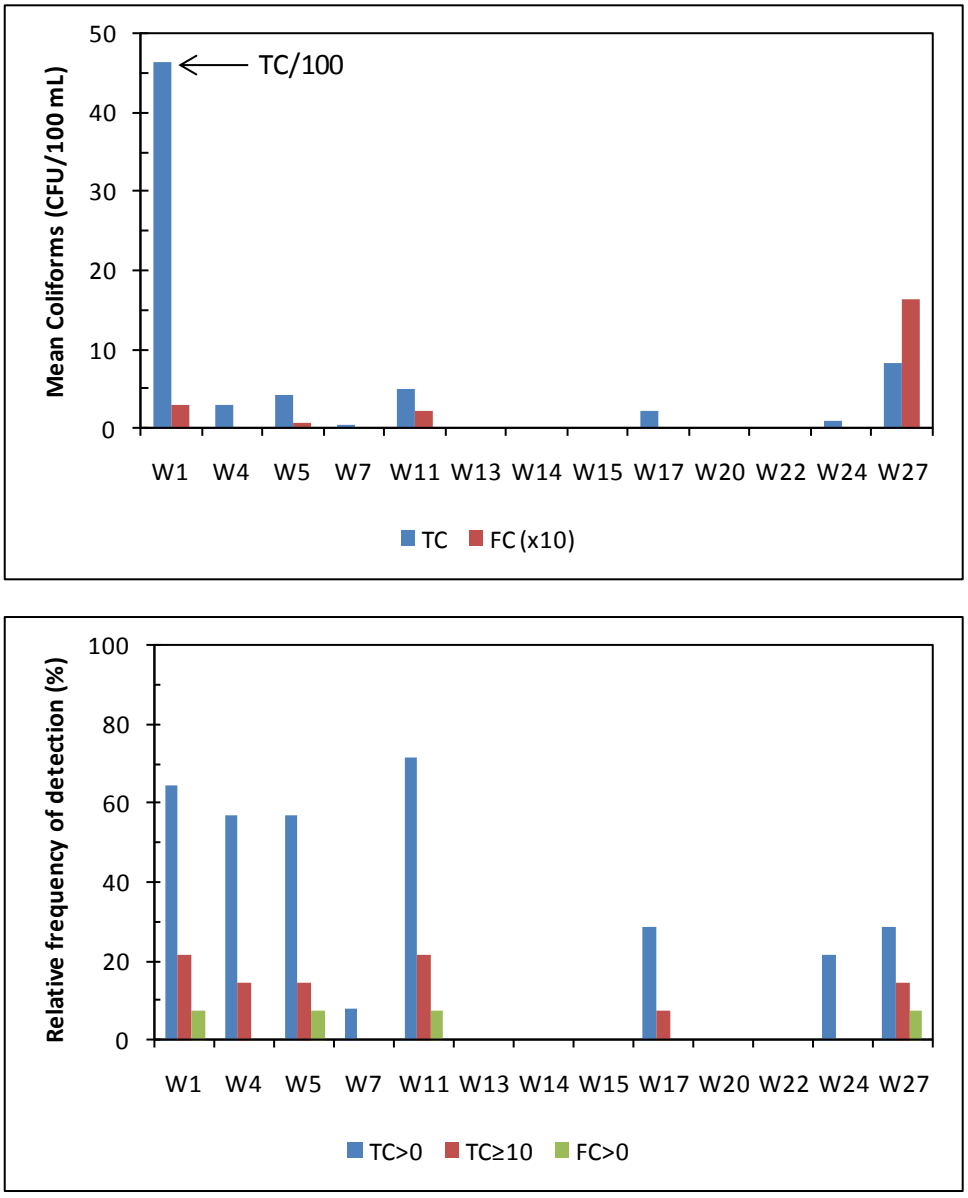


Figure D1: a) mean coliform bacteria concentration and b) relative frequency of samples which tested positive for coliform bacteria in the Ca (Mg)-HCO3 water type.

Na-HCO_3 water type

Figure D2 shows the mean TC concentration and the relative frequency of sample which tested positive for coliform bacteria for wells classified in the Na-HCO_3 water type. Coliform bacteria are frequently detected in wells from this water type. Average concentration for TC ranges from approximately 2 to 20 CFU/100mL. FC are detected in water samples from well-site W10 (May 2009) and W25 (July 2008). Relative frequency of positive TC sample varies from 35 to ~75% while relative frequency for TC contamination (TC≥10) ranges from 10 to 45%.

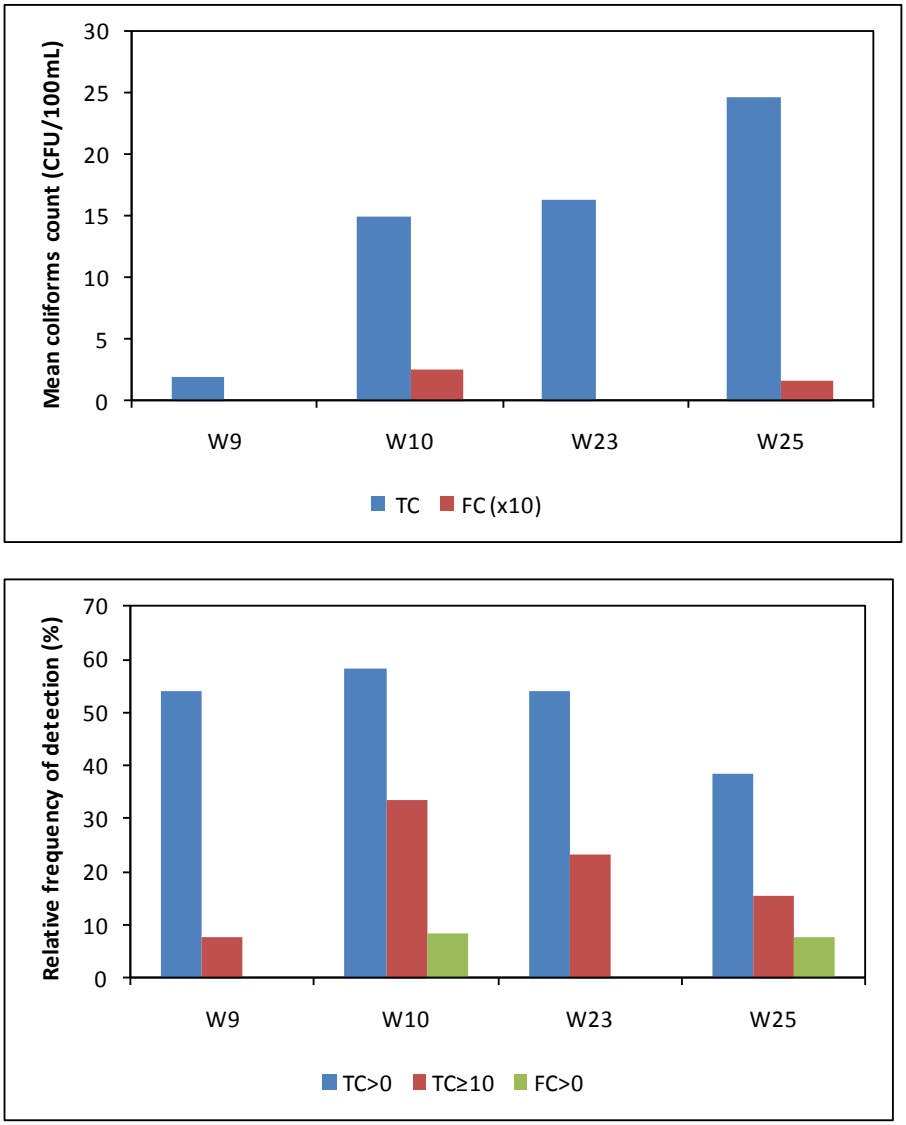


Figure D2: A) Mean coliforms concentration and B) relative frequency of detection for Na-HCO_3 water type.

Mixed-water type

Figure D3 shows the mean TC concentration and the relative frequency of sample which tested positive for coliform bacteria for wells classified in these water types. TC are detected in all wells, at least one month during the sampling period. Average concentration of TC and FC ranges from 0 to ~225 CFU/100mL and from 0 to ~14 CFU/100mL, respectively. The relative frequency of TC positive sample ranges from 25 to ~85% while the relative frequency for TC contamination (TC≥10) ranges from 10 to 50%. Well 2, W3, W16 and W26 are the only wells with FC detection during the sampling period. Relative frequency of FC contamination ranges from 10 to 40%.

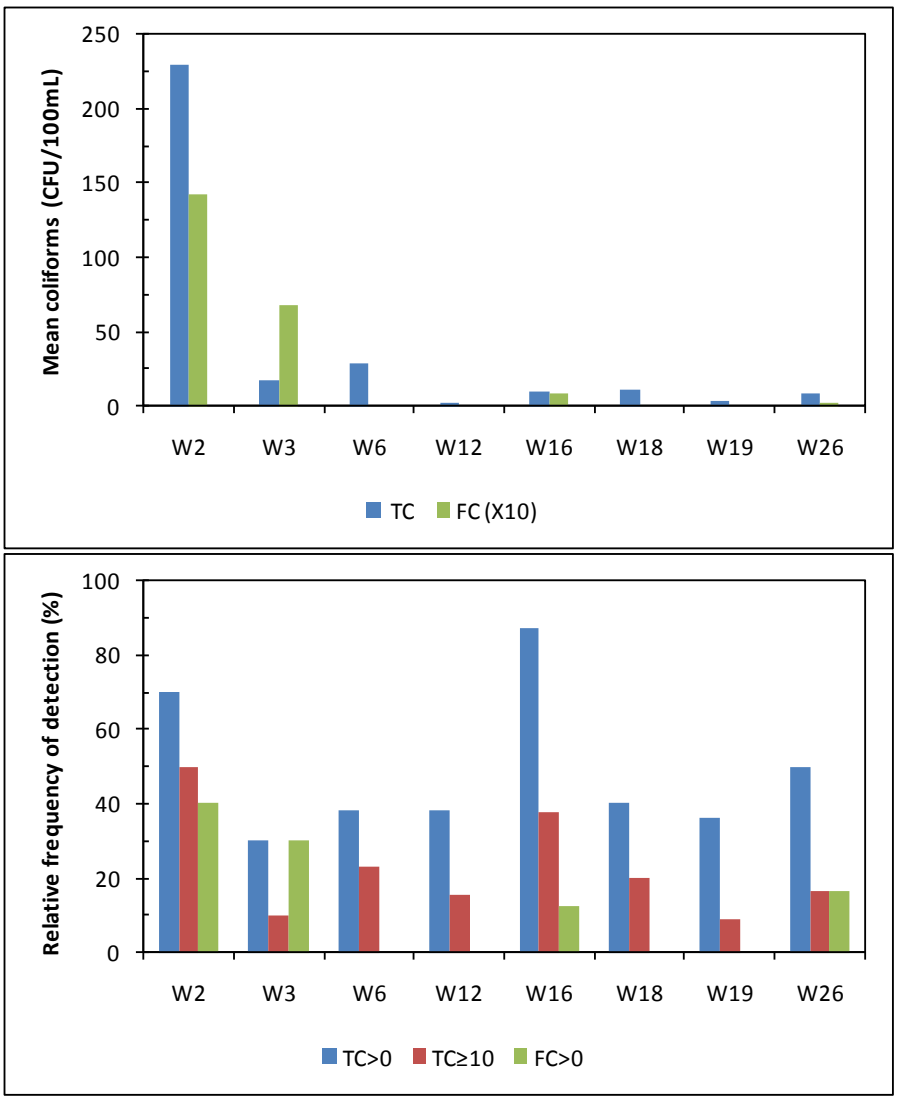


Figure D3: A) Mean coliforms count and B) relative frequency of detection for the mixed ground water facies

Seasonal variability and physical site characteristics

Significant and weak relationships between factors and coliform bacteria concentration are shown in Table 4.4 (Chapter 4). P-values less than 0.05 are considered significant whereas p-values between 0.05 and 0.1 are considered marginally significant (weak relationship). In April 2008, the variable "area sunk around the well" is a significant factor affecting both TC and FC detection. In May 2008, the "presence of bugs in the wellhead" and the "insect proof cap" are significant factors affecting the presence of TC. In October 2008, the variable "water level" affects the presence of TC and the variable "soil depth" has a significant impact in November 2008. Finally, in January 2009, the "water level" and in February 2009 the "presence of an insect proof cap" have a significant impact. Weak relationships include: "insect proof cap" on TC and FC concentrations in April 2008; "water level" affects the TC and FC concentrations in September 2008; "estimated soil depth" on TC concentration in April 2008 and February 2009; "well age" on TC concentration in July 2008, August 2008 and February 2009 and "presence of grout" on FC concentration in October 2008.

Although statistically significant, in some cases, there is no logical reason for a variable to contribute to the coliform bacteria concentration. For example, the presence of an insect proof cap as an important factor contributing to the presence of coliforms in January is questionable since the temperatures are below the freezing point and limit the potential for insects to die-off in the well. This trend may have resulted from none of the wells having an insect proof cap being contaminated in January 2009. In February 2009, "estimated soil depth" and "well age", both related to infiltration of runoff water, are weakly contributing to TC concentration. Technically, the ground is frozen at this time of the year and recharge should not occur unless snow is melting because of warmer temperatures. However, during the sampling period, temperatures above zero are observed on February 7th, February 11th and 12th (Environment Canada, 2010b) and samples were collected on the 9th and the 16th. Snow may have melted and with recharge through a rapid recharge pathway. In this case, these variables may be responsible for the TC concentration in February 2009.

Seasonal variations based on water type

The wells are classified according to their water types to compare the seasonal variations in specific ions. Results for the Ca-Mg-HCO_3 water type, the Na-HCO_3 water type and the mixed- and Ca-Cl water types are displayed in figures 9, 10 and 11, respectively. A CV<1 signifies that the concentration of a specific ion are below the limit of detection.

Ca-Mg-HCO3 water type

Table D2 shows the concentration, the minimum, maximum, mean, standard deviation and the coefficient of variation (C.V.) of the dissolved species for the Ca-HCO_3 water type. Thirteen wells show a Ca-Mg-HCO_3 water type. These wells are mainly located in the recharge area. The pH ranges from 6.3 to 7.9. Fluoride concentration varies from below the limit of detection (<0.5) to 2.0 mg/L. W14 shows the highest concentration of F^- and many wells (W4, W5, W11, W13, W20 and W27) have F^- concentration below the limit of detection. Chloride concentration ranges from 1.0 to 150 mg/L. The lowest Cl^- concentration is observed in W17 and the highest in W15. Nitrate concentration ranges from <0.1 to 4.3 mg-N/L. Nitrate is not consistently detected in wells and in some cases; NO_3-N is not detected during the sampling period (W17, W20 and W22). In other cases, NO_3-N was occasionally detected (W11, W14, W24) or consistently detected (W1, W4, W5, W7, W13, W15, W27). Well-site W13 always shows the highest NO_3-N concentration during the sampling period. Sulphate concentration ranges from 5.9 mg/L to 132.8 mg/L. Calcium concentration ranges from 19.9 to 153.5 mg/L. Potassium concentration ranges from 0.5 to 3.7 mg/L. Magnesium concentration ranges from 2 to 33.2 mg/L and Na^+ concentration ranges from 1 to 32.6 mg/L. Lastly, HCO_3^- concentration ranges from 51 to 400 mg/L of $CaCO_3$.

The ionic strength CV for wells classified in Ca-HCO_3 water type ranges from 2 to 21% (Fig. D4) and does not appear to be influenced by the sub-water type. The degree of variation varies depending on the species and when detected, NO_3-N shows the highest degree of variation for most wells, followed by Cl^-, F^- and Na^+. Calcium and Mg^{2+} show the least amount of seasonal variation in this water type. Certain wells exhibit greater seasonal variation than others. For example, CV for W20 are always below 10% while other wells

have CV ranging between 20-30% for most ion species. This illustrates that most wells in this water type draw water from a dynamic groundwater system likely affected by rapid recharge.

Na-HCO3 water type

Table D2 shows the concentration, the minimum, maximum, mean, standard deviation and the C.V. of dissolved species of wells classified as Na-HCO_3 water type. Four wells were classified as Na-HCO_3 water type (W9, W10, W23 and W25). Three of these well-sites are located under confined aquifer conditions in the southern boundary of the study area. One well-site (W25) is located in a topographic low where the aquifer is unconfined. The pH values range from 6.9 to 8.5. Fluoride concentration varies from 0.7 (W10) to 2.8 mg/L (W23). Chloride concentrations range from 1.0 to 32.7 mg/L. Wells-site W23 shows the lowest Cl^- concentration while W25 shows the highest. Nitrate is not detected in the wells of this water type during the sampling period. Sulphate concentration ranges from 2.4 mg/L (W23) to 85.3 mg/L (W25). Calcium concentration ranges from 4.9 to 49.2 mg/L (W9 and W25 respectively). Potassium concentration ranges from 1.7 to 4.4 mg/L (W9 and W23 respectively). Magnesium concentration ranges from 3.1 to 12.3 mg/L (W9 and W10) and Na^+ concentration ranges from 49.8 to 128.3 mg/L (W9 and W23). Lastly, HCO_3^- concentrations range from 112 to 337 mg/L of $CaCO_3$ (W25 and W23).

The ionic strength CV for wells classified in Na-HCO_3 water type ranges from 4 to 11% (Chapter 4). Anions generally show more seasonal variations compared to cations for wells classified in this water type. Sulphates and Cl^- show the most variability in the CV whereas Mg^{2+}, Na^+ and K^+ show a lower degree of variation. Well W10 has the lowest CV for all dissolved species whereas W23 the highest CV for most dissolved species. Coefficients of variation for W9 are relatively high for Ca^{2+} and Cl^- compared to other ions. Well W25 shows relatively low CV for all ions except for Ca^{2+}, which shows a slightly higher percentage of variation. Overall, most wells from this water type show little seasonal variation in water chemistry which is interpreted to indicate that the groundwater system from which the water is drawn is fairly non-dynamic throughout the sampling period.

Mixed and Ca-Cl water type

Table D2 shows the concentration, the minimum, maximum, mean, standard deviation and the coefficient of variation of dissolved species for wells classified as this mixed water type. Seven well-sites were classified in the mixed water type (W2, W3, W6, W12, W16, W18 and W19) and one well-site (W26) in the Ca-Cl water type. Spatial location and attributes of the wells vary over the study area (Chapter 4). The pH ranges from 6.0 to 9.1. Fluoride concentration ranges from below the detection limit (<0.5) (W3, W6, W16, W26) to 2.1 mg/L (W19). Chloride concentration ranges from 3.4 to 280 mg/L with well-site W3 showing the lowest value and W18 the highest. Nitrate concentration ranges from <0.1 (W3, W12, W19 and W26) to 1.5 mg/L (W18). Well-site W2 is the only well in this group where sporadic detection of NO3-N. Sulphate concentrations range from 6.9 mg/L (W2) to 164 mg/L (W12). Calcium concentration ranges from <1 to 50.2 mg/L (W18 and W16 respectively). Potassium concentration ranges from <0.5 to 15.6 mg/L (W18 and W2 respectively). Magnesium concentration ranges from <0.5 to 74.8 mg/L (W18 and W6) and Na^+ concentration ranges from 11.5 to 360 mg/L (W26 and W18). Lastly, HCO_3^- concentration ranges from 50 to 578 mg/L of $CaCO_3$ (W26 and W2).

The ionic strength CV for wells classified in mixed- and Ca-Cl water types ranges 3 to 16% (Chapter 4). Cations generally show greater seasonal variations compared to anions for wells in this group. From the wells in this group, W18 shows the highest CV for most dissolved species (excepted for SO_4^{2-}) and W19 shows the lowest CV. Coefficients of variation for W2 are relatively higher for NO_3-N, SO_4^{2-} and Ca^{2+} compared to the other ions, whereas W16 has a higher CV for K^+ and has a relatively high CV for Cl^- concentration. Both wells W6 and W12 exhibit a CV range from 15 to 20%. Well W3 is an exception and displays less variation in cation concentration compared to anion concentration.

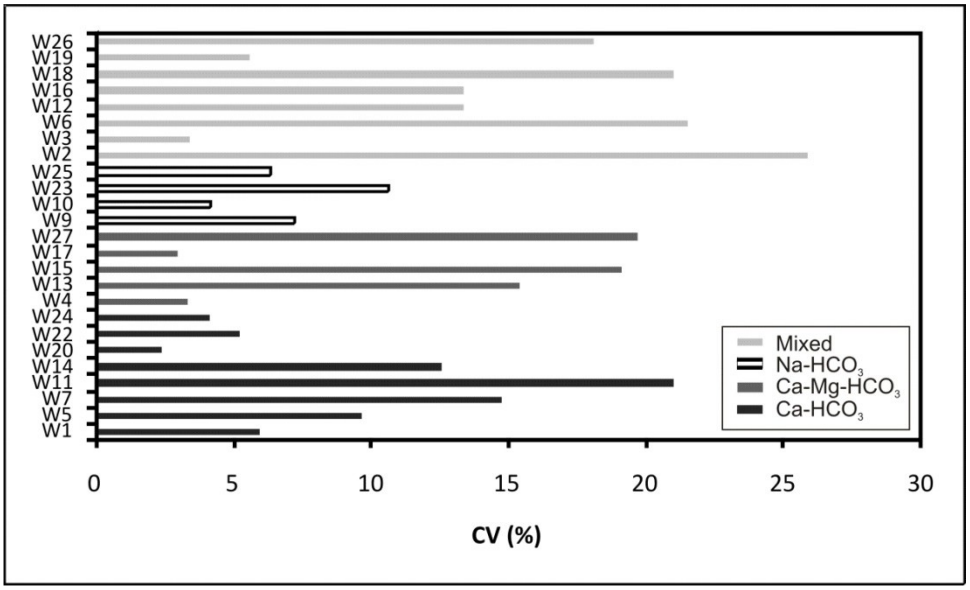


Figure D4: Coefficient of variation of the ionic strength of all wells. The wells are classified depending of the water type.

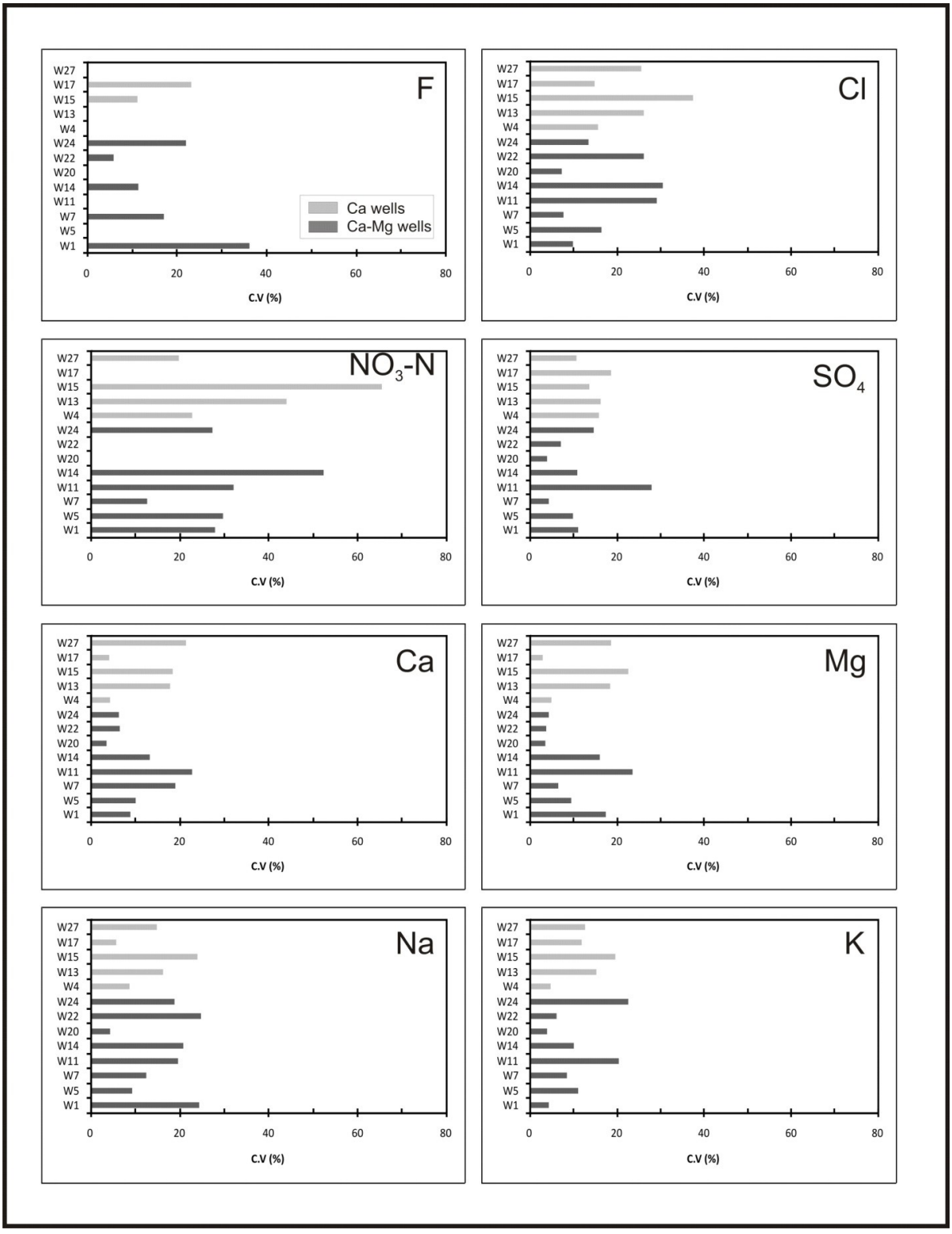


Figure D5: Coefficient of variability (CV) for wells in the Ca-HCO_3 water type and Ca-Mg-HCO_3 subtype.

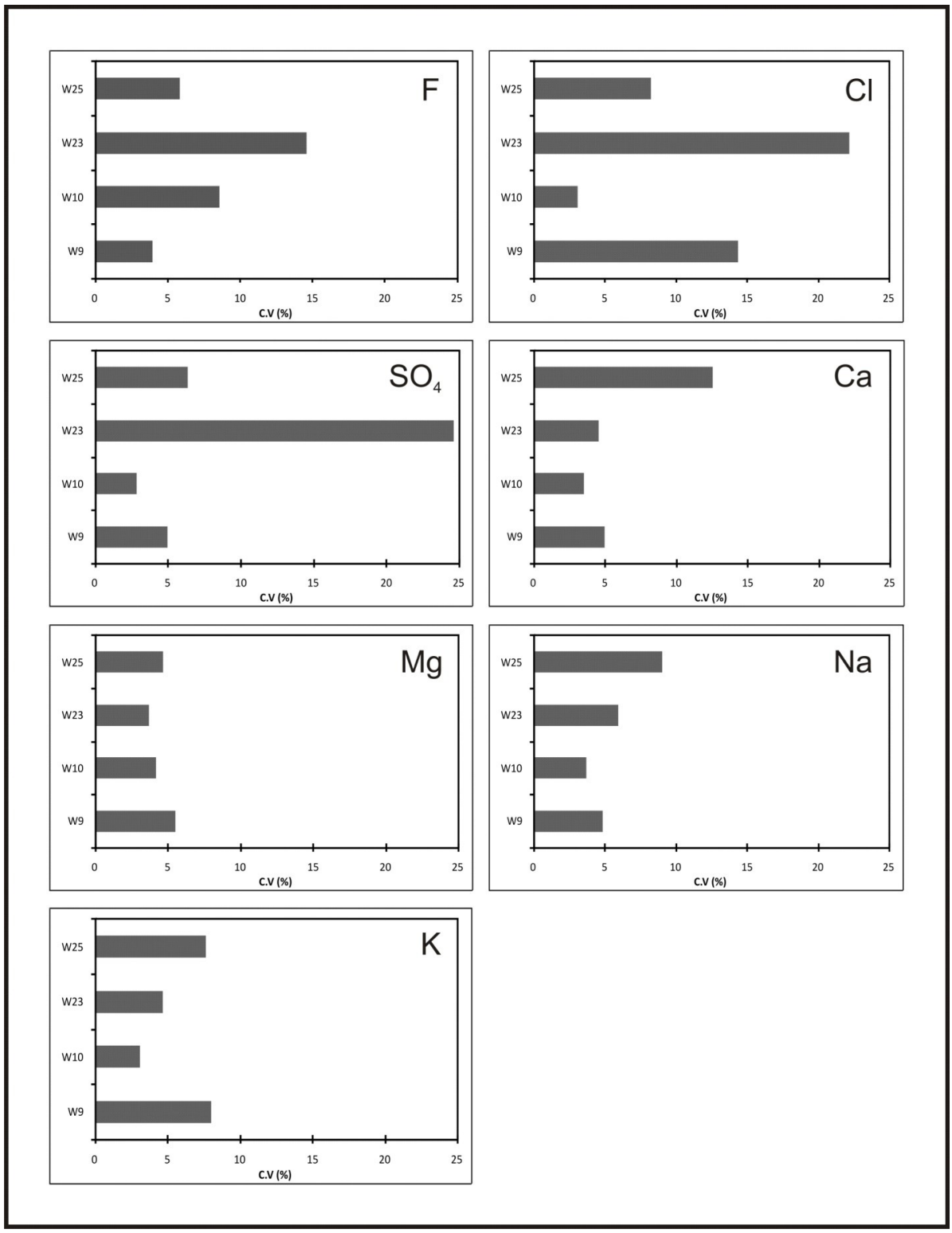


Figure D6: Coefficient of variation for wells classified as Na-HCO_3 water type. There is no CV for NO_3-N since this ion is not detected in the water samples from this group.

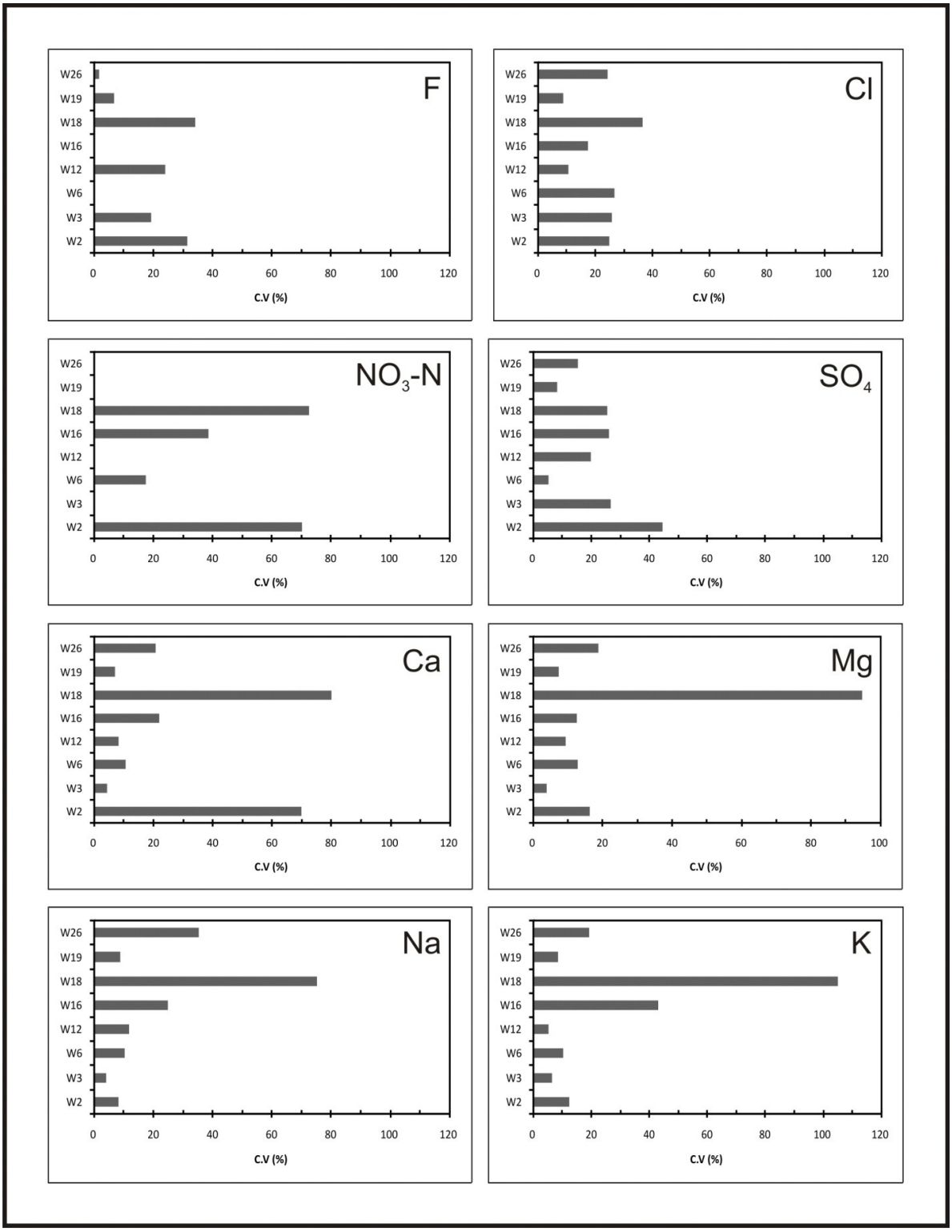


Figure D7: Coefficient of variation for well classified in the mixed- and Ca-Cl (W26) water type.

Seasonal variability in data from individual well-sites

This section describes bacterial and chemical results for each well-site. Monthly concentrations of major ions (Cl^-, NO_3-N, Ca^{2+} and HCO_3^-) and total coliforms (TC) and faecal coliforms (FC) for wells W1 and W2 are shown in Figure D8, W3 and W4 in Figure D9, W5 and W6 in Figure D10, W7 and W9 in Figure D11, W10 and W11 in Figure D12, W12 and W13 in Figure D13, W14 and W15 in Figure D14, W16 and W17 in Figure D15, W18 and W19 in Figure D16, W20 and 22 in Figure D17, W23 and W24 in Figure D18, W25 and W26 in Figure D19 and lastly, W27 in Figure D20. An empty dot and a dash line in the graph indicate that the sample did not meet quality analysis criteria. Average, standard deviation, ranges and coefficient of variability (C.V.) are displays in Table D2. Wells with TC concentration greater or equal to 10 CFU/100mL and FC concentration above 0 CFU/100mL exceeded the Québec drinking water objective (DWO). Months with strong seasonal variation in the results are also identified. Linear correlations, on the transformed data (log transformed and normalized), were also performed to identified correlations between ions and coliforms bacteria specific to each well. This section also presents figures of monthly concentration of F^-, SO_4^{2-}, Mg^{2+}, K^+ and Na^+ along with correlation coefficients (linear with transformed data) and p-values.

W1

Chloride concentration ranges from 23.8 to 33.5 mg/L with an average value of 30 mg/L. Chloride concentration is reasonably consistent during the sampling period with lower concentration observed in October 2008 and April 2009. Calcium concentration ranges from 59 to 76 mg/L with an average of 69 mg/L. Decreases in Ca^{2+} concentration are also observed in October 2008 and April 2009. Bicarbonate concentration follows similar trends to Ca^{2+} concentration with a slight increase observed in March 2009. Nitrate (as N) concentration ranges from 0.2 to 0.7 mg/L with a mean of 0.5 mg-N/L. Nitrate concentration is highly variable throughout the year. Concentration is lower in October 2008, February 2009 and April 2009, with a sharp increase observed from October to November 2008. TC are consistently detected from July 2008 to March 2009 but do not always exceed the Quebec DWO of 10 CFU/100mL. TC concentration ranges from 0 to 65 000 CFU/100mL and FC ranges from 0 to 4 CFU/100mL. The months of July, September and October 2008 exceed the DWO and show elevated TC concentration. FC are also

detected in September. Linear correlations were performed with the transformed dataset to evaluate existing links between ions and possible sources of coliform bacteria. Sulphate negatively correlates with Cl^-, NO_3-N, Ca^{2+} and Mg^{2+} and positively correlates to Na^+. Nitrate positively correlates to Cl^-, Mg^{2+} and Ca^{2+} and negatively correlates to Na^+. Chloride positively correlates to NO_3-N, Ca^{2+} and Mg^{2+} but negatively correlates to Na^+. Lastly, Ca^{2+} and Mg^{2+} positively correlate and both ions negatively correlate to Na^+.

W2

The average Cl^- concentration for W2 is 50.9 mg/L and ranges from 20.5 to 68.9 mg/L. Calcium concentration ranges from 5.6 to 88.7 mg/L with an average value of 41.1 mg/L. A decrease in the Ca^{2+} concentration is observed in June 2008 and values are lower from August to December 2008. Bicarbonate concentration ranges from 227.9 to 578 mg/L with an average value of 380.7 mg/L. Bicarbonate concentration follows similar trends to Ca^{2+} concentration. Nitrate (as N) concentration ranges from <0.1 to 0.5 mg/L with a mean of 0.2 mg-N/L. Nitrate is sporadically detected during the sampling period, from November 2008 to January 2009. TC are consistently detected from July 2008 to January 2009 and exceed the provincial DWO in July, September, October, November and December 2008. FC are also detected in July, September and December 2008. The well was treated in July, after the sample collection. Chloride, SO_4^{2-}, Ca^{2+}, Mg^{2+} and Na^+ positively correlate. Calcium positively correlates with HCO_3^-. Calcium and Mg^{2+} negatively correlate with K^+. Samples were not collected from February to April 2009.

W3

The average Cl^- concentration for W3 is 8.1 mg/L and ranges from 3.4 to 10.3 mg/L. A peak in the Cl^- concentration is observed in July. Decreases are observed in November 2008 and February 2009. The Ca^{2+} concentration ranges from 49.4 to 57.9 mg/L with an average value of 54.4 mg/L. Calcium concentration shows little variation throughout the year. The concentration of HCO_3^- ranges from 198.5 to 278.3 mg/L with an average value of 380.7 mg/L. Bicarbonate concentration shows little variation during the year. Nitrate is not detected during the sampling period. TC are detected from June to August and in December 2008 and exceed the provincial DWO in August. FC are detected in July, August

and December 2008. Positive correlations are observed between Ca^{2+} and Mg^{2+}, between Cl^- and SO_4^{2-} and between Mg^{2+} and FC. A weak positive correlation is observed between Mg^{2+} and TC.

W4

The average Cl concentration for W4 is 4 mg/L and ranges from 2.7 to 4.8 mg/L. Chloride concentration is lower during summer months and higher from December 2008 to May 2009. In November 2008, the concentration decreases to 2.7 mg/L. Calcium concentration ranges from 59 to 76 mg/L with an average value of 69 mg/L. The concentration is consistent throughout the sampling period. Bicarbonate concentration ranges from 140 to 178 mg/L with an average concentration of 161 mg/L. The concentration of HCO_3^- is generally consistent during the sampling period but slight decreases are observed in April and May 2009. Nitrate concentrations ranges from 0.3 to 0.6 mg-N/L with an average value of 0.5 mg-N/L. Nitrate concentration is relatively higher from November 2008 to January 2009. TC are consistently detected during the sampling period and exceed the provincial DWO in July and August 2008. FC are not detected throughout the sampling period. Correlations are positive between SO_4^{2-} and Cl^-, Ca^{2+} and NO_3-N, Ca^{2+} and Mg^{2+}, Ca^{2+} and K^+, Mg^{2+} and Na^+. Negative correlations are observed between Mg^{2+} and Cl^- and between Ca^{2+} and TC. Finally, a weak negative correlation is observed between NO_3-N and TC.

W5

The average Cl^- concentration for W5 is 18.9 mg/L and ranges from 14.4 to 22.5 mg/L. Chloride concentration is lower during summer months and higher from December 2008 to May 2009. Calcium concentration ranges from 44.6 to 61.5 mg/L with an average value of 49.5 mg/L. Calcium concentration is generally consistent throughout the sampling period with a peak value observed in October 2008. Bicarbonate concentration ranges from 110 to 179 mg/L with an average value of 150 mg/L. The concentrations of HCO_3^- are variable during the sampling period. Concentration is higher from July 2008 to February 2009. Nitrate concentration ranges from 0.8 to 1.9 mg-N/L with an average value of 1.2 mg-N/L. Nitrate concentration increases from August to November 2008. TC are consistently

detected during the sampling period and exceed the provincial DWO in August and October 2008. FC are detected in September 2008. Nitrate, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^+ and HCO_3^- positively correlate. Positive correlations are observed between TC and Na^+ and between TC and Mg^{2+}.

W6

The average Cl^- concentration for W6 is 203.6 mg/L and ranges from 119.3 to 263.4 mg/L. The concentration of Cl^- is lower from April to June 2008, gradually increases to reach a maximum value in November 2008, stays consistent until April 2009 and slightly decreases in May 2009. Calcium concentration ranges from 71.6 to 98.4 mg/L with an average value of 85.6 mg/L. The concentrations are generally consistent throughout the year but are slightly higher from August 2008 to February 2009. Concentration of HCO_3^- ranges from 275.6 to 360.6 mg/L with an average value of 303.7 mg/L. Nitrate is consistently detected during the sampling period. Concentration of NO_3-N ranges from 0.6 to 1.0 mg/L with an average of 0.7 mg-N/L. Concentration is higher during spring recharge and decreases during summer, fall and winter. TC are detected in July 2008, September 2008, October 2008, January 2009, February 2009 and May 2009 and exceed the DWO in September, October and January. FC are not detected during the sampling period. All major ions positively correlate. A negative correlation is observed between NO_3-N and TC.

W7

The average Cl^- concentration for W7 is 55.9 mg/L (Table 5) and ranges from 49.8 to 61.3 mg/L. Chloride concentration is relatively consistent throughout the sampling period but a peak value is observed in November 2008. Calcium concentration ranges from 44.2 to 87.0 mg/L with an average value of 75.5 mg/L. Calcium concentration shows a decrease in September 2008 and March 2009 but is fairly consistent throughout the remaining sampling period. Bicarbonate concentration ranges from 76.9 to 295.8 mg/L with an average value of 184.1 mg/L. The concentration of HCO_3^- is variable throughout the sampling period with a peak value observed in August 2008 and decreases in September 2008 and March 2009. Nitrate concentration ranges from 0.6 to 0.9 mg-N/L with an average value of 0.7 mg-N/L. Nitrates are relatively consistent throughout the sampling

period with a peak value observed in November 2008. TC are detected once during the sampling period. TC concentration is below the DWO. FC are not detected during the sampling period. Positive correlations are observed between SO_4^{2-} and F^-, NO_3-N and SO_4^{2-}, Na^+ and Mg^{2+}, Mg^{2+} and K^+, Mg^{2+} and HCO_3^- and between Ca^{2+} and HCO_3^-. A weak positive correlation is observed between Na^+ and Cl^-. Nitrate and K^+, Mg^{2+} and NO_3-N, SO_4^{2-} and Mg^{2+}, SO_4^{2-} and K^+, F^- and Cl^-, and F^- and Na^+ negatively correlate.

W9

The average Cl^- concentration for W9 is 17.3 mg/L and ranges from 13.5 to 20.4 mg/L. Chloride concentration is lower from May to October 2008, higher from December 2008 to May 2009 and a peak value is observed in July 2008. Calcium concentration ranges from 4.9 to 8.5 mg/L with an average value of 7.9 mg/L. The concentration of Ca^{2+} is generally consistent throughout the year. Bicarbonate concentration ranges from 150.7 to 211.5 mg/L with an average value of 178.6 mg/L. The concentration of HCO_3^- is higher during summer months and lower during winter months. Nitrate is not detected during the sampling period. TC are consistently detected from June to December 2008 and exceed the provincial DWO in August 2008. FC are not detected during the sampling period. Chloride positively correlates with SO_4^{2-}, Ca^{2+}, K^+ and Mg^{2+} and negatively correlates with TC. Sulphate positively correlates with Ca^{2+}, K^+ and Mg^{2+} and negatively correlates with TC. Calcium, Mg^{2+}, K^+ and Na^+ positively correlate. Calcium, Mg^{2+}, Na^+ positively correlate with HCO_3^-.

W10

The average Cl^- concentration for W10 is 27.4 mg/L and ranges from 26.1 to 28.8 mg/L. Chloride concentration shows little variation through out the sampling period. Calcium concentration ranges from 22.2 to 825.7 mg/L with an average concentration of 24.2 mg/L. Bicarbonate concentration ranges from 148.7 to 232.2 mg/L with an average concentration of 169.8 mg/L. Bicarbonate concentration is relatively consistent throughout the sampling period with a peak value observed in April 2008. Nitrate is not detected during the sampling period. TC are consistently detected from July to December 2008 and in May 2009. With the exception of December 2008, the DWO is exceeded. FC are also detected

in May 2009. Positive correlations are observed between F^- and Cl^-, C^l- and SO_4^{2-}, Na^+ and K^+, Na^+ and Mg^{2+} and between Ca^{2+} and Mg^{2+}. Chloride and SO_4^{2-} negatively correlate with Ca^{2+}.

W11

The average Cl^- concentration for W11 is 13.3 mg/L and ranges from 4.6 to 20.2 mg/L. A decrease in Cl^- concentration is observed in September 2008 followed by an increase in October 2008. Calcium concentration ranges from 27.7 to 56.4 mg/L with an average concentration of 37.6 mg/L. The concentration of Ca^{2+} is higher during summer and fall recharge while it is lower during winter and spring. Bicarbonate concentration ranges from 85.3 to 176.2 mg/L with an average value of 123.0 mg/L. Bicarbonate concentration follows similar trends to Ca^{2+} concentration. Nitrate concentration ranges from <0.1 to 0.2 mg-N/L with an average concentration of 0.12 mg-N/L. Nitrate is sporadically detected during the sampling period. The concentration is above the detection limit in August and October 2008. TC are consistently detected during the sampling period and are above the DWO in July, August and October 2008. FC are also detected in August 2008. Chloride, SO_4^{2-}, K^+, Mg^{2+} and Na^+ positively correlate. Nitrate positively correlates with Ca^{2+}, Mg^{2+}, Na^+, HCO_3^- and TC and weakly positively correlates with SO_4^{2-}. Calcium, Mg^{2+}, Na^+, HCO_3^- and TC positively correlate. Potassium positively correlates with Ca^{2+}, Mg^{2+} and HCO_3^-.

W12

The average Cl^- concentration for W12 is 67.9 mg/L and ranges from 42.4 to 80.5 mg/L. Chloride concentration is slightly lower during spring recharge. Calcium concentration ranges from 11.4 to 20.8 mg/L with an average concentration of 17.5 mg/L. Calcium concentration is consistent throughout the sampling period. Bicarbonate concentration ranges from 65.1 to 147.0 mg/L with an average concentration of 110.7 mg/L. Bicarbonate concentration follows similar trends to Ca^{2+} concentration. Nitrate is not detected during the sampling period. TC are detected from September 2008 to January 2009 and exceed the provincial DWO in September and October 2008. FC are not detected during the sampling period. Chloride, SO_4^{2-} and Na^+ positively correlate. Calcium,

Cl^- and K^+ positively correlate. Calcium positively correlates with Mg^{2+} and HCO_3^-. Sodium positively correlates with K^+ and HCO_3^-. TC negatively correlates with Ca^{2+} and SO_4^{2-}.

W13

The average Cl^- concentration for W13 is 57.5 mg/L and ranges from 34.2 to 82.9 mg/L. Chloride concentration is lower from May to August 2008 and increases until a peak value is observed in March 2009. Calcium concentration ranges from 81.9 to 135.0 mg/L with an average concentration of 111.3 mg/L. Calcium concentration is higher during fall recharge and winter and is lower during spring and summer. Bicarbonate concentration ranges from 187.0 to 251.3 mg/L with an average concentration of 214.7 mg/L. Bicarbonate concentration follows similar trends to Ca^{2+} concentration. Nitrate concentration ranges from 1.1 to 4.3 mg-N/L with an average concentration of 2.4 mg-N/L. The concentration is lower during spring and summer, increases during fall, peaks in November 2008, and decreases during winter. TC and FC are not detected during the sampling period. Chloride, NO_3-N and HCO_3^- positively correlate. Nitrate positively correlates with SO_4^{2-}, Ca^{2+}, Mg^{2+} and HCO_3^-. Sulphate positively correlates with Ca^{2+}, K^+, Mg^{2+} and Na^+. Potassium positively correlates with Ca^{2+}, Na^+ and Mg^{2+}. Lastly, Ca^{2+}, Mg^{2+}, Na^+ and HCO_3^- positively correlate.

W14

The average Cl- concentration for W14 is 3.2 mg/L and ranges from 0.6 to 25.9 mg/L. Chloride concentration is lower during summer months and slowly returns to the average value after the September 2008. Calcium concentration ranges from 31.4 to 41.3 mg/L with an average concentration of 37.3 mg/L. Calcium concentration is consistent throughout the sampling period but a small decrease is observed in April and May 2009. Bicarbonate concentration ranges from 112.5 to159.0 mg/L with an average concentration of 131.2 mg/L. The concentration of HCO_3^- follows similar trends to Ca^{2+} concentration. Nitrate concentration ranges from <0.1 to 0.4 mg-N/L. Nitrate is detected sporadically during the sampling period, in October and November 08. TC and FC are not detected during the sampling period. Fluoride positively correlates with Cl^-, SO_4^{2-}, Mg^{2+}, Na^+ and

HCO_3^-. Chloride positively correlates with Na^+. Sulphate, Mg^{2+} and Na^+ positively correlate. Lastly, Na^+ positively correlates with HCO_3^-.

W15

The average Cl^- concentration for W15 is 57.5 mg/L and ranges from 28.6 to 150.1 mg/L. Chloride concentration decreases from spring to summer, increases during fall, peaks in December 2008, and decreases during winter months. Calcium concentration ranges from 65.3 to 153.5 mg/L with an average of 121.6 mg/L. Calcium concentration decreases from May to September and gradually increases until December 2008. Bicarbonate concentration ranges from 118.9 to 396.3 mg/L with an average concentration of 248.8 mg/L. Bicarbonate concentration follows similar trends to Ca^{2+} concentration where September 2008 shows the lowest concentration of HCO_3^-. Nitrate concentration ranges from 0.1 to 1.1 mg-N/L with an average concentration of 0.5 mg-N/L. The concentration is lower during spring and summer, increases during fall, peaks is observed in November 2008, and decreases during winter. TC and FC are not detected during the sampling period. Fluoride positively correlates with Cl^- and SO_4^{2-}. All other major ions positively correlate within each other.

W16

Many samples are missing for this well because samples were not collected or errors on the analysis were too high (>>10%). The average Cl^- concentration for W16 is 97.4mg/L and ranges from 68.0 to 122.3 mg/L. Calcium concentration ranges from 50.2 to 90.6 mg/L with an average concentration of 71.6 mg/L. Bicarbonate concentration ranges from 89.1 to 215.1 mg/L with an average concentration of 151.6 mg/L. The concentrations of Ca^{2+} and HCO_3^- gradually increase from April to June 2008 and gradually decrease from October 2008 to May 2009. Nitrate is consistently detected during the sampling period. The concentration of NO_3-N ranges from 0.1 to 0.7 mg/L with an average of 0.5 mg/L. Nitrate concentration is higher during spring recharge. TC are consistently detected during the sampling period and TC concentration consistently exceed the DWO. The months of July 2008, December 2008, January 2009 and May 2009 did not exceed the DWO. FC are detected from July to September 08 and in February 2009. Sulphate positively correlates

with K^+. Calcium positively correlates with Mg^{2+} and HCO_3^-. A negative correlation exists between NO_3-N and FC.

W17

The average Cl^- concentration for W17 is 1.3 mg/L and ranges from 1 to 1.5 mg/L. Chloride concentration is lower during June and July 2008 and is consistently higher from October 2008 to May 2009. Calcium concentration ranges from 42.5 to 49.5 mg/L with an average concentration of 47.0 mg/L. The concentration of Ca^{2+} is reasonably consistent throughout the year. The concentration of HCO_3^- ranges from 163.0 to 205.2 mg/L with an average concentration of 181.8 mg/L. Bicarbonate concentration follows similar trends to Ca^{2+} concentration. Nitrate is not detected in this well during the sampling period. TC are sporadically detected from July to December 2008 and exceed the DWO of 10 CFU/100mL in August 2008. FC are not detected during the sampling period. Chloride and SO_4^{2-} positively correlate and negatively correlate with HCO_3^-. Calcium, Mg^{2+} and Na^+ positively correlate.

W18

The average Cl^- concentration for W18 is 167.8 mg/L and ranges from 84.8 to 279.1 mg/L. Concentration of Cl^- is higher during spring 2008 and is lower from July 2008 to April 2009. Calcium concentration ranges from 0.9 to 154.6 mg/L with an average concentration of 70.1 mg/L. Concentration of Ca^{2+} is lower from May August 2008 and significantly higher from January to May 2009. The concentration of HCO_3^- ranges from 177.7 to 215.1 mg/L with an average concentration of 400.1 mg/L. Bicarbonate concentration is lower during springs 2008 and 2009 and higher during the remaining sampling period. Nitrate is consistently detected during the sampling period. The concentration of NO_3-N ranges from 0.2 to 1.5 mg/L with an average of 0.7 mg/L. Nitrate concentration follows similar trends to Cl^- concentration. TC are sporadically detected during the sampling period and exceed the DWO in September and October 2008 and in March 2009. FC are not detected during the sampling period. Positive correlations are observed between Cl^- and NO_3-N, between Cl^- and Na^+, between SO_4^{2-} and HCO_3^-, between Ca^{2+} and Mg^{2+} and between Mg^{2+} and K^+. Calcium and Na^+ negatively correlate.

W19

The average Cl^- concentration for W19 is 60.0 mg/L and ranges from 51.5 to 69.6 mg/L. Calcium concentration ranges from 11.9 to 15.0 mg/L with an average of 13.7 mg/L. Bicarbonate concentration ranges from 107.7 to 136.5 mg/L with an average of 123.5 mg/L. Chloride, Ca^{2+} and HCO_3^- concentrations are consistent throughout the sampling period. Nitrate is not detected during the sampling period. TC are sporadically detected during the sampling period and exceed the DWO in March 2009. FC are not detected during the sampling period. Positive correlations are observed between Cl^- and F^-, between Ca^{2+} and Mg^{2+}, between Ca^{2+} and K^+, between Mg^{2+} and Na^+ and between K^+ and TC. Fluoride and TC negatively correlate.

W20

The average Cl^- concentration for W20 is 66.0 mg/L and ranges from 59.2 to 74.4 mg/L. Calcium concentration ranges from 49.5 to 55.1 mg/L with an average of 52.4 mg/L. The concentration of Ca^{2+} is generally consistent throughout the year. Bicarbonate concentration ranges from 117.9 to 186.2 mg/L with an average concentration of 141.9 mg/L. The concentration of HCO_3^- follows similar trends to Ca^{2+} concentration. Nitrate, TC and FC are not detected in during the sampling period. Positive correlations are observed between Ca^{2+}, Mg^{2+} and Na^+. Potassium, Na^+ and HCO_3^- positively correlate. A weak negative correlation is observed between SO_4^{2-} and Ca^{2+}.

W22

The average Cl- concentration for W22 is 20.5 mg/L and ranges from 14.6to 30.5 mg/L Chloride concentration is higher from May to November 2008, lower from December 2008 to April 2009 and increases in May 2009. Calcium concentration ranges from 56.9 to 70.9 mg/L with an average of 64.1 mg/L. The concentration of Ca^{2+} is consistent throughout the year. Bicarbonate concentration ranges from 140.2 to 185.7 mg/L with an average of 167.4 mg/L. The concentration of HCO_3^- follows a similar trend to Ca^{2+} concentration. Nitrate, TC and FC are not detected during the sampling period. Calcium positively

correlates with Mg^{2+} and with Cl^-. A negative correlation is observed between F^- and Ca^{2+}. Weak positive correlations are observed between SO_4^{2-} and Cl^- and between Mg^{2+} and Cl^-.

W23

The average Cl^- concentration for W23 is 10.7 mg/L and ranges from 1.0 to 13.9 mg/L. Chloride concentration is variable between July and October 2008. Calcium concentration ranges from 7.0 to 9.2 mg/L with an average of 8.5 mg/L. Calcium concentration is consistent throughout the year. Bicarbonate concentration ranges from 242.7 to 337.3 mg/L with an average of 306.4 mg/L. The concentration of HCO_3^- follows a similar trend to Ca^{2+} concentration. Nitrate is not detected during the sampling period. TC are sporadically detected during the sampling period and exceed the DWO in August, September and December 2008. FC are not detected during the sampling period. All major ions positively correlate to each other. TC negatively correlates with Cl^-, SO_4^{2-} and Mg^{2+}.

W24

The average Cl^- concentration for W24 is 32.0 mg/L and ranges from 22.5 to 39.5 mg/L. An increase in the Cl^- concentration is observed in September 2008 and a decrease in January 2009. Calcium concentration ranges from 50.1 to 60.7 mg/L with an average of 56.6 mg/L. The concentration of Ca^{2+} is consistent throughout the sampling period. Bicarbonate concentration ranges from 142.6 to 199.8 mg/L with an average of 171.0 mg/L. The concentration of HCO_3^- follows the same trends to Ca^{2+} concentration. Nitrate concentration ranges from <0.11 to 0.2 mg-N/L with an average concentration of 0.12 mg-N/L. Nitrate is sporadically detected during the sampling period and is detected in July and August 2008. TC are sporadically detected during the sampling period and did not exceed above the DWO during the sampling period. FC are not detected during the sampling period. Positive correlations are observed between Ca^{2+} and Mg^{2+} and between NO_3-N and TC. Negative correlations are observed between F^- and NO_3-N, between K^+ and SO_4^{2-} and between Mg^{2+} and Na^+.

W25

The average Cl^- concentration for W25 is 29.4 mg/L and ranges from 24.8 to 32.7 mg/L. Chloride concentration is consistent through the sampling period with a small decrease in January 2009. Calcium concentration ranges from 30.2 to 49.2 mg/L with an average of 43.0 mg/L. The concentration of Ca^{2+} is consistent through out the year with a decrease in September 2008. Bicarbonate concentration ranges from 112.4 to 197.3 mg/L with an average of 157.0 mg/L. The concentration of HCO_3^- follows the same trends to Ca^{2+} concentration. Nitrate is not detected during the sampling period. TC are sporadically detected during the sampling period and exceed the DWO in May and July 2008. FC are also detected in July. A positive correlation is observed between Cl^- and SO42-. Calcium positively correlates with Mg^{2+} and Na^+ positively correlates with K^+. Fluoride weakly negatively correlates with TC.

W26

The average Cl^- concentration for W26 is 89.6 mg/L and ranges from 59.0 to 115.1 mg/L. Chloride concentration is higher from June to August 2008 and in May 2009 and lower in April and December 2008. Calcium concentration ranges from 36.6 to 59.2 mg/L with an average of 48.3 mg/L. Calcium concentration is higher from June to August 2008. Bicarbonate concentration ranges from 50.5 to 89.2 mg/L with an average of 65.8 mg/L. Nitrate is not detected during the sampling period. TC are sporadically detected during the sampling period, consistently detected from July to September 2008, and exceed the DWO in August 2008 where FC are also detected. Positive correlations are observed between F^- and HCO_3^-, between K^+ and Na^+, between TC and FC and between Mg^{2+} and Na^+. Chloride positively correlates with Ca^{2+}, Mg^{2+} and Na^+. Sulphate positively correlates with K^+, Na^+, TC and FC. Sodium positively correlates with TC and FC and TC positively correlates with HCO_3^-. Samples were not collected from February to April 2009.

W27

The average Cl^- concentration for W27 is 1.1 mg/L and ranges from 0.8 to 1.5 mg/L. Chloride concentration is lower from May 08 to August 08, increases from September 2008 to March 2009 and decreases in April 2009. Calcium concentration ranges from 19.9 to 38.2 mg/L with an average of 30.1 mg/L. Bicarbonate concentration ranges from 50.5 to 112.0 mg/L with an average of 83.7 mg/L. The concentration of Ca^{2+} and HCO_3^- follow a similar trend to Cl^- concentration. Nitrate concentration ranges from 0.5 to 0.9 mg-N/L with an average of 0.7 mg-N/L. Nitrate concentration follows similar trends to Cl^- concentration where peak values in NO_3-N concentration are observed in November 2008 and March 2009. TC are detected in April, May and June 08 and September 08 and exceed the DWO from April and May 2008. FC are also detected in April 2008. All major ions positively correlate with each other.

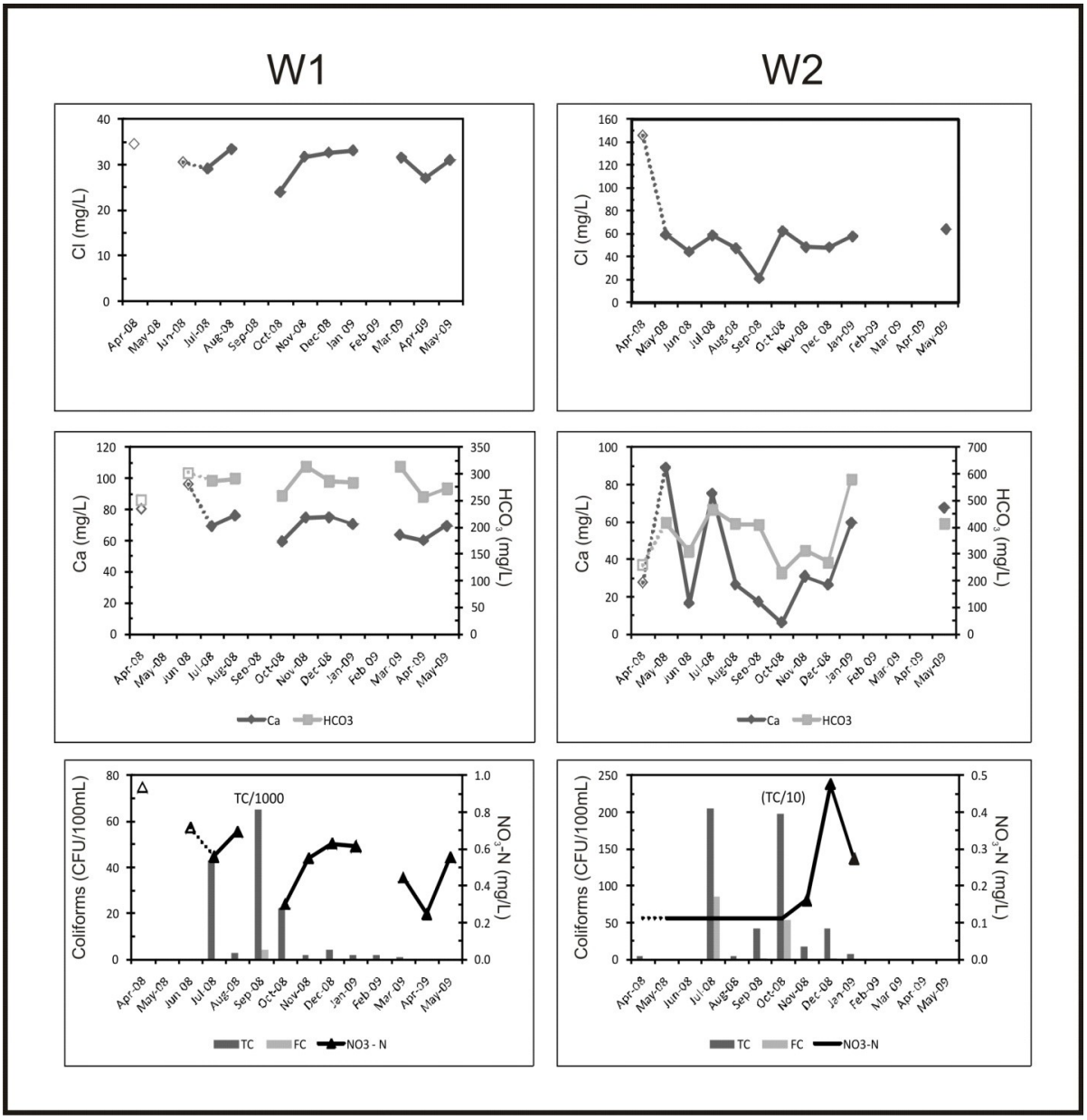


Figure D8: Seasonal variability in ion and coliform bacteria concentrations for well-sites W1 and W2

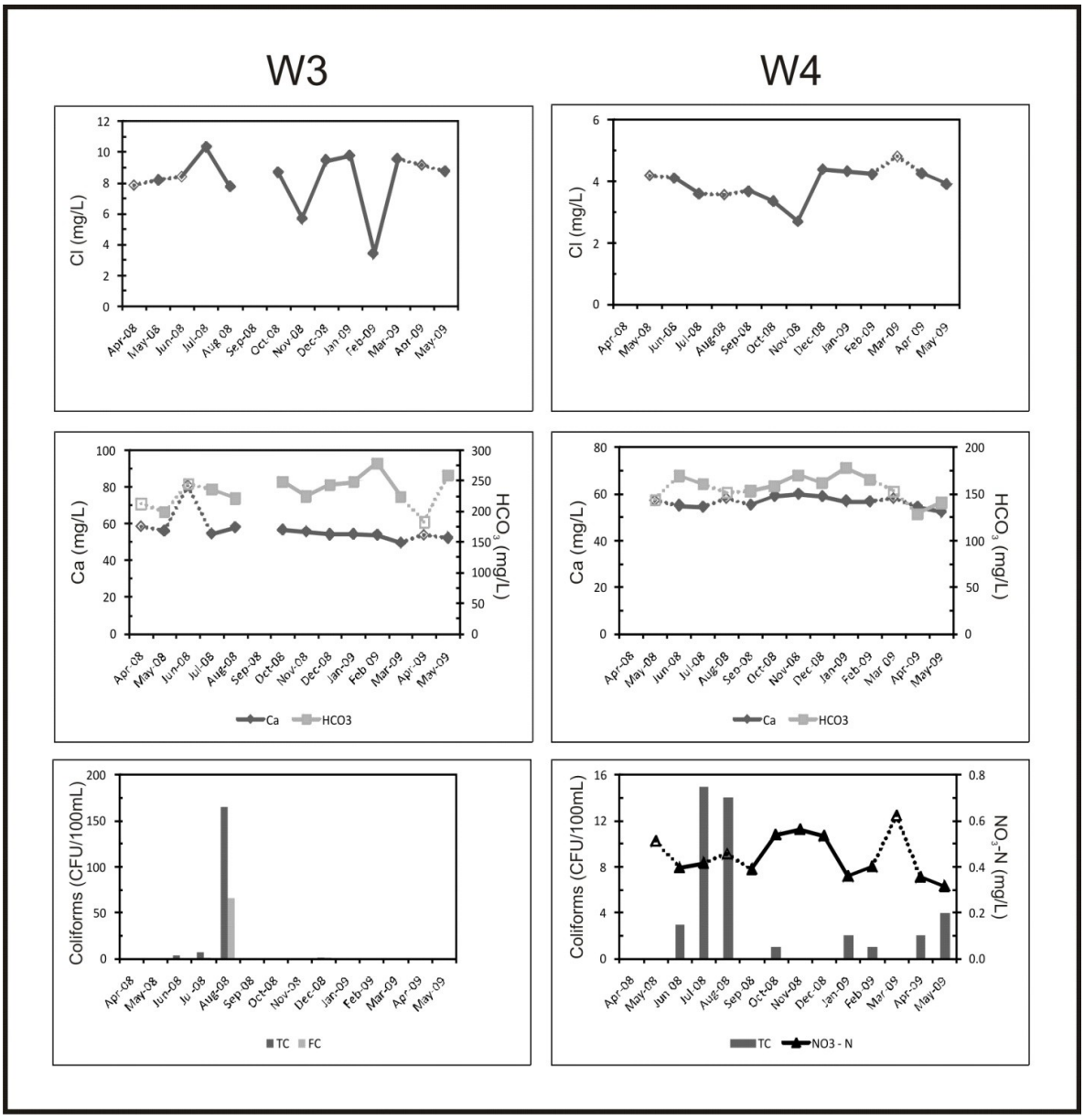


Figure D9: Seasonal variability in ion and coliform bacteria concentrations for well-sites W3 and W4

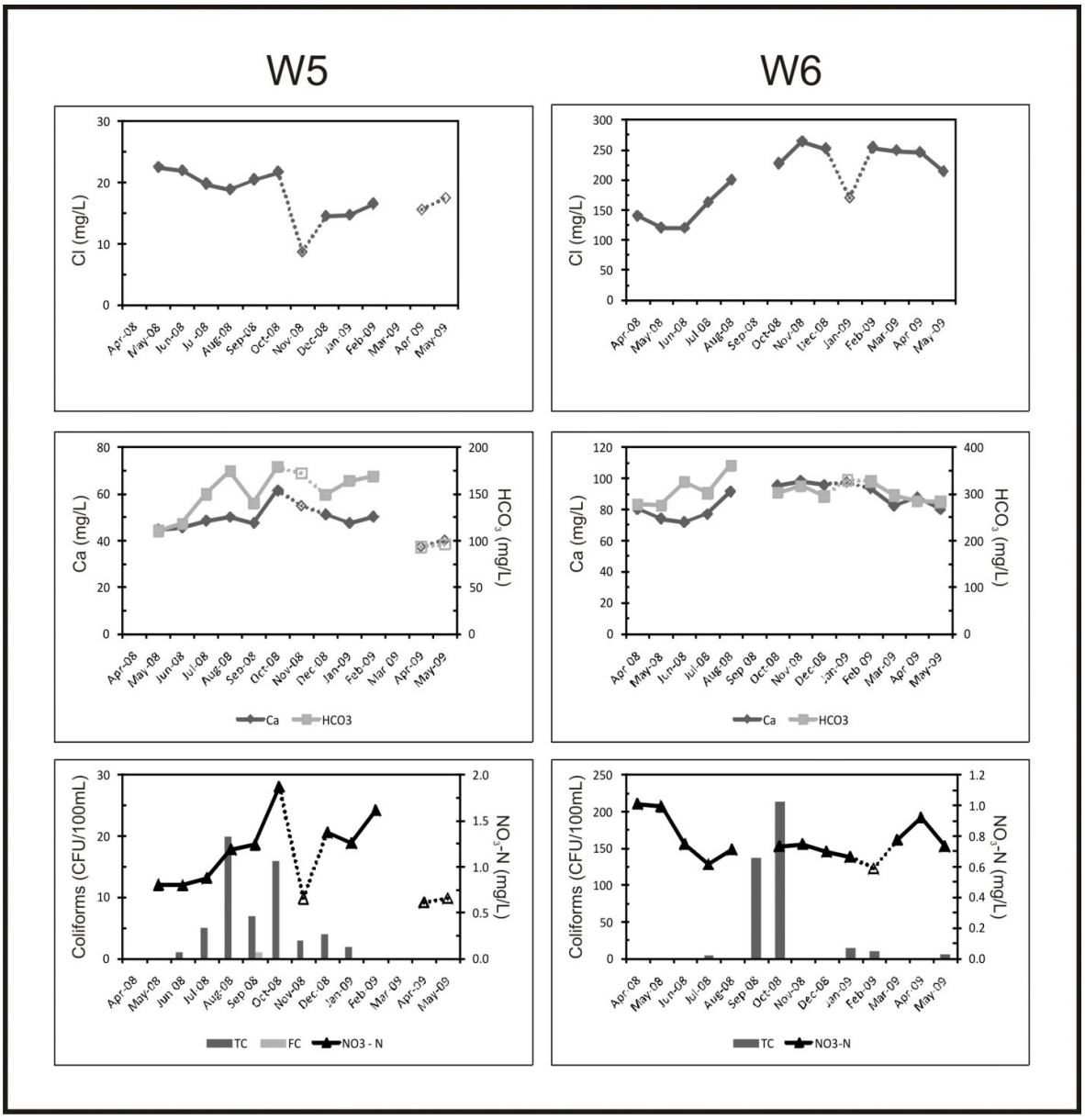


Figure D10: Seasonal variability in ion and coliform bacteria concentrations for well-sites W5 and W6

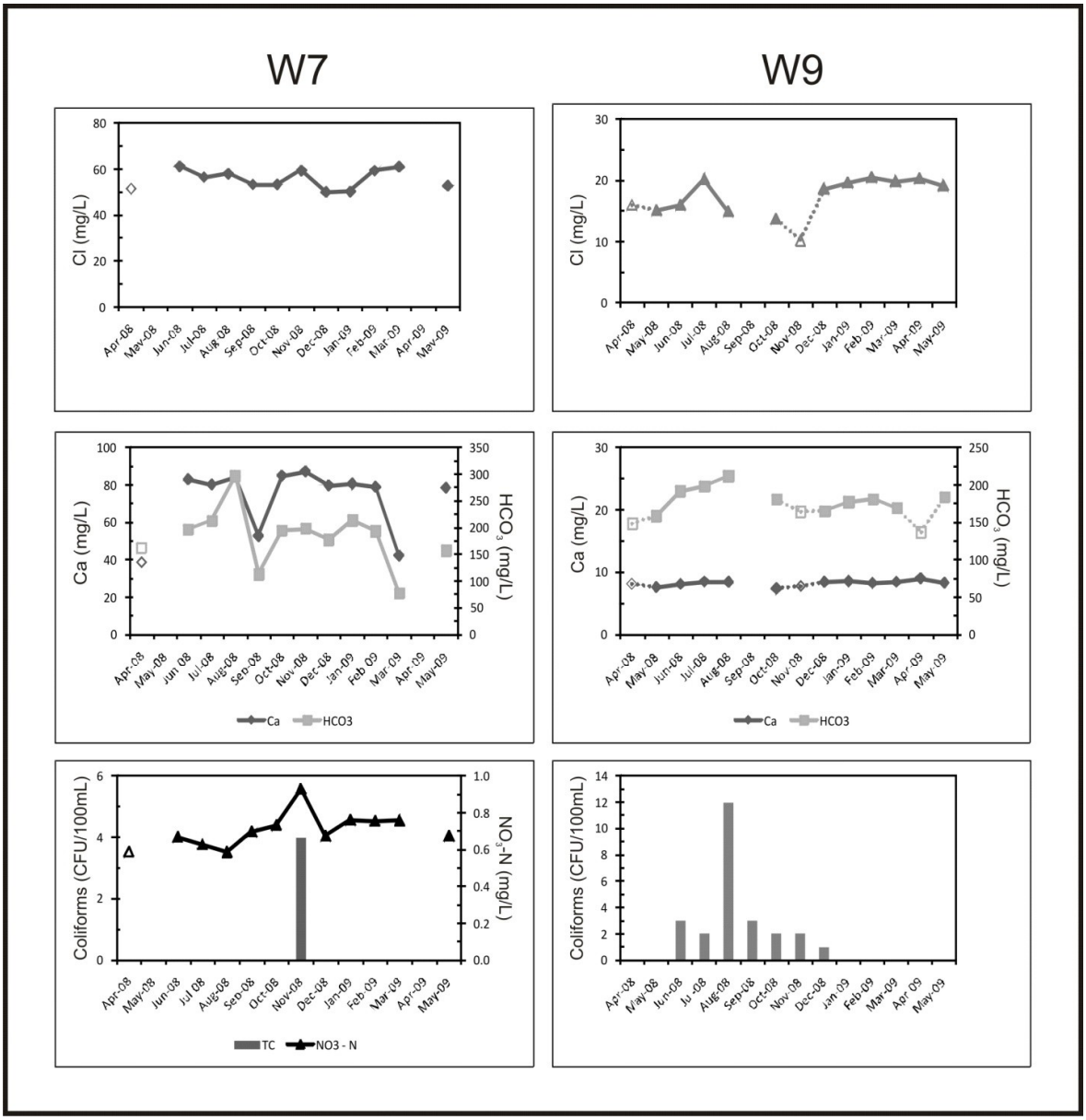


Figure D11: Seasonal variability in ion and coliform bacteria concentrations for well-sites W7 and W9

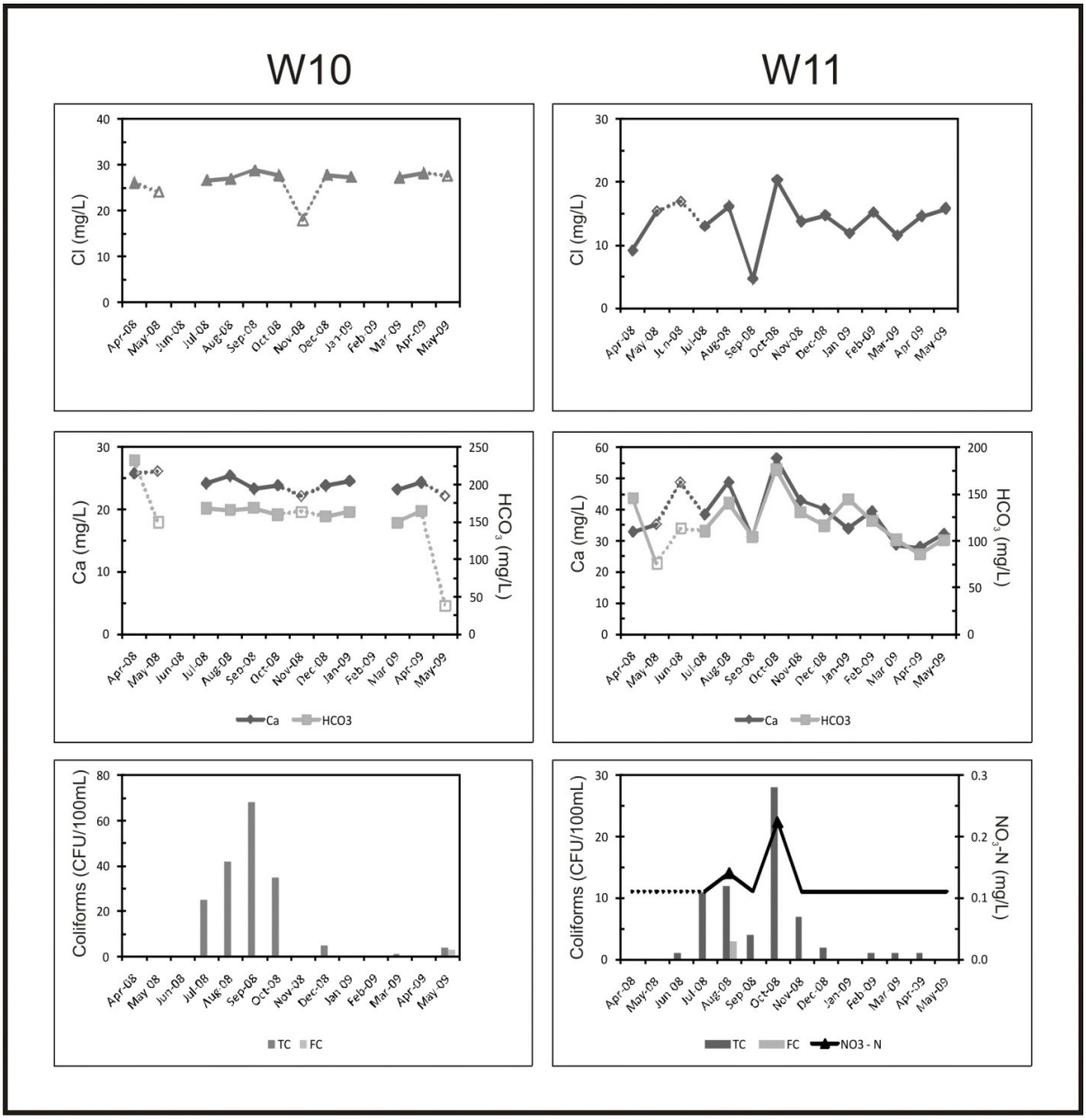


Figure D12: Seasonal variability in ion and coliform bacteria concentrations for well-sites W10 and W11

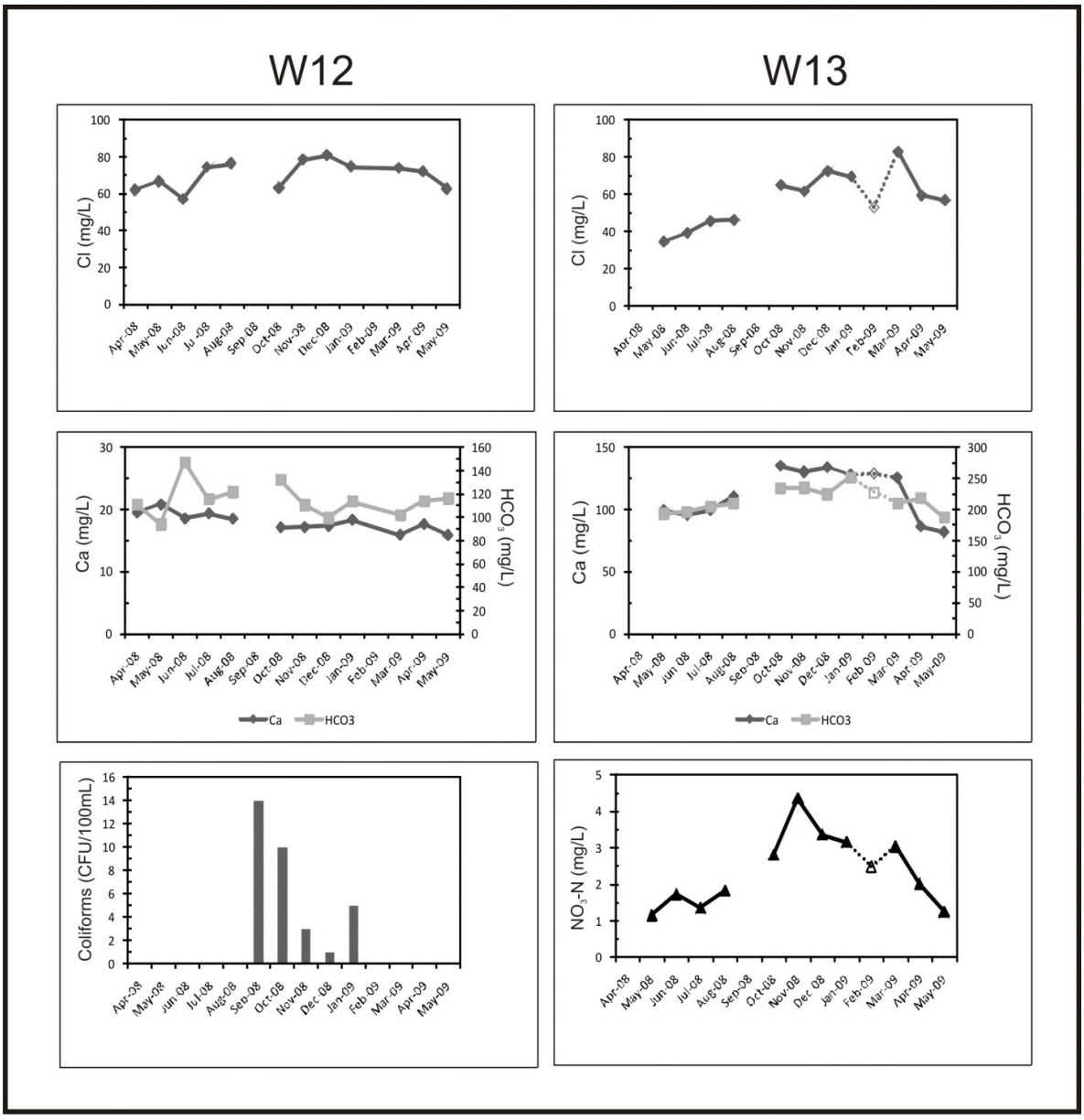


Figure D13: Seasonal variability in ion and coliform bacteria concentrations for well-sites W12 and W13

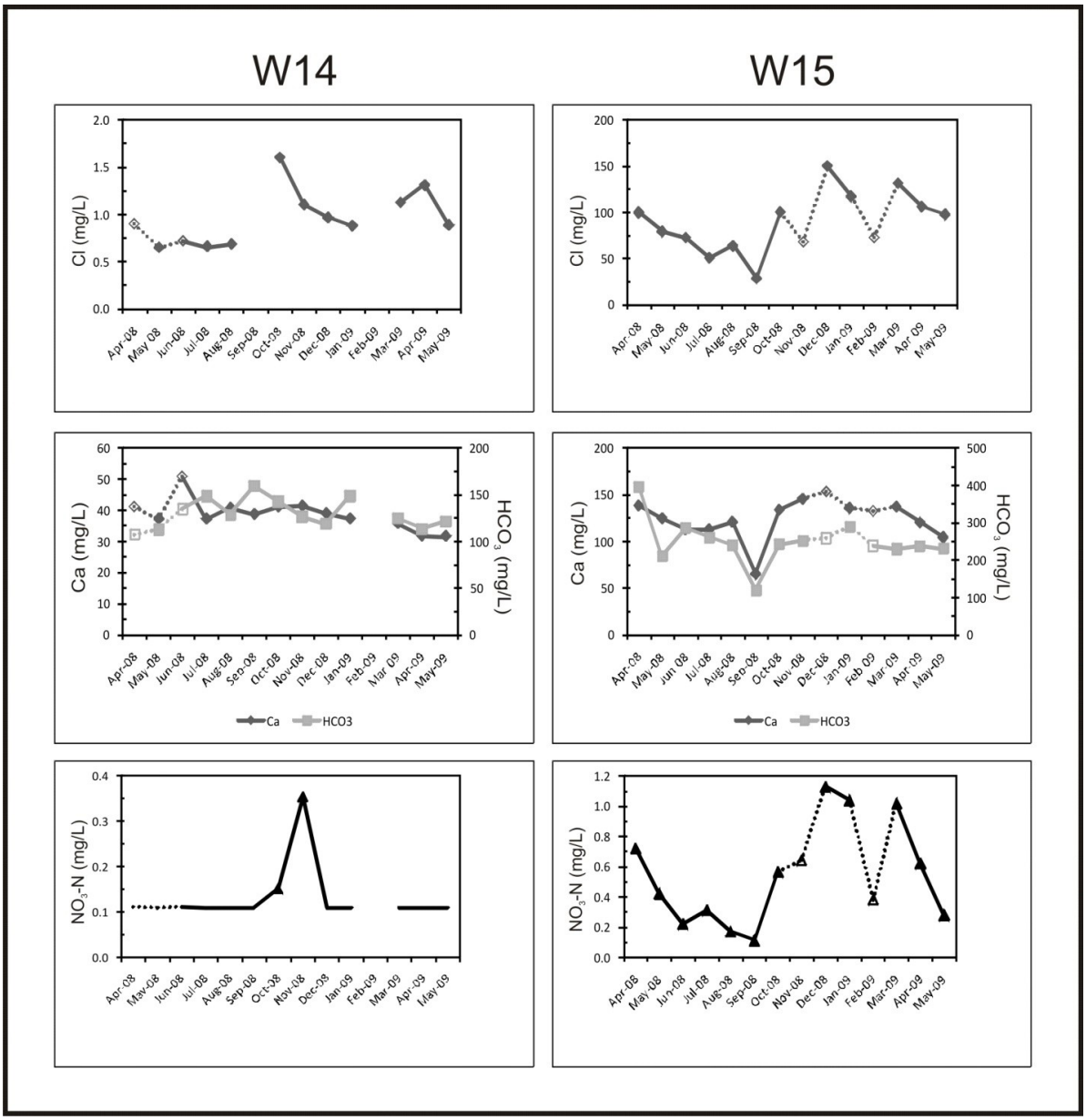


Figure D14: Seasonal variability in ion and coliform bacteria concentrations for well-sites W14 and W15

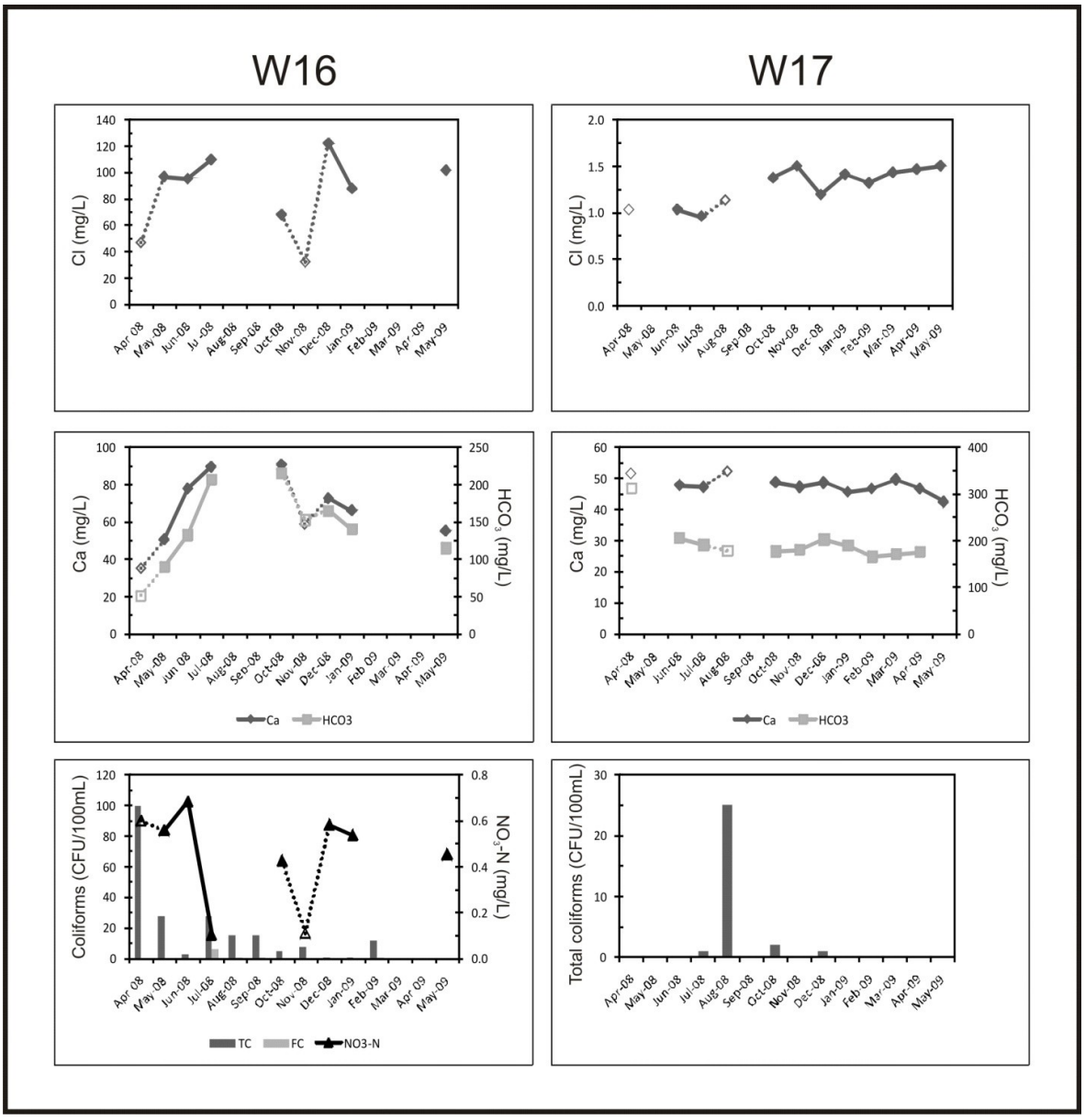


Figure D15: Seasonal variability in ion and coliform bacteria concentrations for well-sites W16 and W17

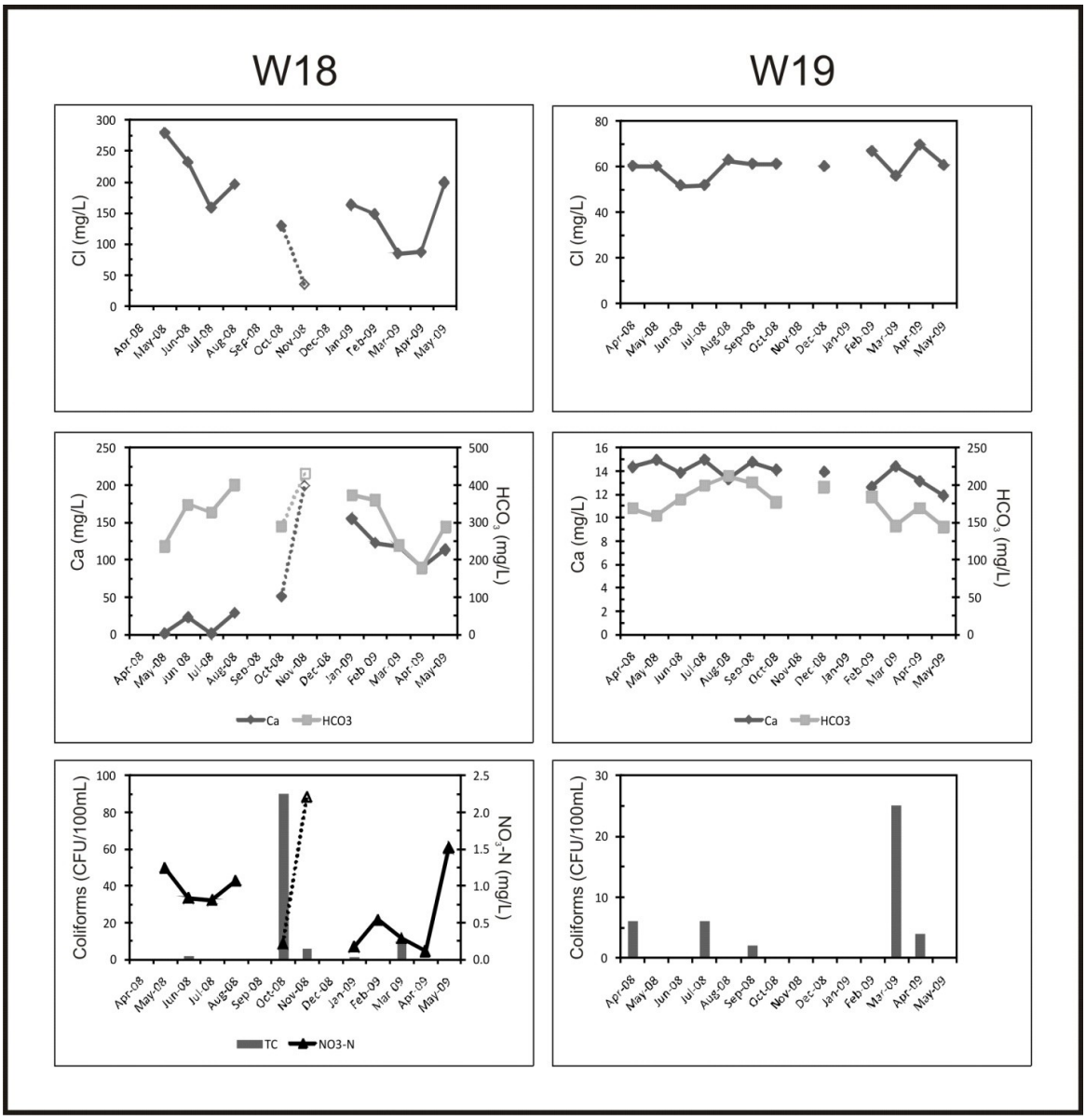


Figure D16: Seasonal variability in ion and coliform bacteria concentrations for well-sites W18 and W19

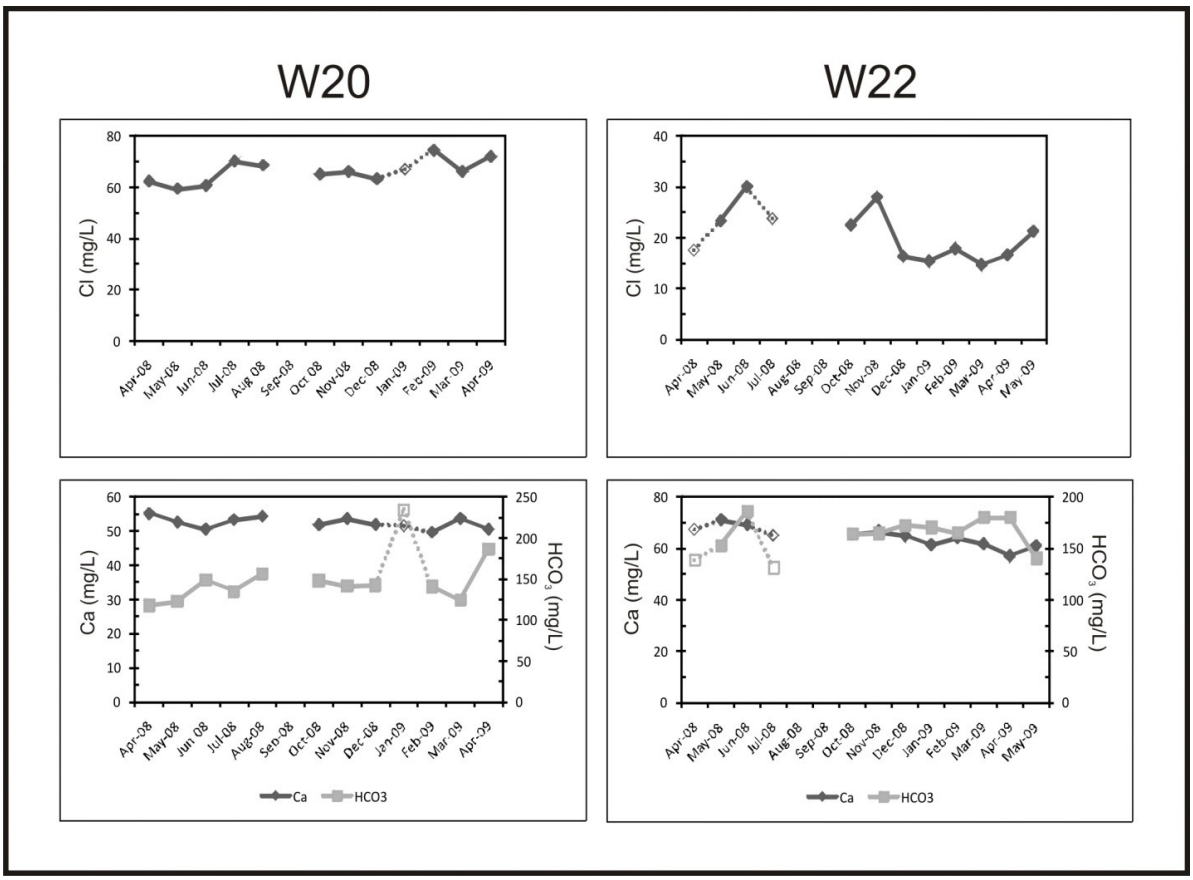


Figure D17: Seasonal variability in ion and coliform bacteria concentrations for well-sites W20 and W22

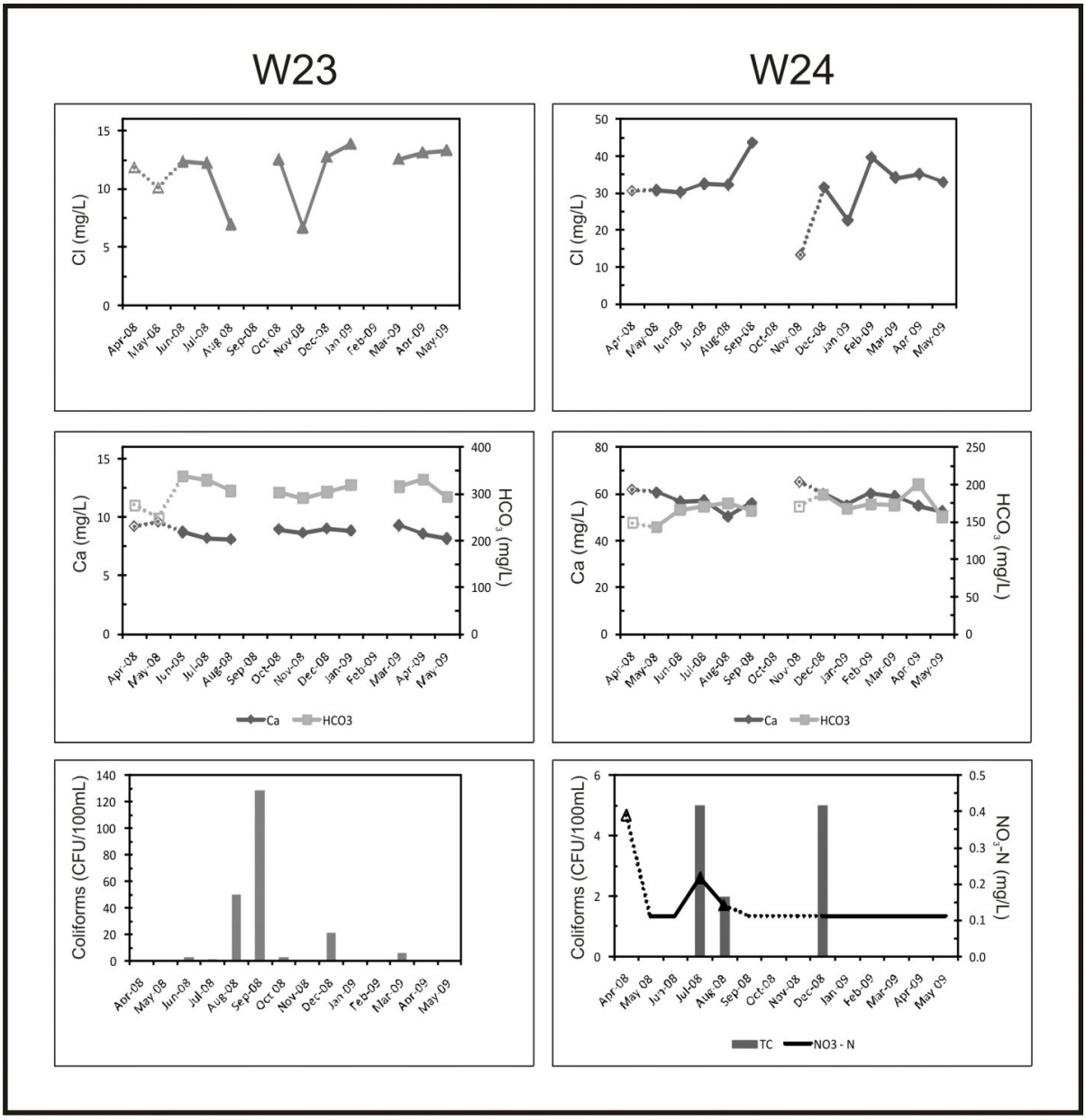


Figure D18: Seasonal variability in ion and coliform bacteria concentrations for well-sites W23 and W24

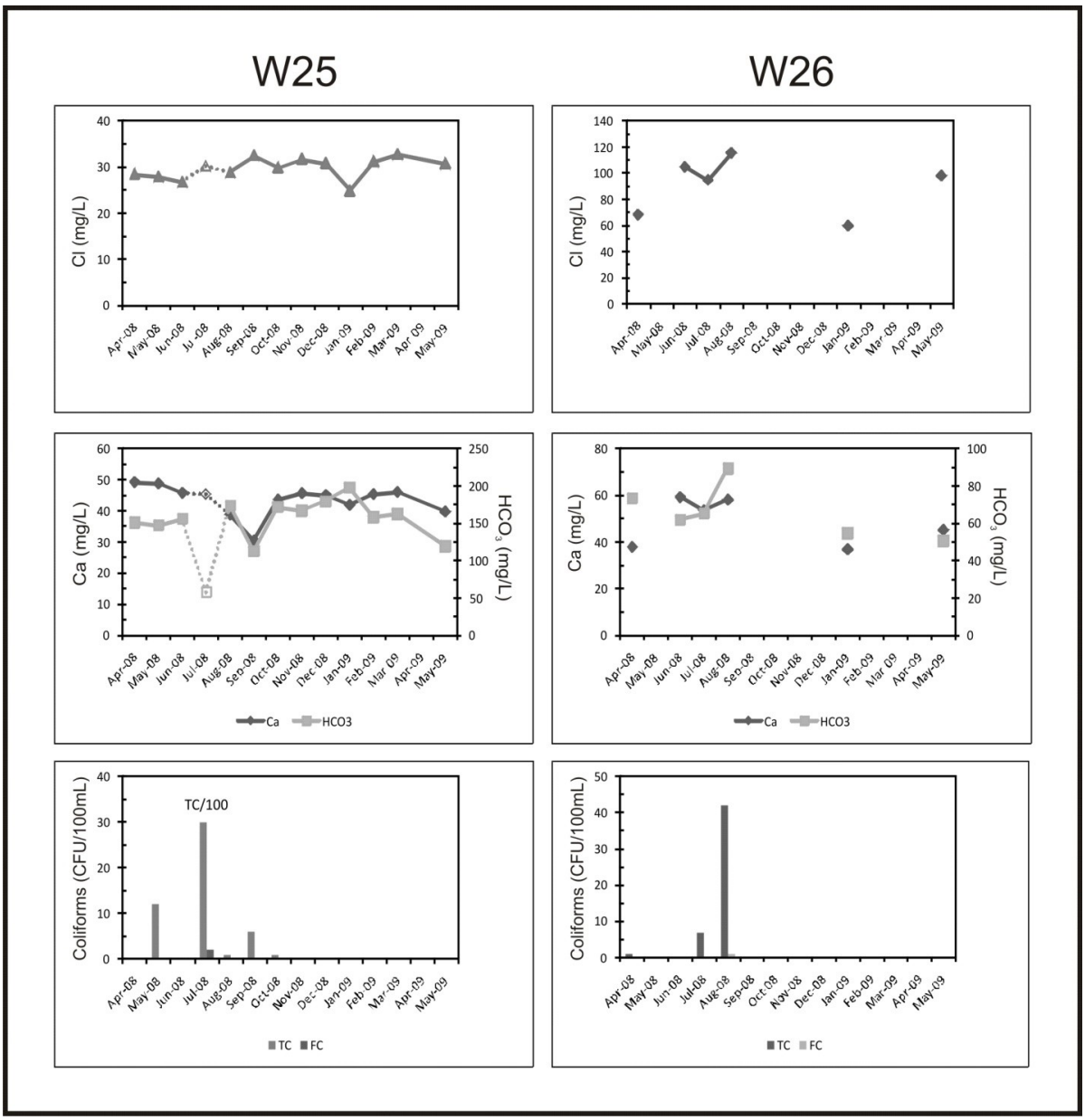


Figure D19: Seasonal variability in ion and coliform bacteria concentrations for well-sites W25 and W26

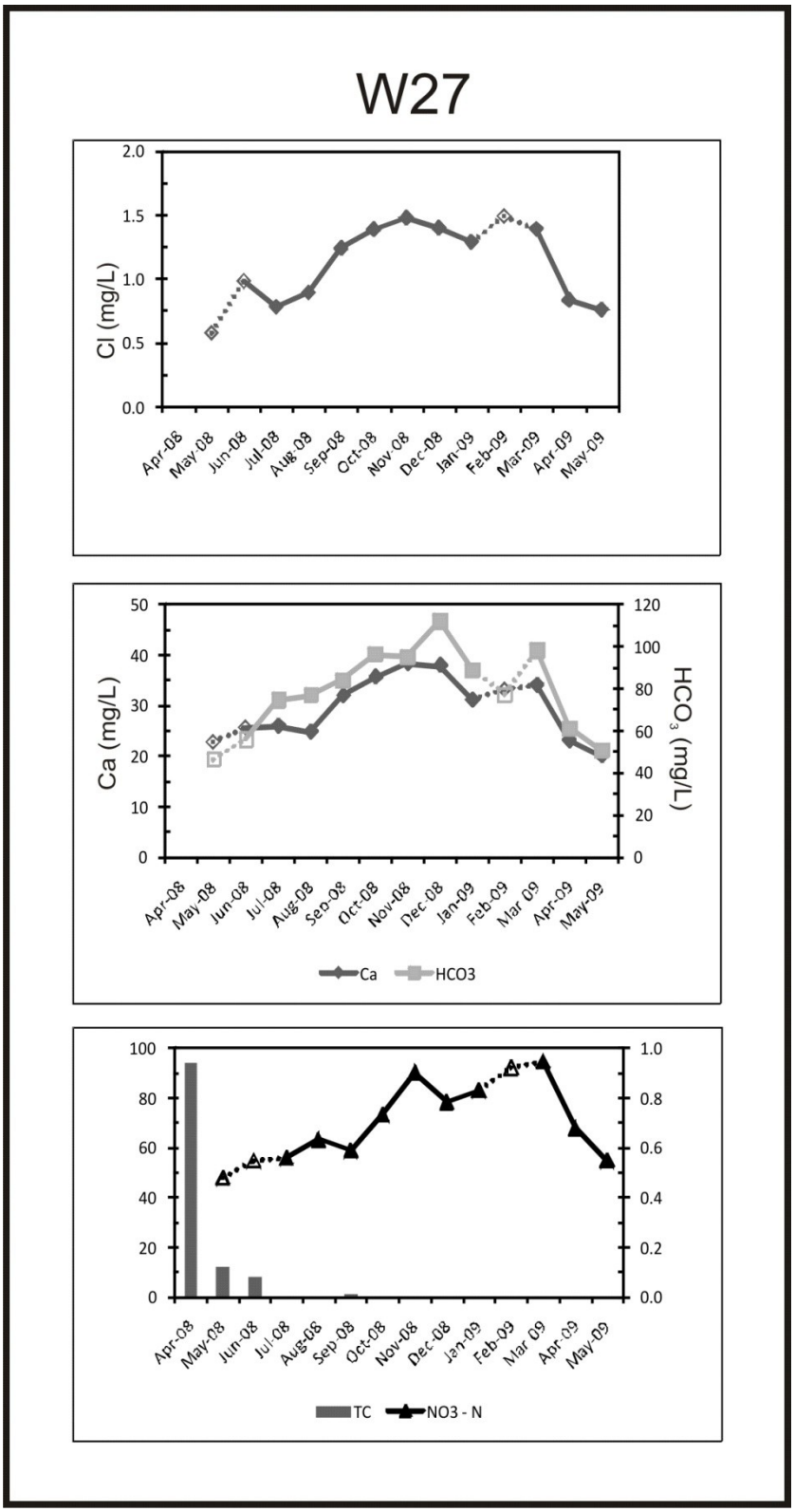
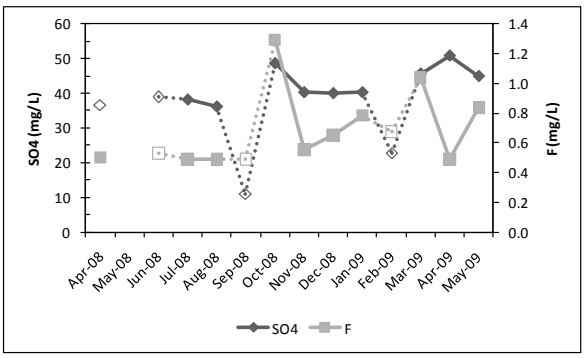
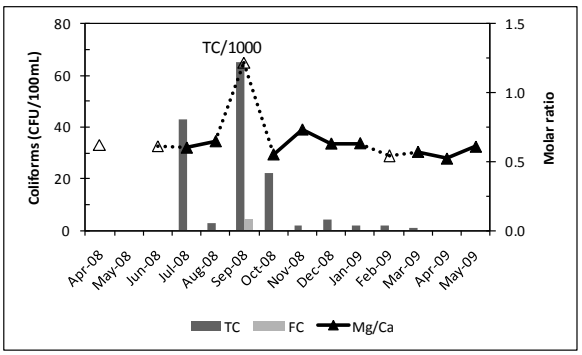
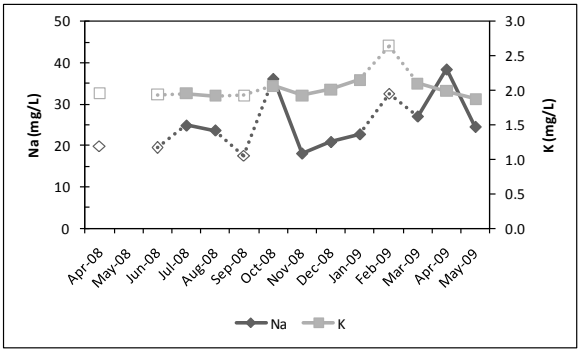


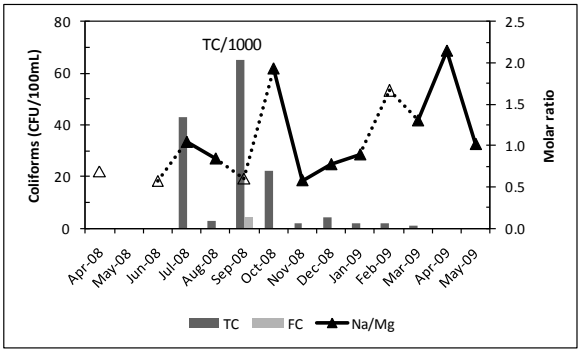
Figure D20: Seasonal variability in ion and coliform bacteria concentrations for well-site W27

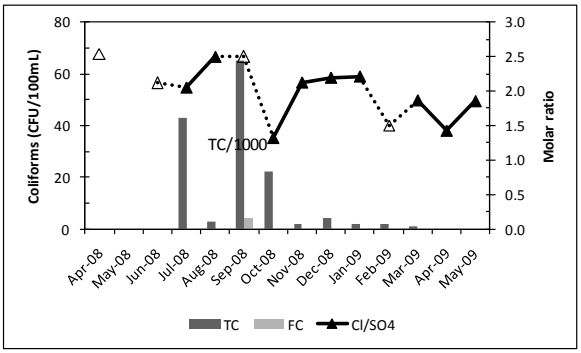
W1: Additional data

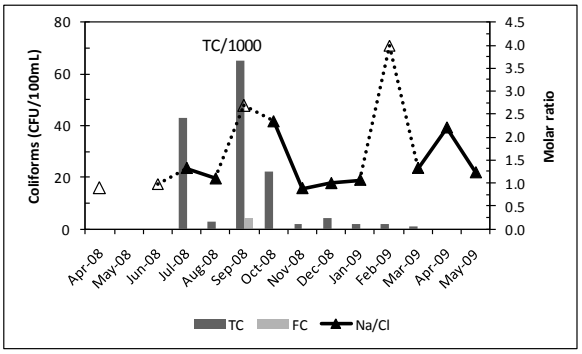












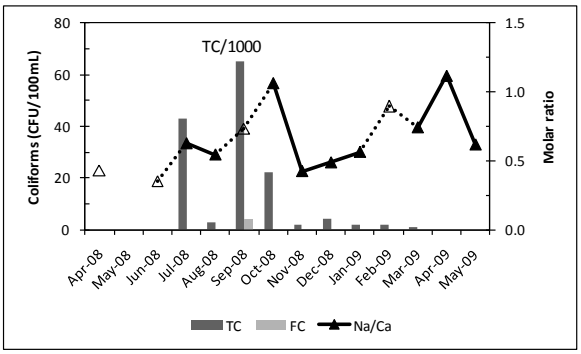
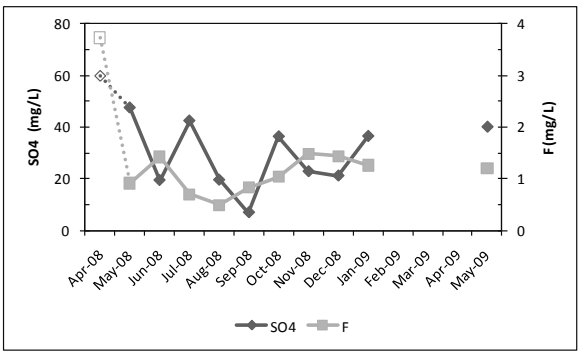
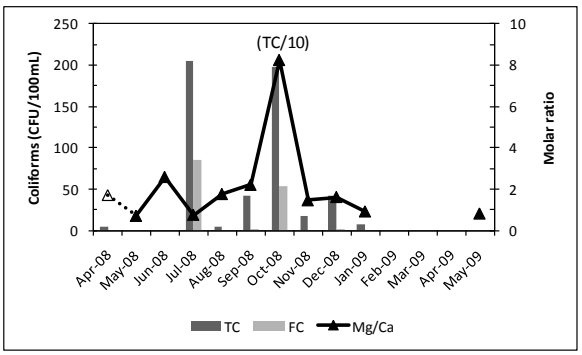


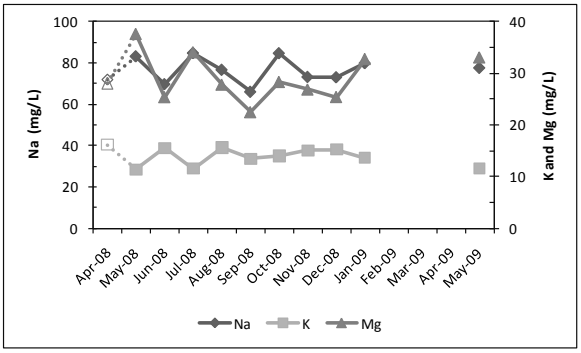
Table W1: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

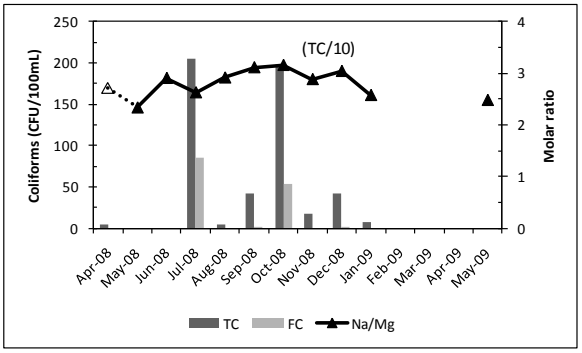
Coefficients of correlation	p-values										
	F^-	Cl^-	NO_3-N	SO_4^{2-}	HCO_3^-	Ca^{2+}	K^+	Mg^{2+}	Na^+	pH	TC
F^-	1.00	0.34	0.48	0.18	0.79	0.19	0.14	0.28	0.50	0.59	0.92
Cl^-	-0.36	1.00	**0.00**	**0.03**	**0.04**	**0.01**	0.73	**0.01**	**0.01**	*0.07*	0.35
NO_3-N	-0.27	**0.85**	1.00	**0.00**	0.09	**0.00**	0.53	**0.00**	**0.00**	0.51	0.83
SO_4^{2-}	0.49	**-0.72**	**-0.91**	1.00	0.12	**0.00**	0.53	**0.00**	**0.01**	0.60	0.38
HCO_3^-	-0.10	**0.70**	0.59	-0.56	1.00	0.13	0.98	**0.06**	**0.02**	0.37	0.87
Ca^{2+}	-0.48	**0.83**	**0.93**	**-0.89**	0.54	1.00	0.27	**0.00**	**0.00**	0.63	0.98
K^+	0.54	-0.13	-0.24	0.24	0.01	-0.41	1.00	0.32	0.53	0.63	0.76
Mg^{2+}	-0.41	**0.79**	**0.88**	**-0.85**	**0.64**	**0.96**	-0.37	1.00	**0.00**	0.82	0.98
Na^+	0.26	**-0.82**	**-0.89**	**0.78**	**-0.75**	**-0.91**	0.24	-0.96	1.00	0.82	0.97
pH	0.21	-0.62	-0.25	0.21	-0.34	-0.19	-0.19	-0.09	0.09	1.00	0.12
TC	0.04	-0.35	0.08	-0.33	-0.07	0.01	0.12	0.01	0.01	0.56	1.00

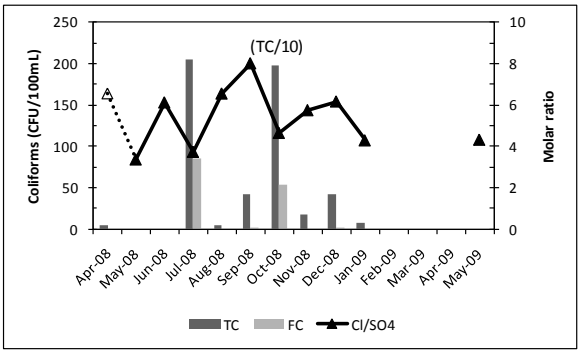
W2: Additional data

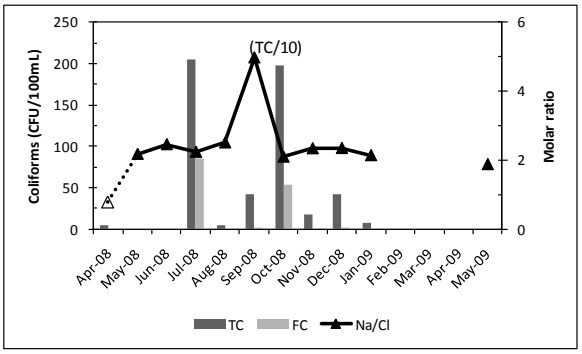












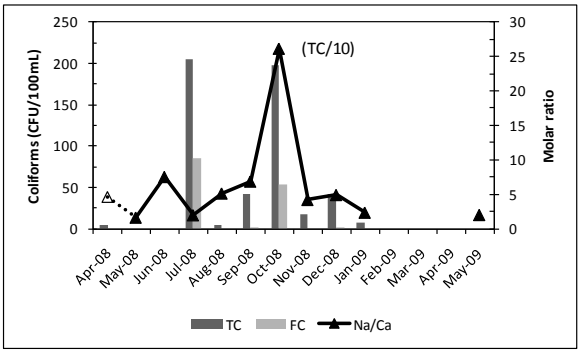
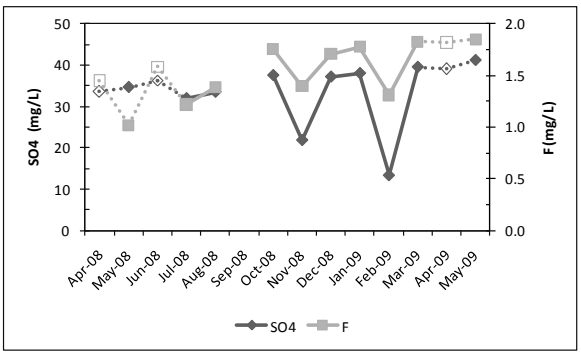
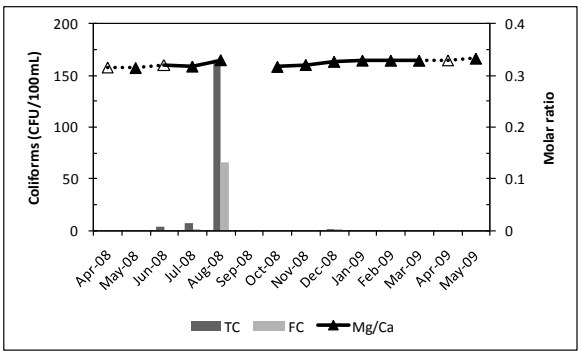


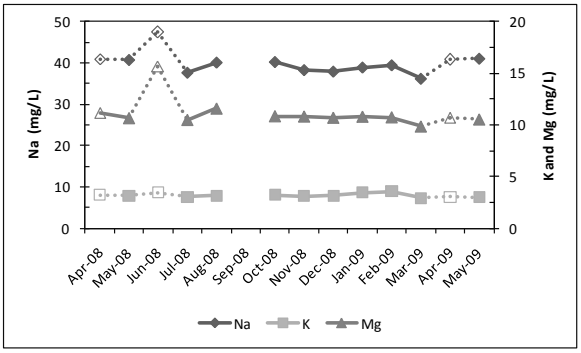
Table W2: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

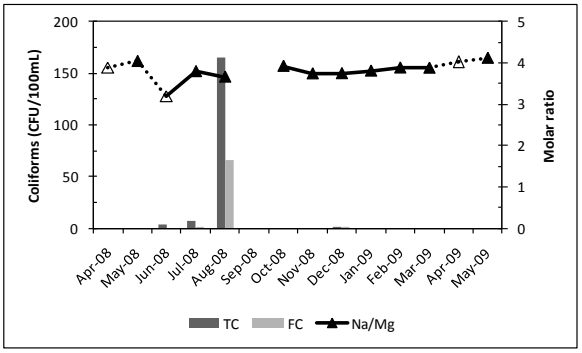
Coefficients of correlation	p-values											
	F^-	Cl^-	NO_3-N	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	pH	TC	FC
F^-		0.69	0.15	0.80	0.82	0.61	0.69	0.49	0.31	0.77	0.72	0.41
Cl^-	0.15		0.83	**0.00**	0.34	0.41	**0.01**	**0.00**	0.96	0.35	0.87	0.70
NO_3-N	0.49	0.08		0.97	0.83	0.33	0.67	0.73	0.79	0.76	0.72	0.50
SO_4^{2-}	0.09	**0.96**	-0.01		0.16	0.12	**0.00**	**0.00**	0.71	0.28	0.84	0.57
Ca^{2+}	-0.08	0.34	0.08	0.48		**0.05**	**0.02**	0.38	**0.01**	**0.00**	0.13	0.42
K^+	0.19	-0.29	0.35	-0.53	**-0.64**		**0.01**	0.12	0.16	0.31	0.76	0.43
Mg^{2+}	-0.14	**0.76**	-0.15	**0.90**	**0.73**	**-0.75**		**0.00**	0.15	*0.08*	0.49	0.81
Na^+	-0.25	**0.83**	-0.13	**0.89**	0.31	-0.53	**0.83**		0.70	0.62	0.50	0.15
HCO_3^-	-0.36	-0.02	-0.09	0.14	0.75	-0.48	0.49	0.14		**0.03**	0.28	0.54
pH	0.11	-0.33	-0.11	-0.38	**-0.93**	0.36	-0.58	-0.18	**-0.69**		0.07	0.21
TC	-0.13	-0.06	0.13	-0.07	-0.51	0.11	-0.25	0.24	-0.38	0.59		**0.00**
FC	-0.30	0.14	-0.24	0.21	-0.29	-0.28	0.09	0.49	-0.22	0.43	**0.82**	

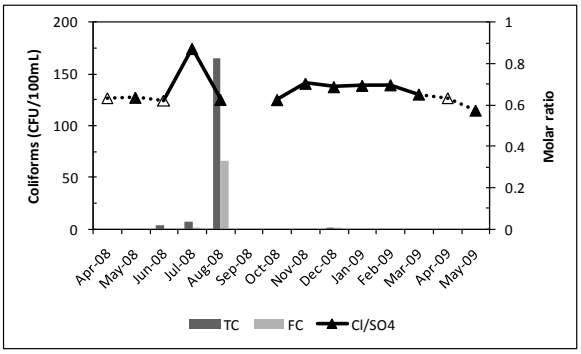
W3: Additional data

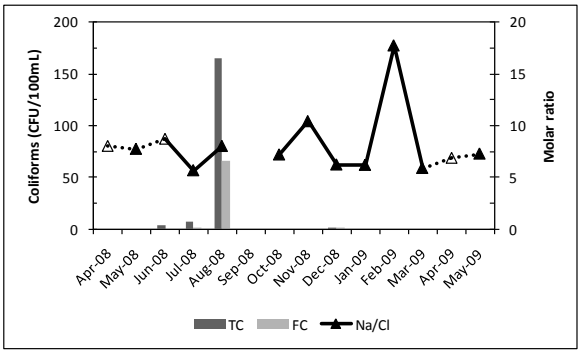












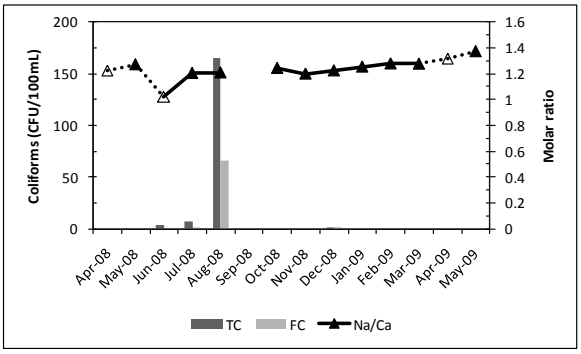
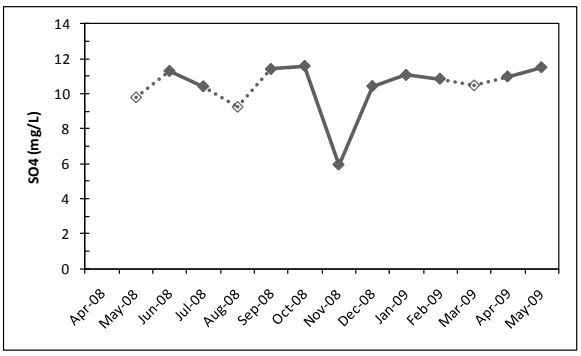
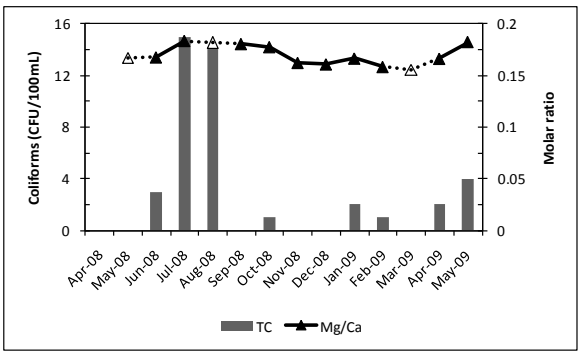


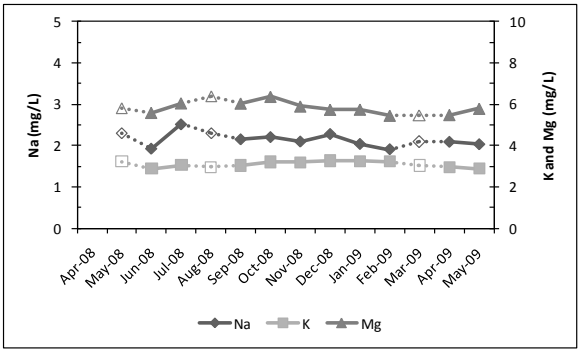
Table W3: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

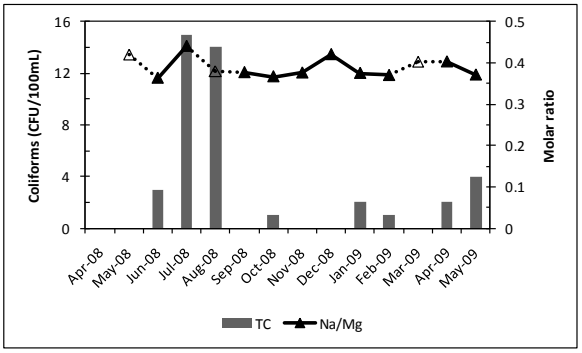
		p-values										
		F^-	Cl^-	NO_3-N	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	TC	FC
Coefficients of correlation	F^-		0.33	0.20	0.16	0.79	0.50	0.55	0.42	*0.06*	0.47	0.66
	Cl^-	0.34		**0.00**	0.70	0.09	0.55	0.58	0.53	0.87	0.68	0.84
	NO_3-N	0.44	**0.94**		0.66	0.08	0.62	0.99	0.29	0.95	0.82	0.80
	SO_4^{2-}	-0.48	-0.14	-0.16		0.43	**0.00**	0.11	0.97	0.96	0.15	0.14
	Ca^{2+}	-0.09	-0.56	-0.58	0.28		0.25	0.43	0.51	0.21	0.62	0.76
	K^+	-0.24	-0.22	-0.18	**0.89**	0.40		*0.08*	0.94	0.30	0.07	**0.03**
	Mg^{2+}	-0.22	-0.20	0.00	0.54	0.28	*0.58*		0.25	0.87	0.86	0.66
	Na^+	0.29	-0.23	-0.37	0.01	0.24	0.03	-0.40		0.27	0.68	0.55
	HCO_3^-	-0.62	0.06	0.02	0.02	-0.44	-0.37	0.06	-0.39		0.51	0.31
	TC	-0.26	0.15	0.08	0.49	-0.18	0.59	0.06	-0.15	-0.23		**0.00**
	FC	-0.16	0.07	0.09	0.50	-0.11	**0.68**	0.16	-0.22	-0.36	**0.95**	

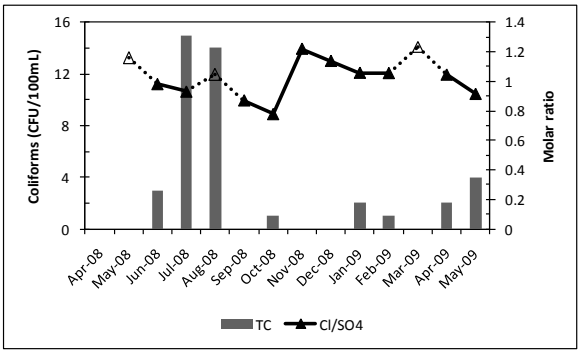
W4: additional data

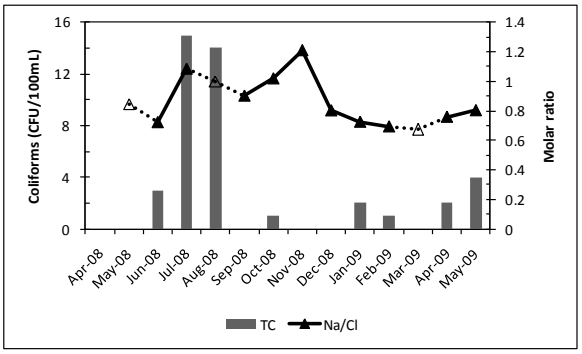












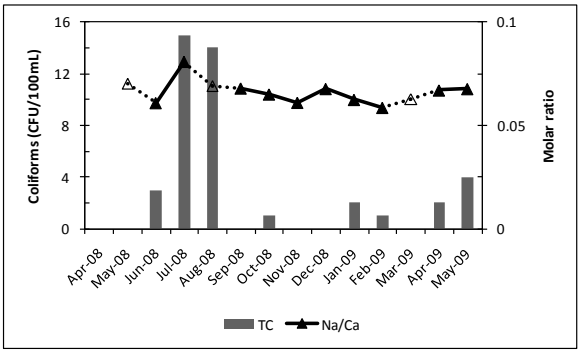
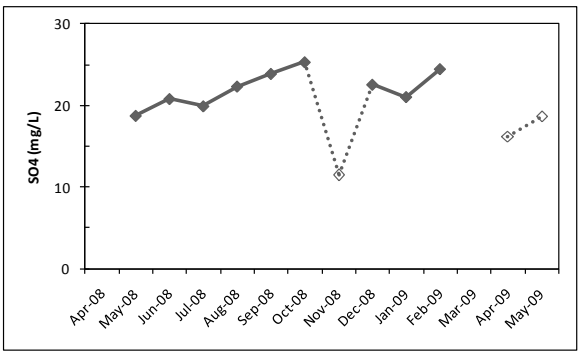
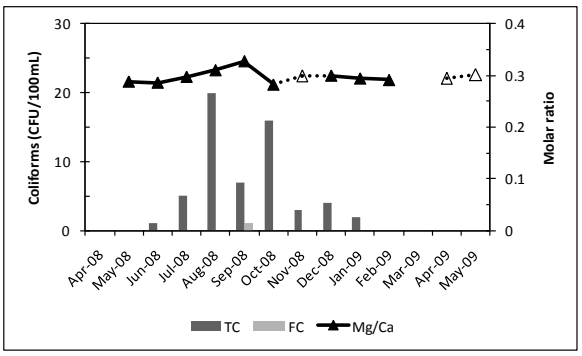


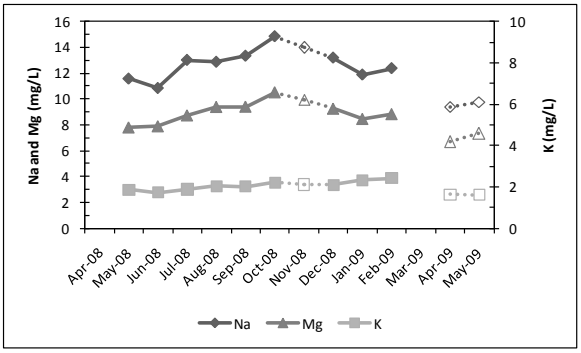
Table W4: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

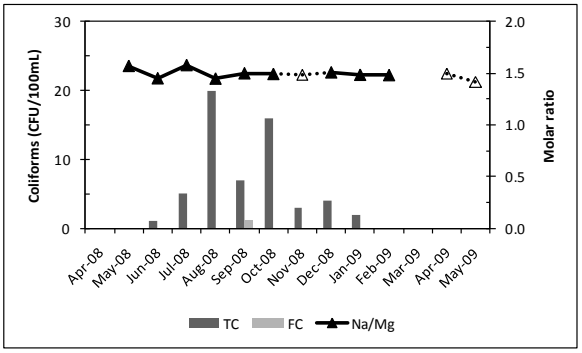
		p-values									
		F^-	Cl^-	NO_3-N	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	pH	TC
Coefficients of correlation	F^-		0.46	0.79	0.53	0.55	0.69	0.92	0.45	0.30	0.57	0.88
	Cl^-	-0.26		0.61	**0.03**	0.53	0.80	**0.04**	0.48	0.76	0.19	0.95
	NO_3-N	0.10	-0.18		0.20	**0.00**	0.25	0.82	0.44	0.72	0.29	*0.08*
	SO_4^{2-}	-0.22	**0.67**	-0.45		0.14	0.44	0.97	0.88	0.31	0.80	0.43
	Ca^{2+}	-0.22	-0.23	**0.84**	-0.50		**0.01**	0.81	0.85	0.15	0.17	**0.02**
	K^+	0.14	-0.09	0.40	-0.27	**0.78**		0.72	0.66	0.11	0.23	0.19
	Mg^{2+}	-0.04	**-0.65**	0.08	-0.01	0.09	0.13		*0.05*	0.73	*0.06*	0.74
	Na^+	-0.27	-0.25	0.27	-0.05	0.07	0.16	*0.62*		0.69	0.22	0.45
	HCO_3^-	-0.36	-0.11	0.13	-0.36	0.49	0.54	-0.13	-0.15		0.16	0.87
	pH	-0.21	-0.45	0.38	-0.09	0.47	0.42	*0.61*	0.43	0.48		0.96
	TC	0.05	0.02	*-0.58*	0.28	**-0.70**	-0.45	0.12	0.27	-0.06	0.02	

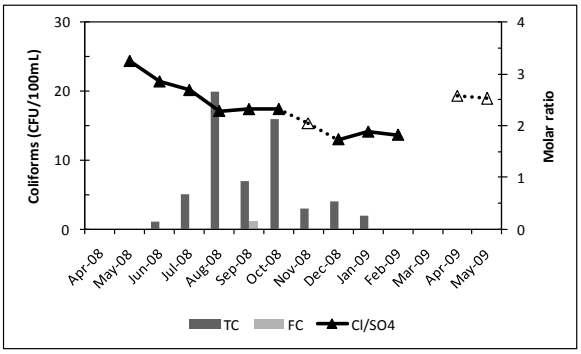
W5: Additional data

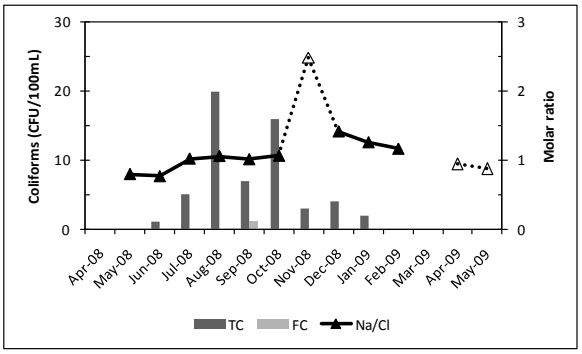












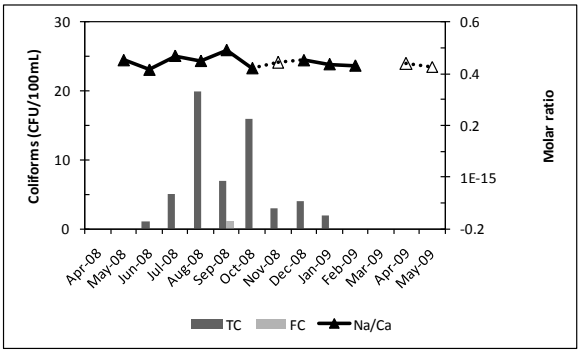
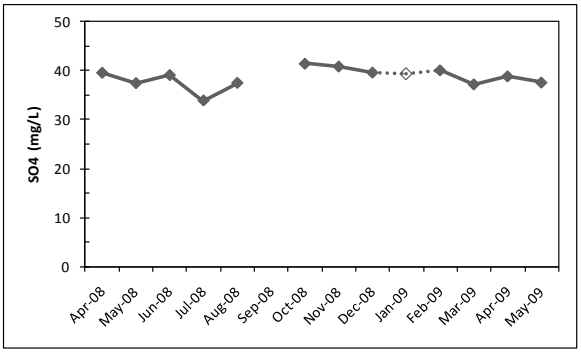
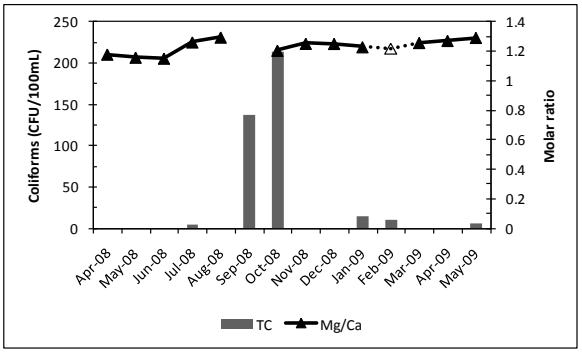


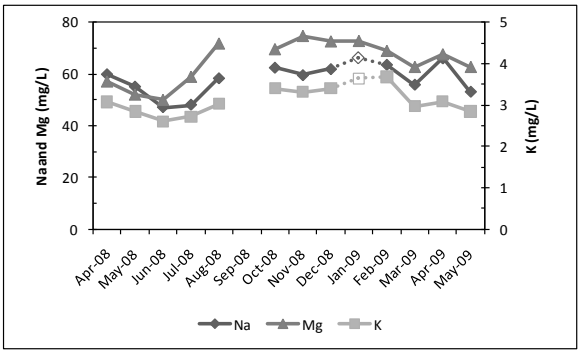
Table W5: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

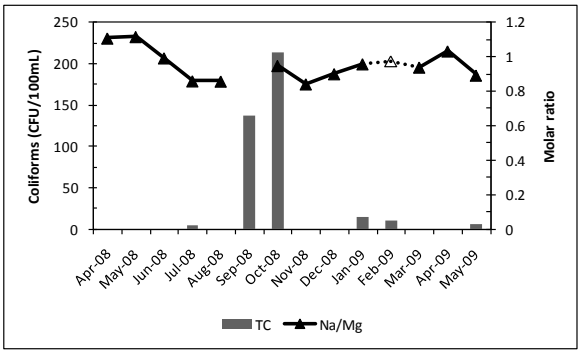
Coefficients of correlation		p-values									
	Cl^-	NO_3-N	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	pH	TC	FC
Cl^-		0.28	0.67	0.98	*0.07*	0.83	0.95	0.21	0.28	0.90	0.63
NO_3-N	-0.40		**0.00**	**0.01**	**0.00**	**0.01**	**0.03**	**0.01**	0.57	0.31	0.83
SO_4^{2-}	-0.16	**0.90**		**0.03**	*0.06*	**0.01**	**0.05**	**0.04**	0.24	0.28	0.43
Ca^{2+}	-0.01	**0.80**	**0.73**		0.17	**0.00**	**0.00**	**0.03**	0.72	0.08	0.71
K^+	-0.63	**0.86**	*0.64*	0.50		0.18	0.25	**0.01**	0.98	0.87	0.86
Mg^{2+}	-0.09	**0.81**	**0.81**	**0.88**	0.49		**0.00**	**0.02**	0.21	**0.01**	0.55
Na^+	-0.02	**0.73**	**0.67**	**0.86**	0.43	**0.95**		*0.05*	0.30	**0.02**	0.56
HCO_3^-	-0.46	**0.81**	**0.69**	**0.71**	**0.77**	**0.76**	*0.66*		0.73	0.11	0.77
pH	0.40	0.22	0.44	0.14	-0.01	0.46	0.39	0.13		0.21	**0.05**
TC	0.05	0.38	0.41	0.61	0.06	0.81	**0.75**	0.57	0.46		0.56
FC	0.18	0.08	0.30	-0.14	-0.07	0.23	0.22	-0.12	**0.67**	0.23	

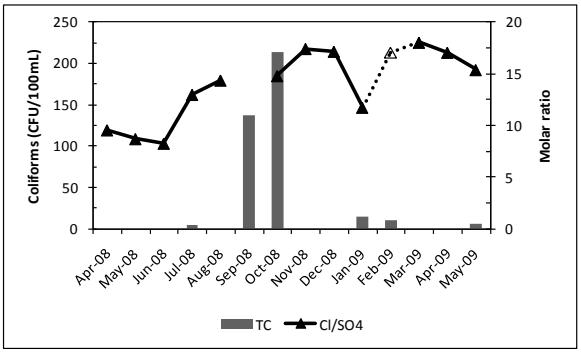
W6: Additional data

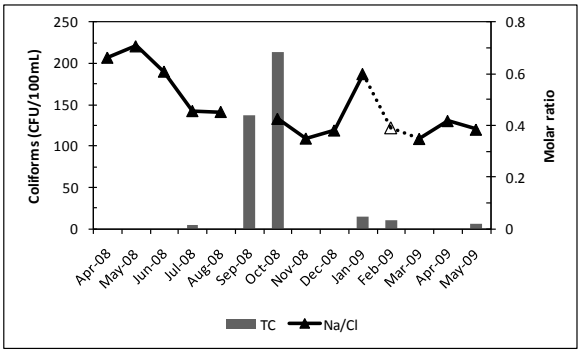












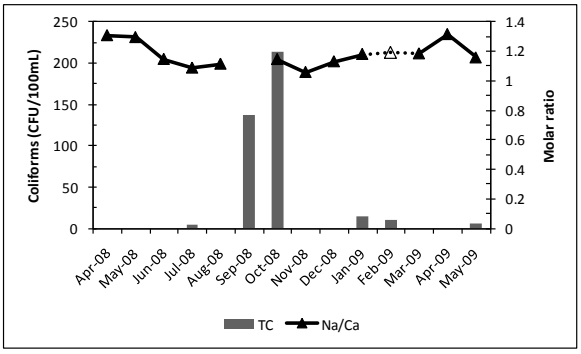
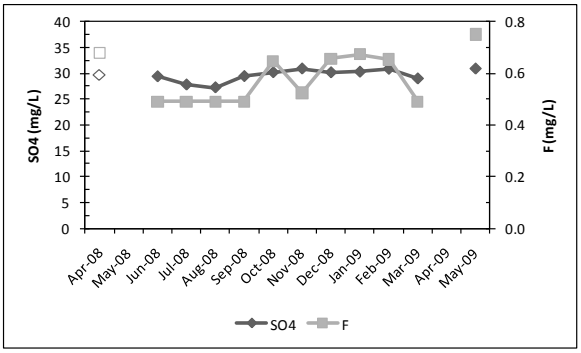
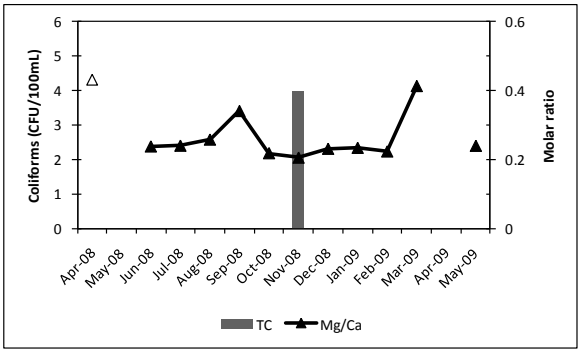


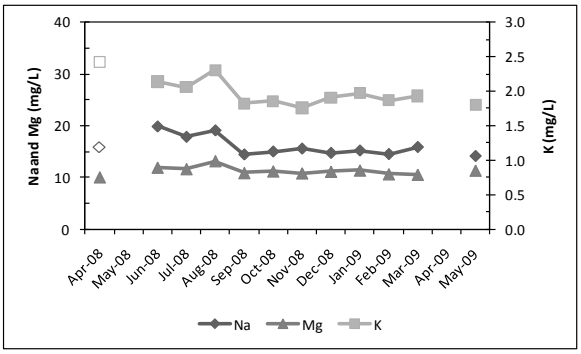
Table W6: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

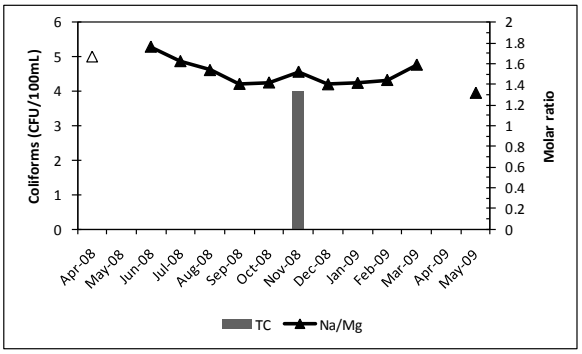
	p-values									
	Cl^-	NO_3-N	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	pH	TC
Cl^-		0.17	0.31	**0.00**	**0.01**	**0.00**	**0.03**	0.59	0.16	0.46
NO_3-N	-0.42		0.64	0.28	0.45	0.20	0.59	**0.04**	0.53	0.16
SO_4^{2-}	0.32	0.15		**0.05**	**0.02**	0.22	**0.03**	0.79	0.47	0.54
Ca^{2+}	**0.84**	-0.34	**0.57**		**0.00**	**0.00**	**0.00**	0.28	0.30	0.41
K^+	**0.70**	-0.24	**0.67**	**0.88**		**0.00**	**0.00**	0.66	0.72	0.27
Mg^{2+}	**0.90**	-0.40	0.38	**0.96**	**0.76**		**0.01**	0.28	0.09	0.50
Na^+	**0.64**	0.17	**0.63**	**0.78**	**0.85**	**0.70**		0.85	0.47	0.70
HCO_3^-	0.17	**-0.60**	0.09	0.34	0.14	0.34	-0.06		0.29	0.95
pH	-0.44	0.20	0.23	-0.33	-0.12	-0.51	-0.23	-0.33		0.35
TC	0.23	-0.44	0.20	0.26	0.35	0.21	0.12	0.02	0.30	

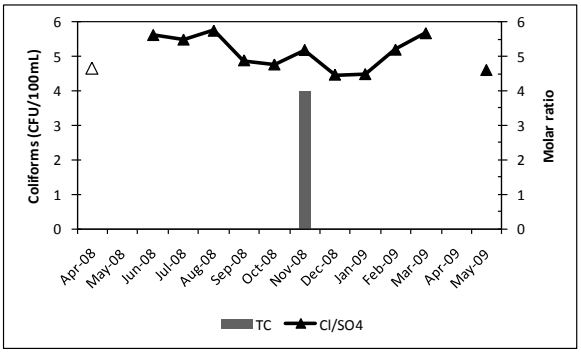
W7: Additional data

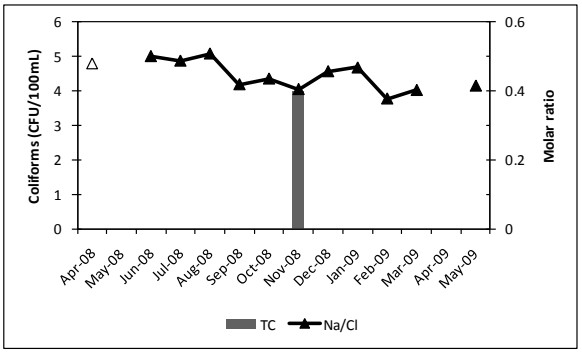












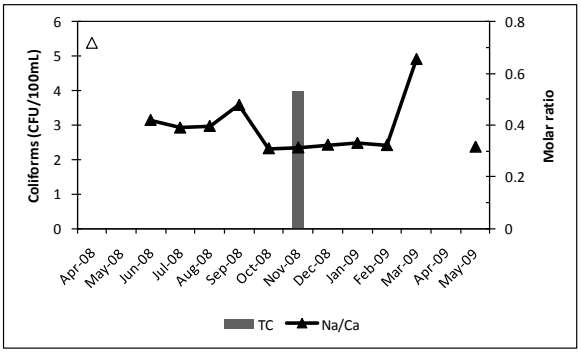
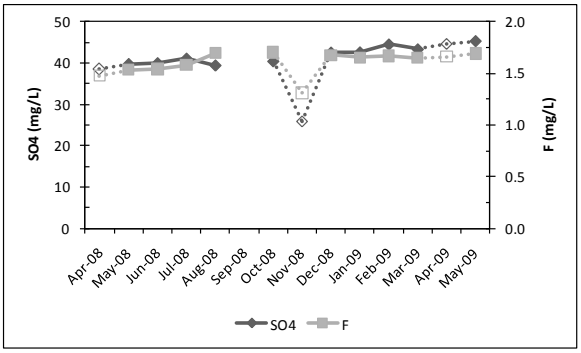
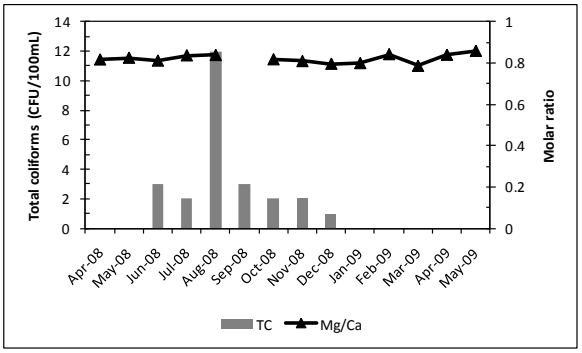


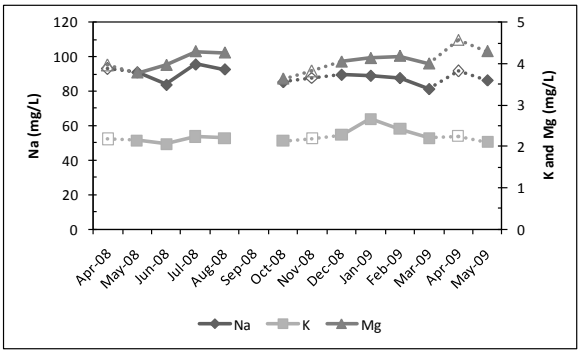
Table W7: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

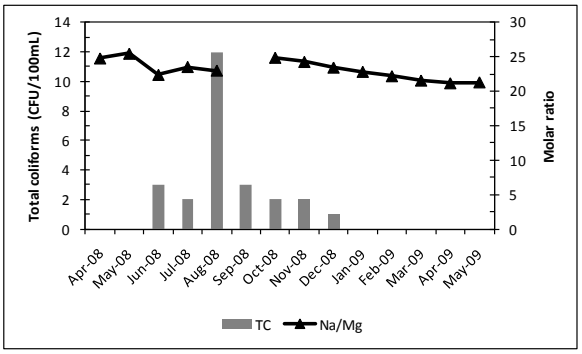
Coefficients of correlation	p-values										
	F^-	Cl^-	NO_3-N	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	pH	TC
F^-		**0.03**	0.67	**0.02**	0.28	0.16	0.48	**0.02**	0.71	0.65	0.45
Cl^-	**-0.65**		0.73	0.41	0.61	0.41	0.91	*0.07*	0.80	0.49	0.57
NO_3-N	0.15	0.12		**0.02**	0.89	**0.01**	**0.01**	0.15	0.43	0.70	0.77
SO_4^{2-}	**0.70**	-0.28	**0.70**		0.65	**0.00**	**0.02**	**0.01**	0.58	0.67	0.63
Ca^{2+}	0.36	-0.17	-0.05	0.15		0.65	0.16	0.52	**0.00**	**0.01**	0.54
K^+	-0.46	0.28	**-0.72**	**-0.82**	0.15		**0.00**	**0.00**	0.15	0.72	0.61
Mg^{2+}	-0.24	0.04	**-0.73**	**-0.68**	0.46	**0.84**		**0.01**	**0.02**	0.26	0.87
Na^+	**-0.67**	*0.56*	-0.47	**-0.72**	0.22	**0.87**	**0.72**		0.20	0.45	0.64
HCO_3^-	0.13	-0.09	-0.26	-0.19	**0.91**	0.46	**0.70**	0.42		**0.04**	0.80
pH	0.16	-0.24	-0.13	0.15	**0.76**	0.12	0.38	0.26	**0.63**		0.32
TC	0.26	-0.19	0.10	0.16	0.21	-0.17	-0.06	-0.16	0.09	0.33	

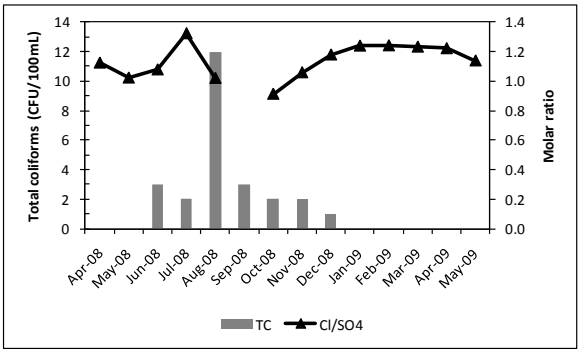
W9: Additional data

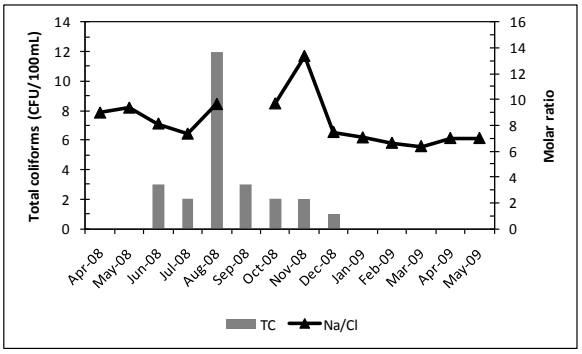












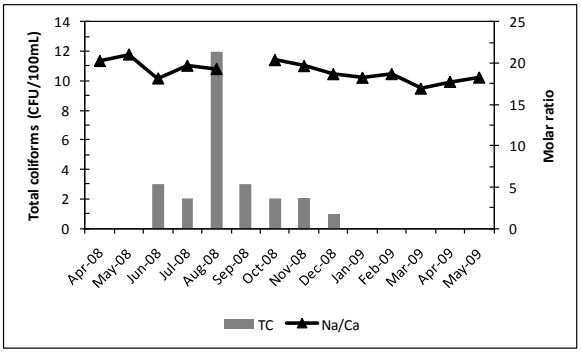
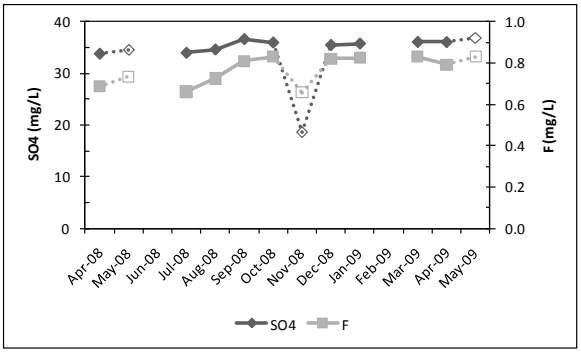
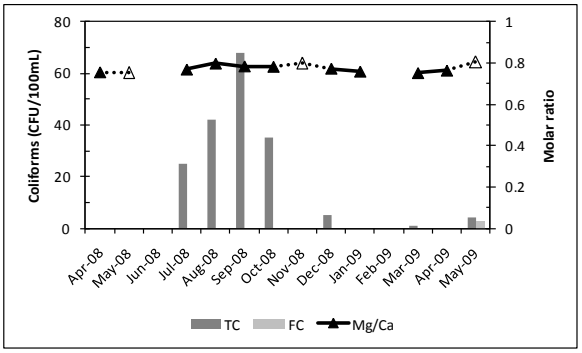


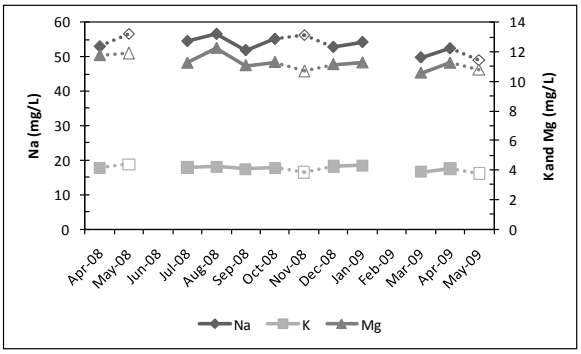
Table W9: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

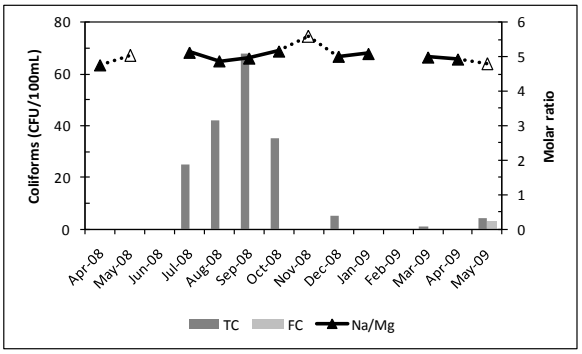
Coefficients of correlation	p-values									
	F^-	Cl^-	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	pH	TC
F^-		0.66	0.17	0.54	0.39	0.47	0.85	0.51	0.06	1.00
Cl^-	0.15		**0.00**	**0.03**	**0.02**	**0.01**	0.21	0.56	0.32	**0.05**
SO_4^{2-}	0.45	**0.83**		**0.01**	**0.03**	**0.01**	0.20	0.54	0.16	**0.02**
Ca^{2+}	0.21	**0.66**	**0.73**		**0.00**	**0.00**	**0.00**	**0.05**	0.10	0.45
K^+	0.29	**0.67**	**0.66**	**0.80**		**0.01**	**0.01**	0.28	0.11	0.20
Mg^{2+}	0.24	**0.73**	**0.73**	**0.93**	**0.73**		**0.00**	**0.02**	0.24	0.61
Na^+	0.06	0.41	0.42	**0.83**	**0.71**	**0.81**		**0.05**	0.56	0.87
HCO_3^-	0.22	0.20	0.21	**0.61**	0.36	**0.71**	**0.60**		0.46	0.14
pH	-0.59	-0.33	-0.46	-0.53	-0.51	-0.39	-0.20	-0.25		0.65
TC	0.00	**-0.60**	**-0.68**	-0.25	-0.42	-0.17	-0.06	0.47	0.16	

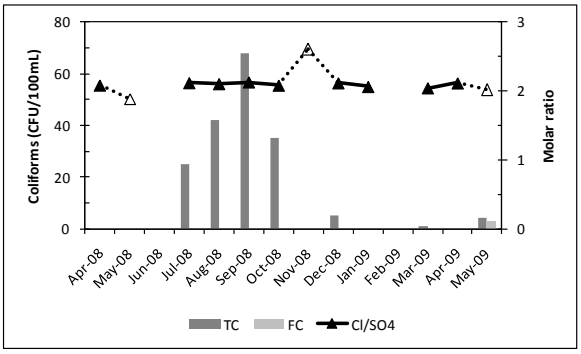
W10: Additional data

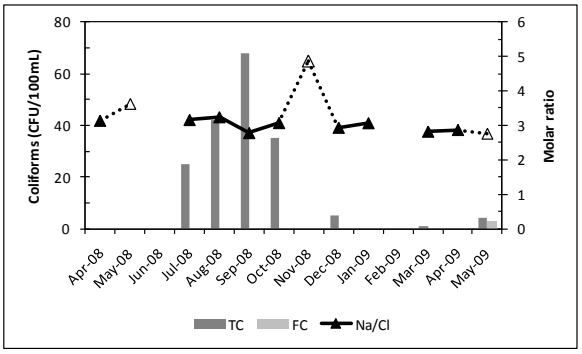












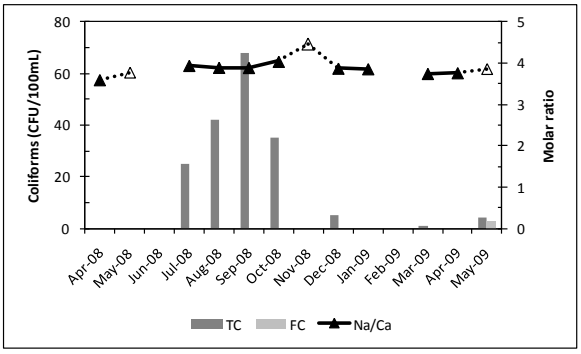
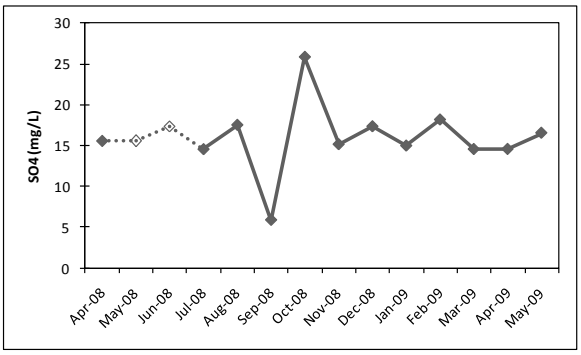
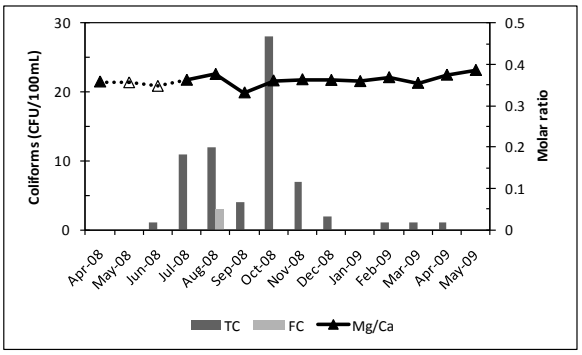


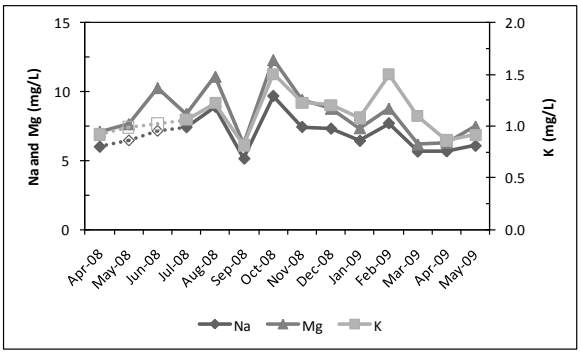
Table W10: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

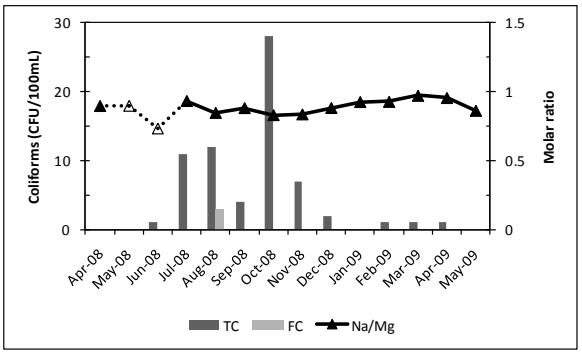
Coefficients of correlation	p-values									
	F^-	Cl^-	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	pH	TC
F^-		**0.03**	**0.00**	*0.06*	0.62	0.11	0.30	*0.07*	*0.06*	0.19
Cl^-	**0.72**		**0.00**	**0.04**	0.71	0.24	0.47	0.11	**0.03**	0.12
SO_4^{2-}	**0.92**	**0.89**		**0.02**	0.39	0.09	0.25	0.05	**0.00**	0.24
Ca^{2+}	*-0.64*	**-0.70**	**-0.74**		0.17	**0.00**	0.12	**0.03**	**0.04**	0.58
K^+	-0.19	-0.14	-0.33	0.50		0.10	**0.02**	0.66	**0.03**	0.32
Mg^{2+}	-0.57	-0.44	-0.59	**0.87**	0.58		**0.01**	0.14	0.09	0.62
Na^+	-0.39	-0.28	-0.43	0.55	**0.75**	**0.79**		0.77	0.06	0.28
HCO_3^-	*-0.64*	-0.57	-0.66	**0.72**	0.17	0.53	0.12		0.23	0.41
pH	*-0.65*	**-0.72**	**-0.84**	**0.70**	**0.72**	0.60	0.65	0.45		0.67
TC	0.48	0.56	0.43	-0.21	0.37	0.19	0.40	-0.32	-0.17	

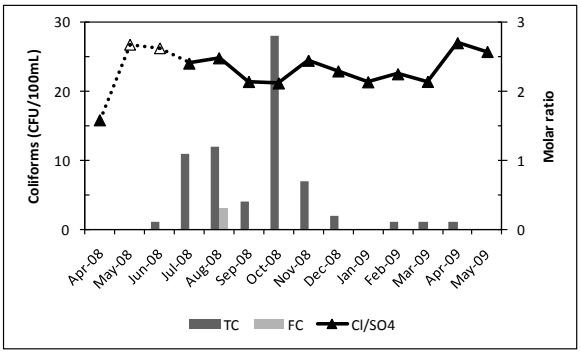
W11: Additional data

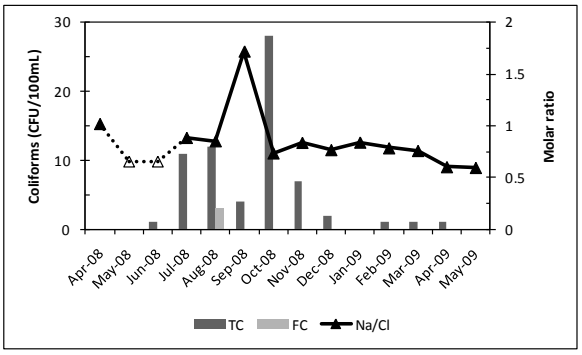












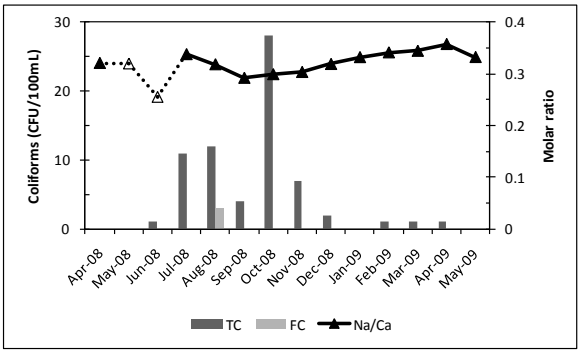
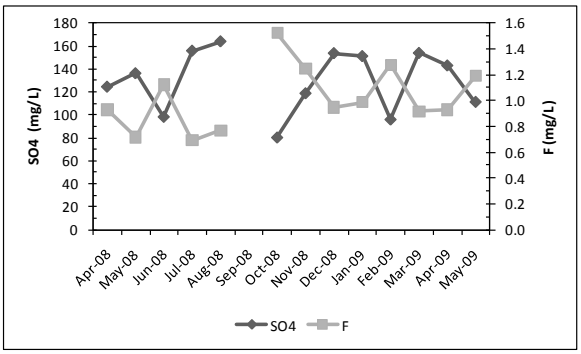
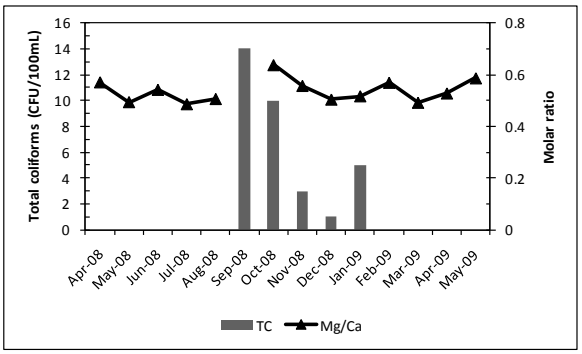


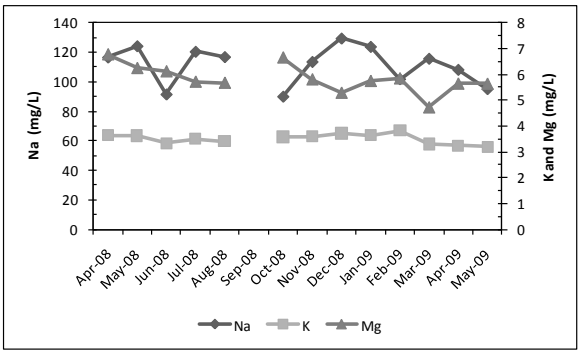
Table W11: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

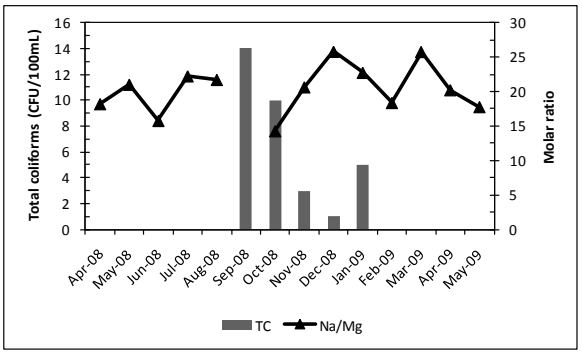
Coefficients of correlation	p-values										
	Cl^-	NO_3-N	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	pH	TC	FC
Cl^-		0.14	**0.00**	0.07	**0.02**	**0.02**	**0.01**	0.43	0.51	0.51	0.56
NO_3-N	0.46		*0.08*	**0.01**	*0.07*	**0.01**	**0.01**	**0.02**	0.20	**0.02**	0.42
SO_4^{2-}	**0.93**	*0.52*		*0.06*	**0.01**	**0.02**	**0.01**	0.11	0.19	0.69	0.71
Ca^{2+}	0.53	**0.75**	*0.56*		**0.00**	**0.00**	**0.00**	**0.00**	0.63	**0.00**	0.19
K^+	**0.65**	*0.54*	**0.69**	**0.78**		**0.00**	**0.00**	**0.04**	0.65	0.16	0.63
Mg^{2+}	**0.66**	**0.72**	**0.66**	**0.99**	**0.80**		**0.00**	**0.01**	0.62	**0.01**	0.16
Na^+	**0.72**	**0.70**	**0.72**	**0.96**	**0.85**	**0.98**		**0.01**	0.75	**0.02**	0.15
HCO_3^-	0.25	**0.65**	0.48	**0.77**	0.59	**0.71**	**0.68**		0.38	0.21	0.49
pH	0.21	0.40	0.41	0.16	0.15	0.16	0.10	0.28		0.99	0.27
TC	0.21	**0.66**	0.13	**0.77**	0.43	**0.71**	**0.67**	0.39	0.00		0.24
FC	0.19	0.25	0.12	0.41	0.16	0.43	0.44	0.22	-0.34	0.36	

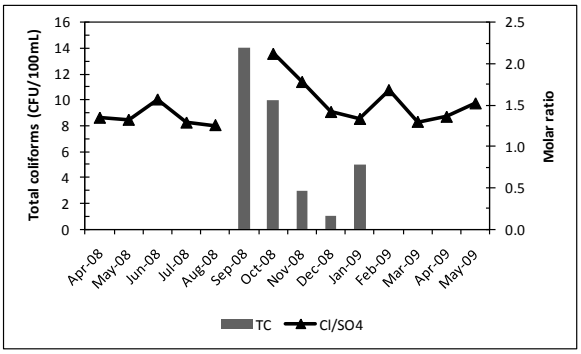
W12: Additional data

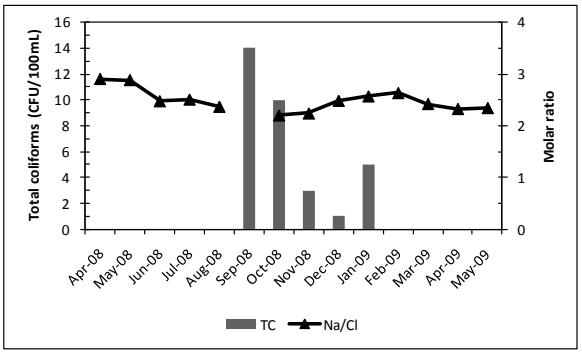












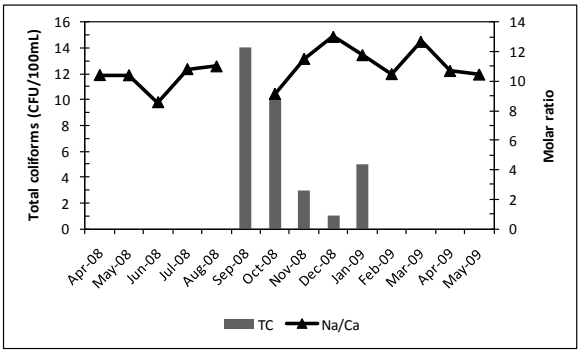
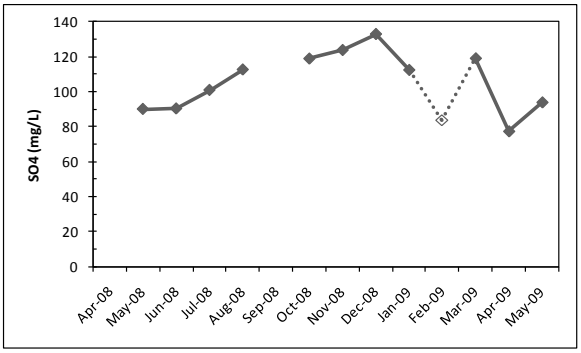
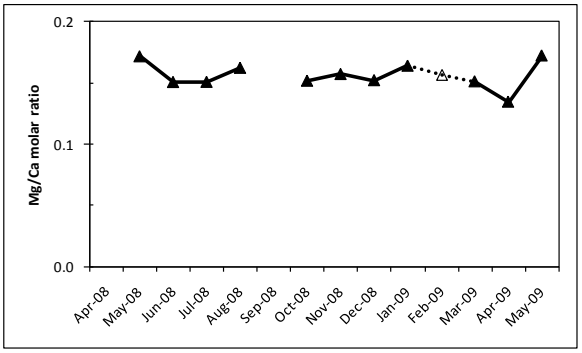


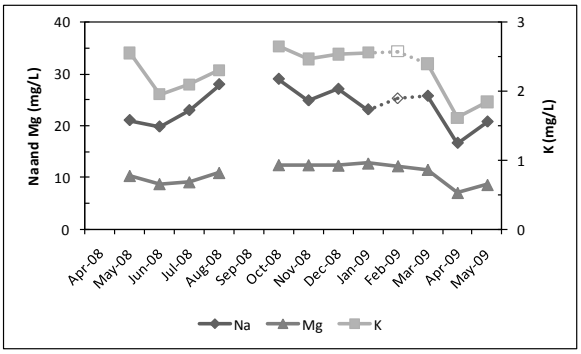
Table W12: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

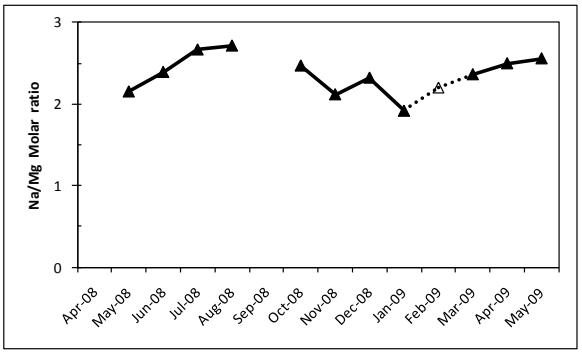
Coefficients of correlation	p-values									
	F^-	Cl^-	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	pH	TC
F^-		0.88	**0.03**	0.91	0.37	0.19	0.34	0.07	0.13	0.28
Cl^-	0.05		**0.01**	**0.02**	**0.00**	0.14	**0.00**	0.13	0.08	0.17
SO_4^{2-}	**-0.60**	**0.71**		0.17	0.21	0.94	**0.00**	0.91	**0.02**	**0.05**
Ca^{2+}	-0.04	**0.63**	0.41		**0.00**	**0.00**	**0.00**	**0.02**	**0.00**	**0.04**
K^+	0.27	**0.81**	0.38	**0.89**		**0.00**	**0.00**	**0.01**	**0.04**	0.14
Mg^{2+}	0.39	0.43	-0.02	**0.87**	**0.84**		0.16	**0.00**	0.09	0.25
Na^+	-0.29	**0.87**	**0.84**	**0.73**	**0.77**	0.41		0.50	**0.00**	0.08
HCO_3^-	0.52	0.44	-0.03	**0.65**	**0.69**	**0.78**	0.20		0.45	0.21
pH	-0.44	0.51	**0.63**	**0.73**	**0.58**	0.49	**0.73**	0.23		**0.02**
TC	0.32	-0.40	**-0.55**	**-0.58**	-0.43	-0.35	-0.50	-0.37	**-0.64**	

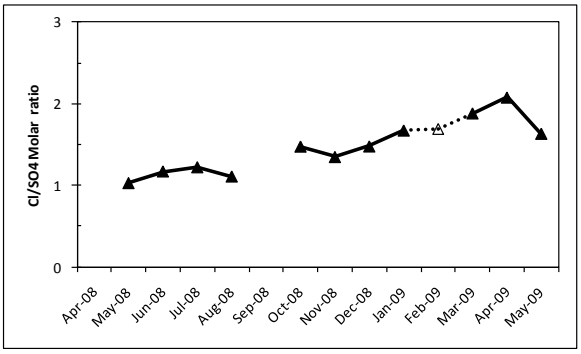
W13: Additional data

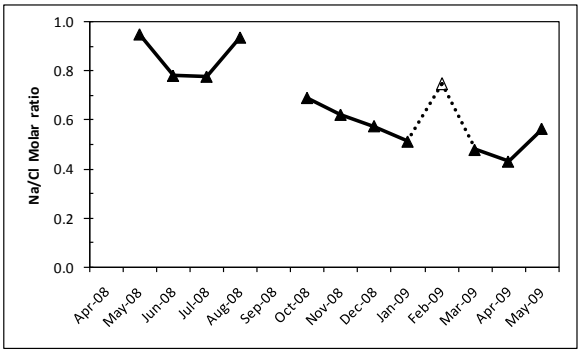












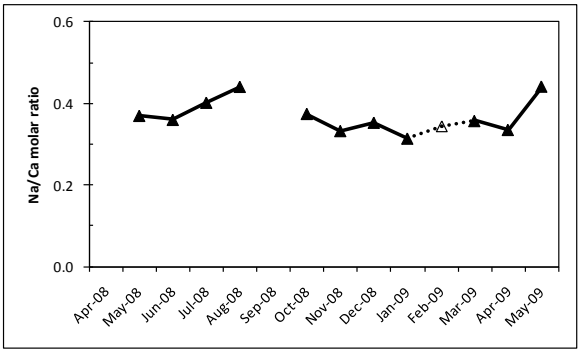
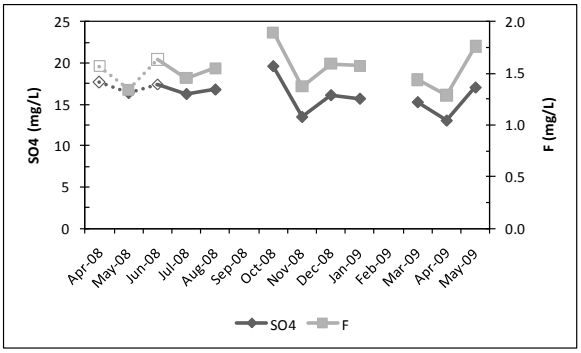
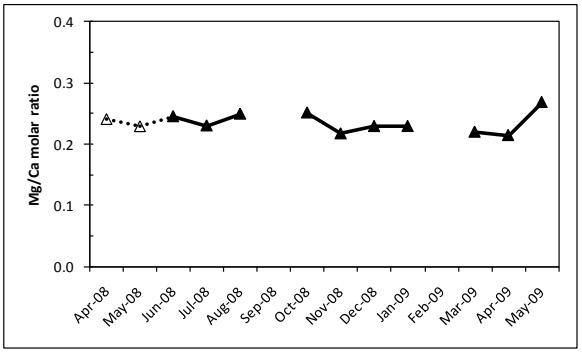


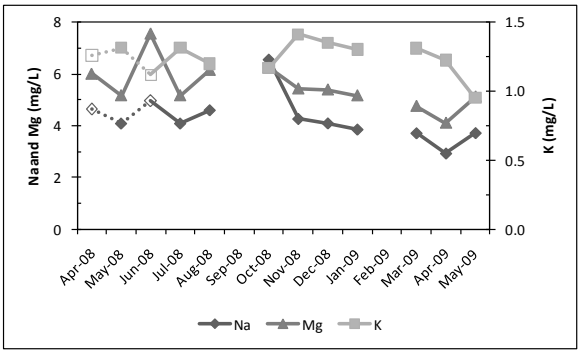
Table W13: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

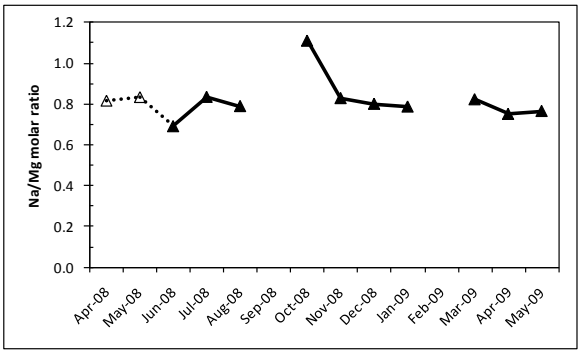
		p-values								
		Cl^-	NO_3-N	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	pH
Coefficients of correlation	Cl^-		**0.01**	*0.06*	*0.07*	0.54	0.19	0.26	**0.04**	**0.01**
	NO_3-N	**0.77**		**0.01**	**0.00**	0.14	**0.02**	0.13	**0.00**	**0.02**
	SO_4^{2-}	*0.58*	**0.72**		**0.00**	**0.00**	**0.00**	**0.00**	*0.08*	0.62
	Ca^{2+}	*0.57*	**0.83**	**0.90**		**0.00**	**0.00**	**0.00**	**0.01**	0.41
	K^+	0.21	0.47	**0.78**	**0.86**		**0.00**	**0.00**	0.14	0.74
	Mg^{2+}	0.43	**0.67**	**0.90**	**0.93**	**0.95**		**0.00**	**0.04**	0.82
	Na^+	0.37	0.48	**0.91**	**0.81**	**0.80**	**0.85**		0.23	0.74
	HCO_3^-	**0.62**	**0.84**	*0.55*	**0.76**	0.48	**0.62**	0.39		**0.02**
	pH	**-0.72**	**-0.68**	-0.17	-0.28	0.11	-0.08	0.12	**-0.68**	

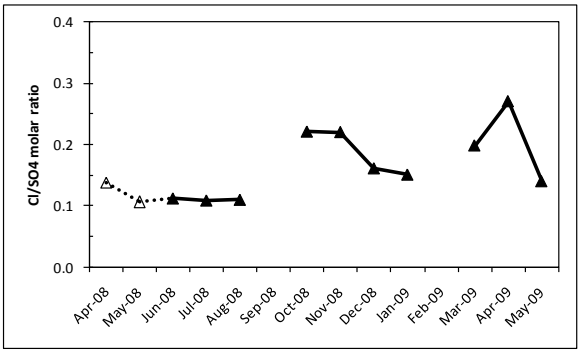
W14: Additional data

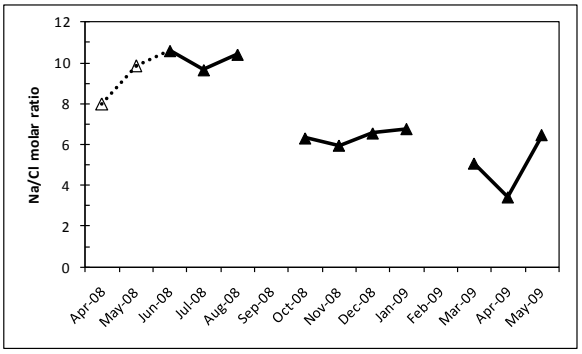












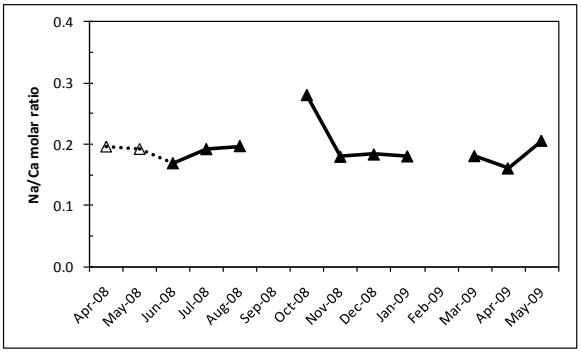
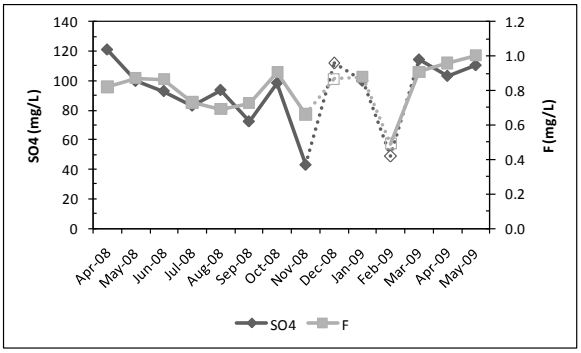
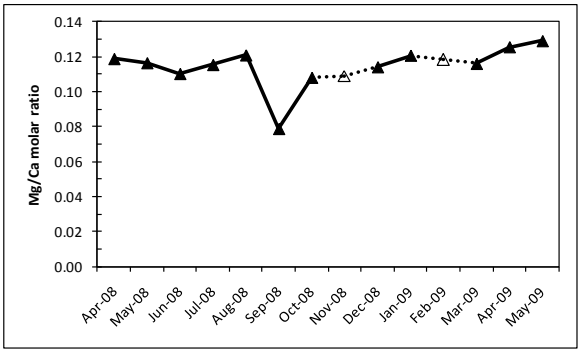


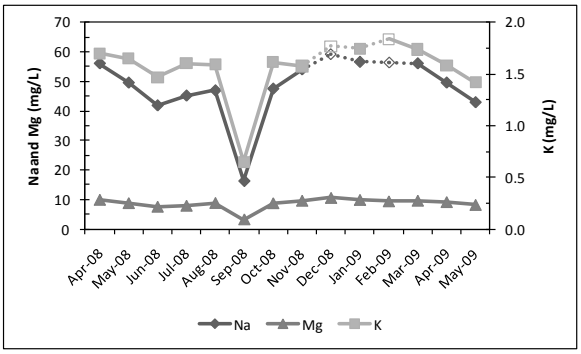
Table W14: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

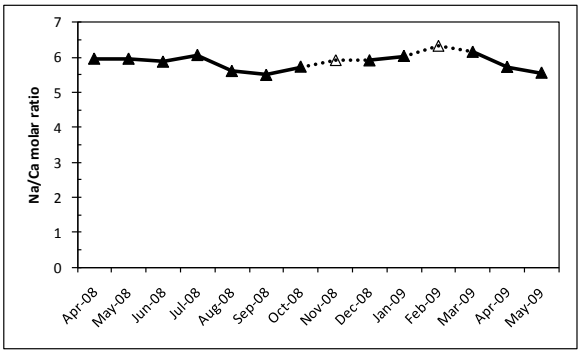
		p-values									
		F^-	Cl^-	NO_3-N	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	pH
Coefficients of correlation	F^-		0.48	0.77	**0.00**	0.60	*0.08*	**0.04**	**0.04**	0.20	0.87
	Cl^-	0.25		0.33	0.82	0.94	0.84	0.76	0.61	0.97	0.94
	NO_3-N	-0.11	0.34		0.37	0.16	0.35	0.49	0.43	0.87	0.57
	SO_4^{2-}	**0.82**	-0.08	-0.32		0.40	0.21	**0.02**	**0.01**	0.26	0.37
	Ca^{2+}	0.19	-0.03	0.49	0.30		0.11	**0.01**	**0.01**	0.26	0.22
	K^+	*-0.59*	-0.08	0.33	-0.44	0.53		0.86	0.93	0.84	0.71
	Mg^{2+}	**0.64**	-0.11	0.25	**0.72**	**0.80**	-0.06		**0.00**	0.22	0.26
	Na^+	**0.66**	0.18	0.28	**0.77**	**0.76**	-0.03	**0.90**		0.17	0.13
	HCO_3^-	0.44	-0.01	0.06	0.39	0.39	0.08	0.43	0.47		0.43
	pH	-0.06	-0.03	0.21	0.32	0.42	0.13	0.39	0.51	-0.28	

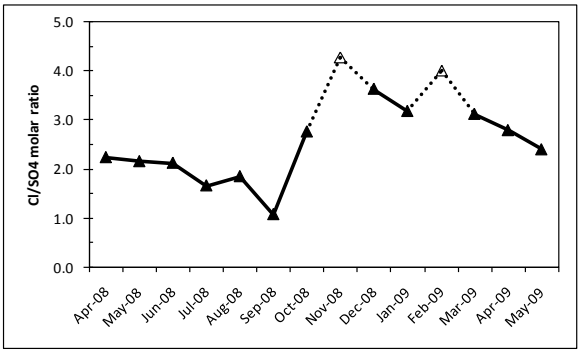
W15: Additional data

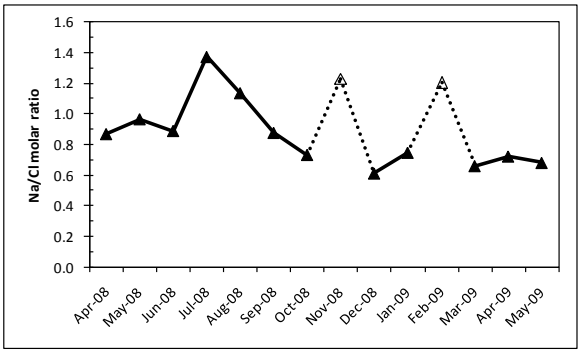












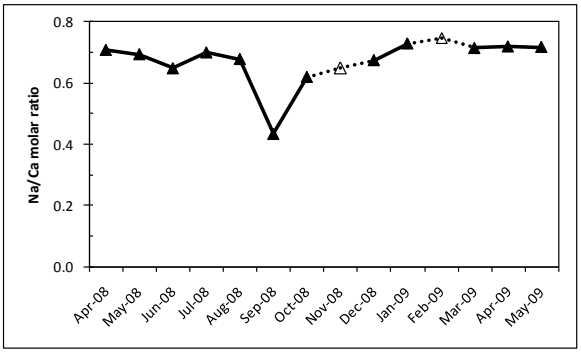
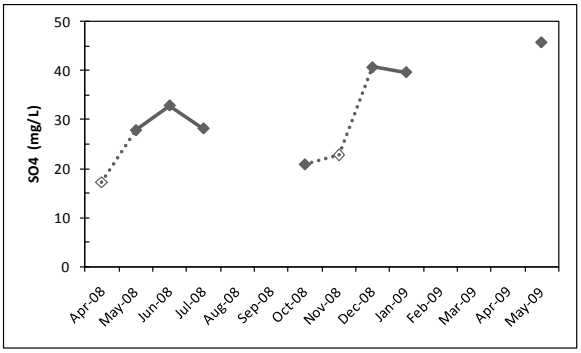
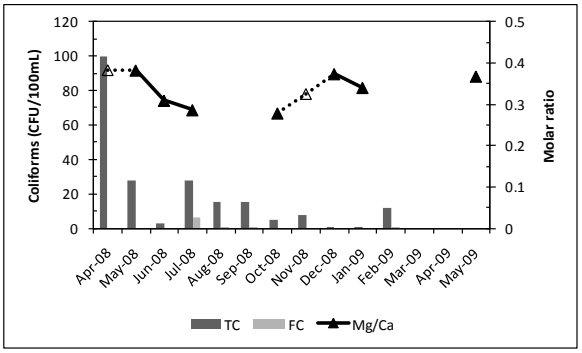


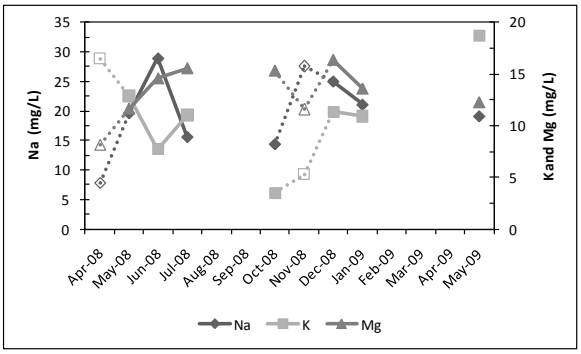
Table W15: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

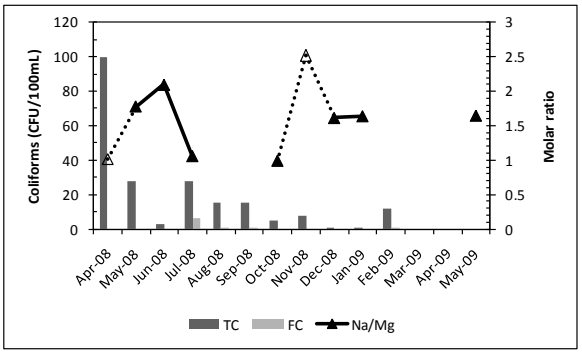
		p-values								
		F^-	Cl^-	NO_3-N	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	pH
Coefficients of correlation	F^-		**0.01**	0.07	**0.03**	0.25	0.24	0.16	0.18	0.49	0.55
	Cl^-	**0.71**		**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.03**	0.14
	NO_3-N	0.55	**0.89**		**0.00**	**0.00**	**0.01**	**0.00**	**0.00**	**0.05**	**0.02**
	SO_4^{2-}	**0.63**	**0.90**	**0.76**		**0.00**	**0.01**	**0.00**	**0.00**	**0.02**	0.48
	Ca^{2+}	0.36	**0.87**	**0.84**	**0.78**		**0.00**	**0.00**	**0.00**	**0.00**	0.16
	K^+	0.37	**0.80**	**0.73**	**0.73**	**0.95**		**0.00**	**0.00**	**0.00**	0.14
	Mg^{2+}	0.43	**0.87**	**0.77**	**0.81**	**0.96**	**0.99**		**0.00**	**0.00**	0.14
	Na^+	0.41	**0.86**	**0.79**	**0.80**	**0.97**	**0.99**	**1.00**		**0.00**	0.12
	HCO_3^-	0.22	**0.62**	**0.57**	**0.67**	**0.78**	**0.81**	**0.81**	**0.82**		0.31
	pH	-0.19	-0.45	**-0.66**	-0.23	-0.43	-0.45	-0.45	-0.48	-0.32	

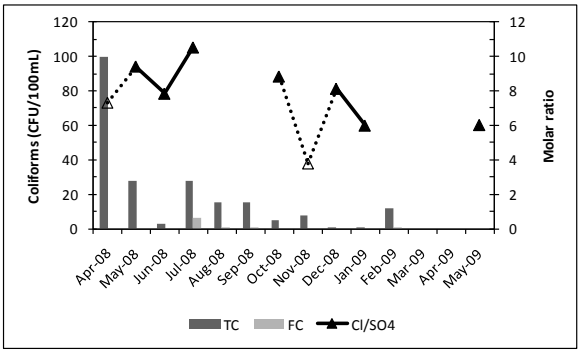
W16: Additional data

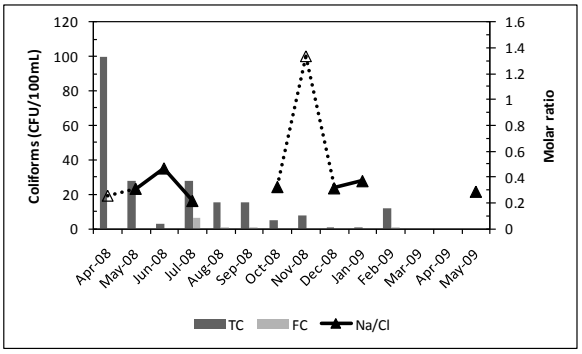












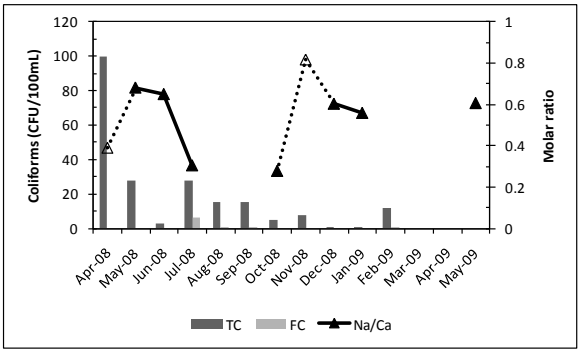
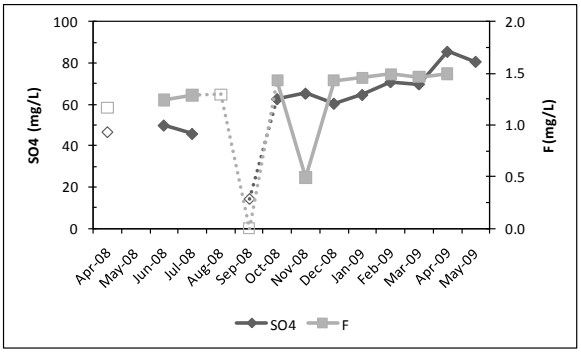
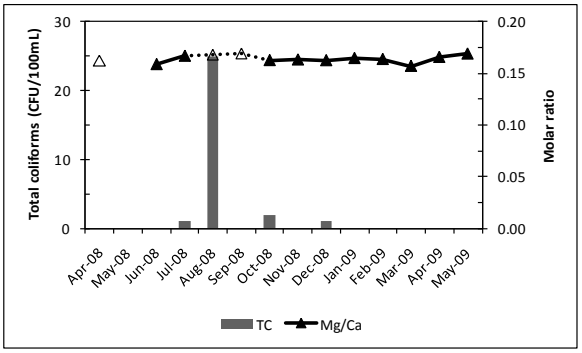


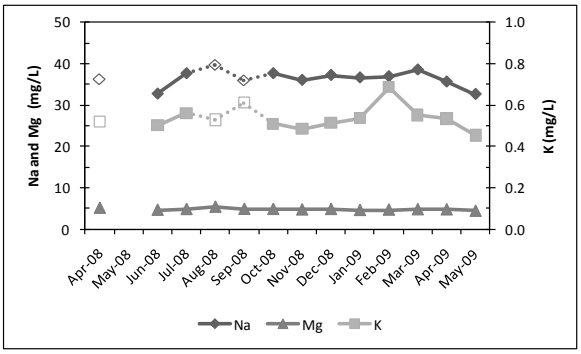
Table W16: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

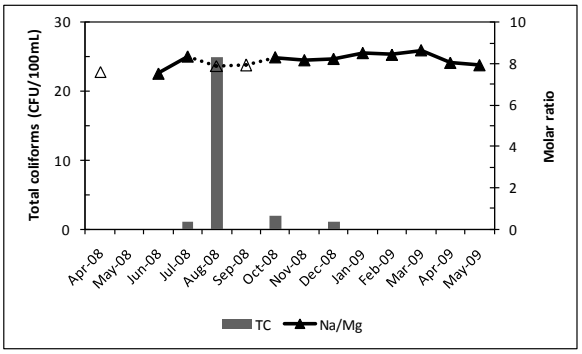
Coefficients of correlation					p-values						
	Cl^-	NO_3-N	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	pH	TC	FC
Cl^-		0.69	0.14	0.61	*0.05*	0.84	0.31	0.66	**0.02**	0.88	0.49
NO_3-N	-0.18		0.53	0.29	0.92	0.52	0.12	0.21	0.56	0.23	**0.00**
SO_4^{2-}	0.62	0.29		0.26	**0.04**	0.66	0.17	0.37	*0.09*	*0.06*	0.61
Ca^{2+}	-0.24	-0.47	-0.49		*0.07*	**0.01**	0.58	**0.00**	0.40	0.70	0.28
K^+	**0.75**	-0.05	**0.78**	*-0.71*		0.24	0.52	0.14	0.12	0.64	0.84
Mg^{2+}	0.10	-0.30	-0.20	**0.88**	-0.51		0.98	**0.01**	0.98	0.95	0.45
Na^+	0.45	0.64	0.58	-0.26	0.29	0.01		0.32	**0.04**	0.36	0.31
HCO_3^-	-0.21	-0.54	-0.41	**0.93**	-0.61	**0.87**	-0.44		0.36	0.88	0.27
pH	**-0.83**	-0.27	*-0.68*	0.38	-0.64	-0.01	**-0.77**	0.41		0.63	0.85
TC	-0.07	-0.52	*-0.74*	0.18	-0.22	-0.03	-0.41	0.07	0.22		0.18
FC	0.32	**-0.97**	-0.24	0.47	0.10	0.34	-0.45	0.49	0.09	0.57	

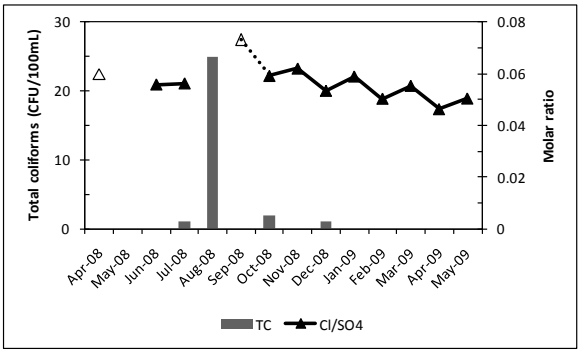
W17: Additional data

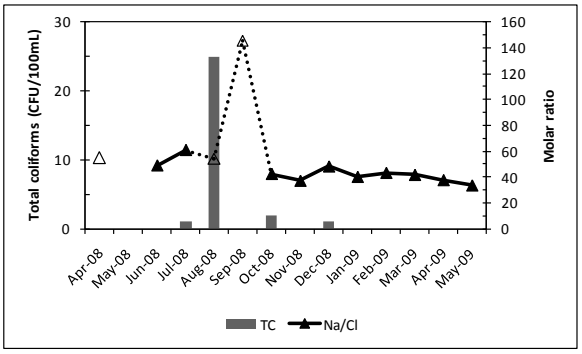












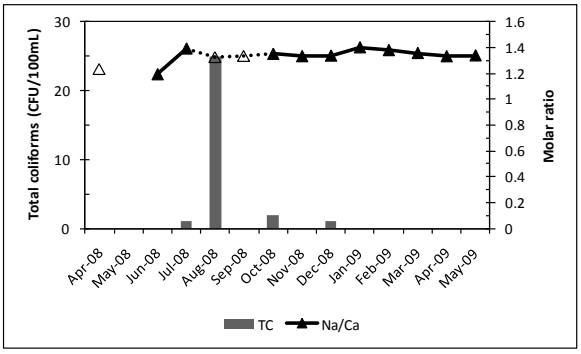
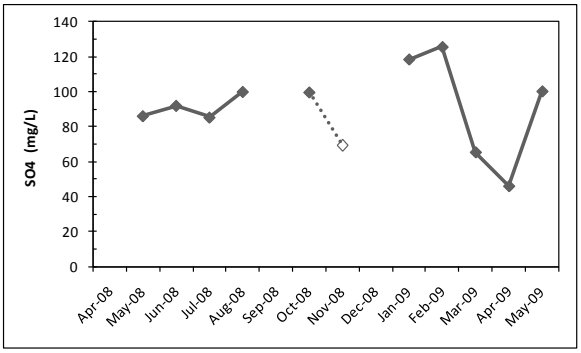
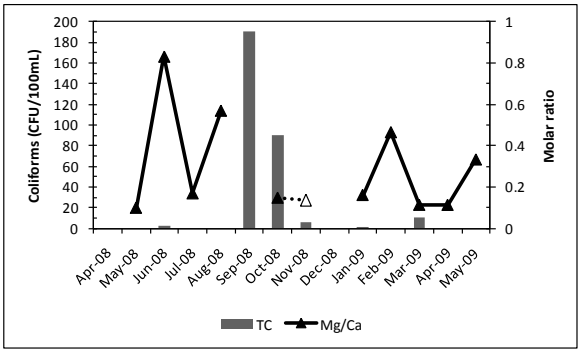


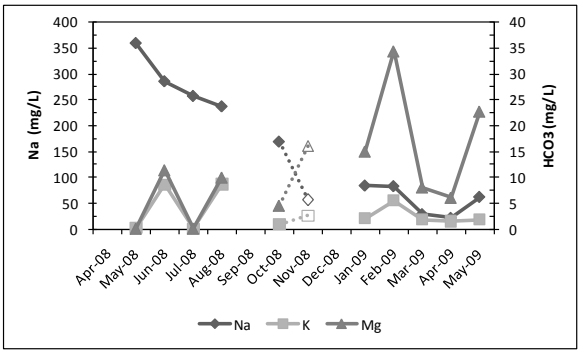
Table W17: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

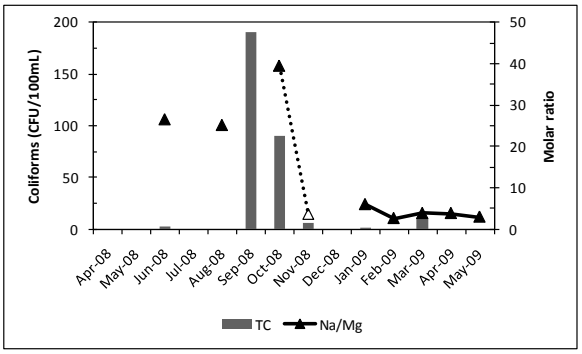
		p-values									
		F^-	Cl^-	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	pH	TC
Coefficients of correlation	F^-		0.70	0.68	0.81	0.40	0.83	0.89	0.77	0.46	0.65
	Cl^-	-0.14		**0.00**	0.40	0.60	0.32	0.98	**0.03**	**0.01**	0.41
	SO_4^{2-}	0.15	**0.89**		0.25	0.90	0.24	0.76	**0.01**	**0.01**	0.27
	Ca^{2+}	-0.09	-0.30	-0.40		0.43	**0.00**	**0.05**	0.27	0.54	0.26
	K^+	0.30	-0.19	-0.05	0.28		0.37	0.13	0.58	0.77	0.82
	Mg^{2+}	-0.08	-0.35	-0.41	**0.88**	0.32		**0.01**	0.31	0.47	*0.06*
	Na^+	0.05	0.01	-0.11	**0.64**	0.52	**0.76**		0.89	0.56	0.21
	HCO_3^-	-0.11	**-0.69**	**-0.74**	0.39	-0.20	0.36	-0.05		*0.08*	0.54
	pH	-0.27	**-0.75**	**-0.79**	0.22	-0.10	0.26	-0.21	*0.59*		0.54
	TC	0.16	-0.30	-0.38	0.39	-0.08	0.61	0.43	0.22	0.22	

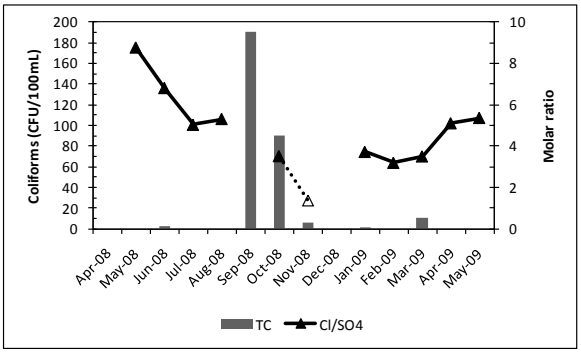
W18: Additional data

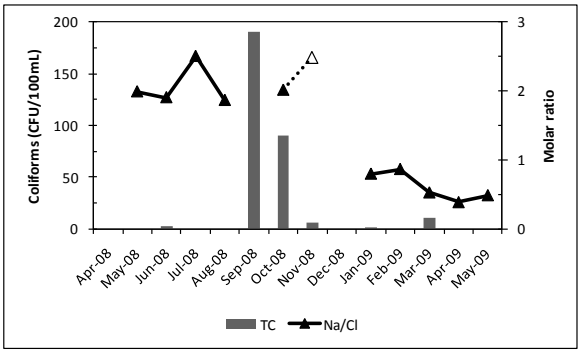












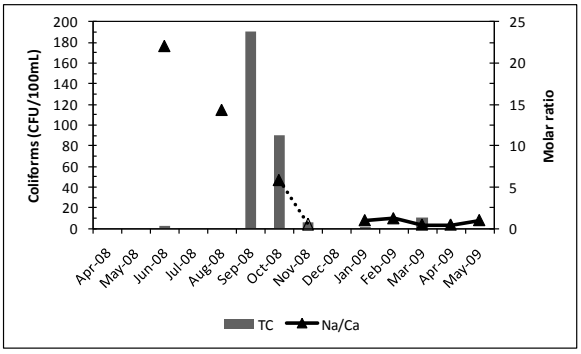
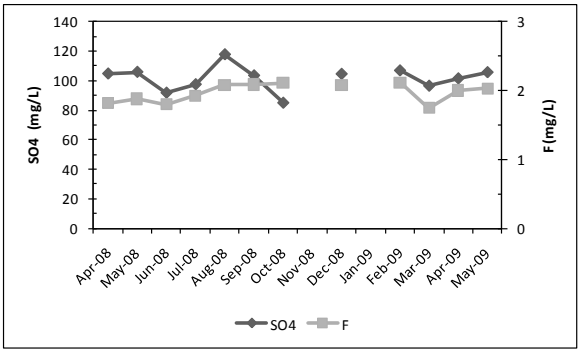
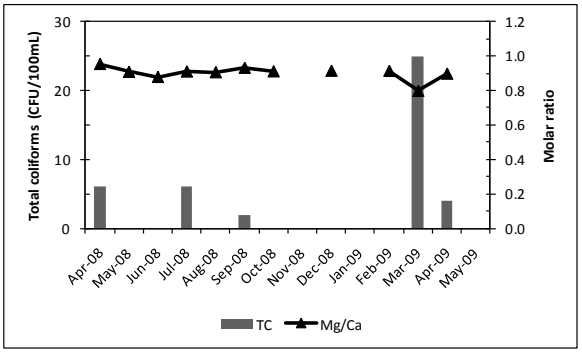


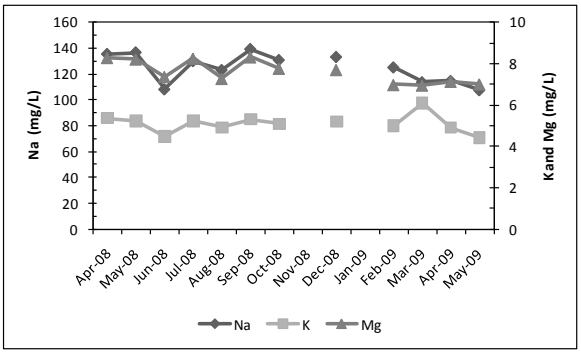
Table W18: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

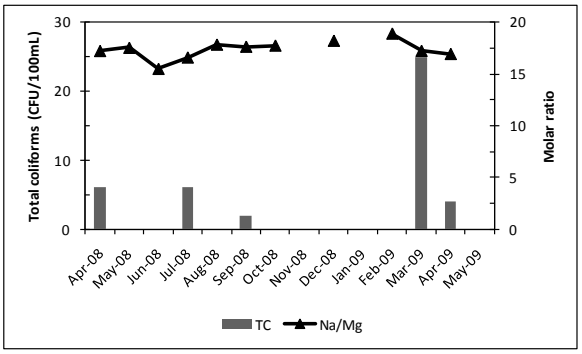
		p-values										
		F^-	Cl^-	NO_3-N	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	pH	TC
Coefficients of correlation	F^-		0.63	0.39	0.70	0.80	0.73	0.97	0.68	0.93	0.39	**0.00**
	Cl^-	-0.18		**0.01**	*0.08*	0.14	0.92	0.43	**0.00**	0.16	0.65	0.28
	NO_3-N	-0.31	**0.79**		0.23	0.15	0.88	0.47	**0.05**	0.26	0.57	0.26
	SO_4^{2-}	0.14	*0.58*	0.42		0.88	0.54	0.53	0.13	**0.00**	0.79	0.96
	Ca^{2+}	0.09	-0.50	-0.50	0.06		**0.02**	**0.00**	**0.02**	0.94	0.70	0.49
	K^+	-0.13	-0.03	-0.06	0.22	**0.72**		**0.00**	0.55	0.29	0.94	0.96
	Mg^{2+}	0.01	-0.28	-0.26	0.22	**0.94**	**0.88**		0.13	0.46	0.92	0.71
	Na^+	0.15	**0.82**	**0.63**	0.51	**-0.72**	-0.22	-0.51		0.11	0.91	0.88
	HCO_3^-	-0.03	0.48	0.39	**0.86**	0.03	0.37	0.27	0.54		0.78	0.79
	pH	0.31	-0.16	-0.21	-0.09	0.14	0.03	0.04	-0.04	-0.10		**0.01**
	TC	**0.83**	-0.38	-0.39	-0.02	0.25	0.02	0.13	-0.06	-0.10	**0.74**	

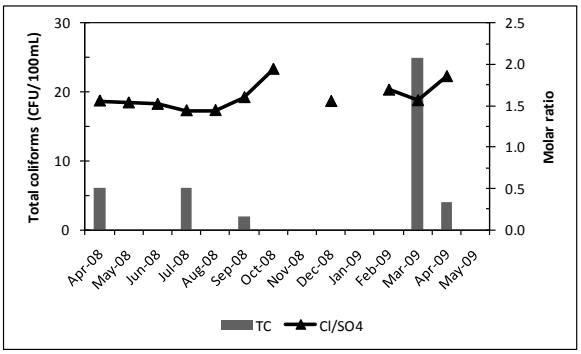
W19: Additional data

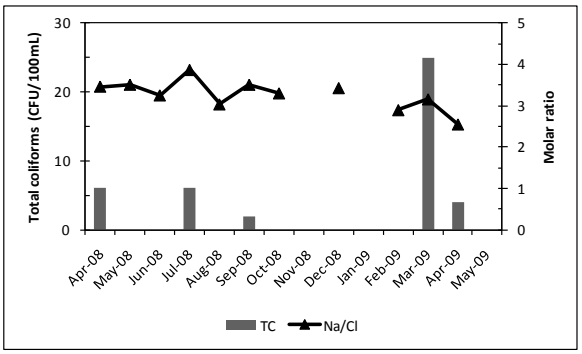












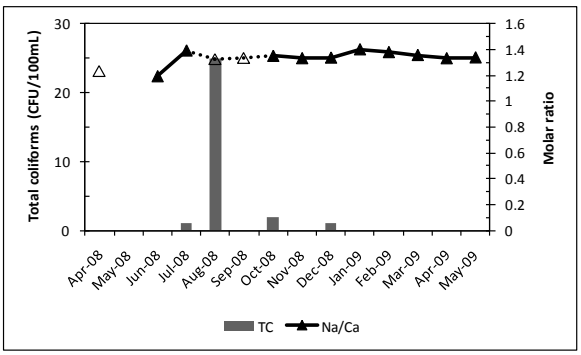
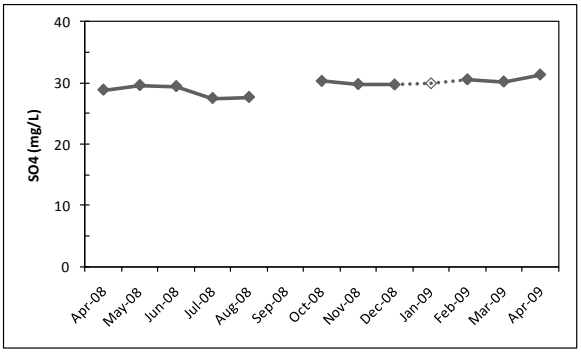
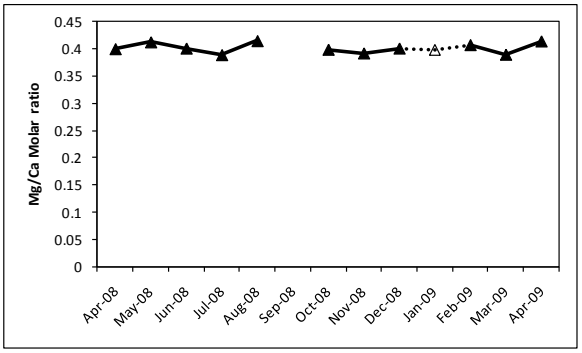


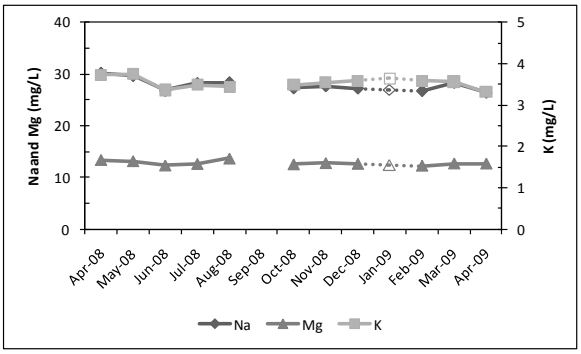
Table W19: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

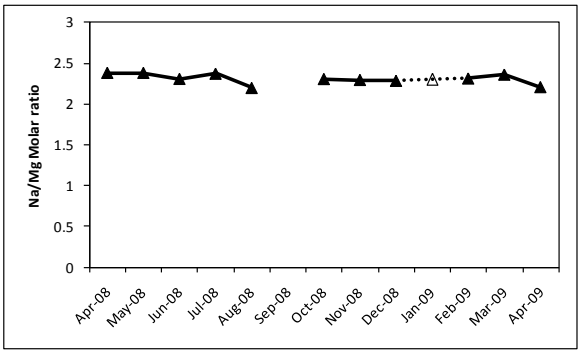
		p-values									
		F^-	Cl^-	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	pH	TC
Coefficients of correlation	F^-		**0.05**	0.51	0.10	0.24	0.57	0.58	0.16	0.53	**0.04**
	Cl^-	**0.61**		0.20	0.09	0.78	0.32	0.74	0.95	0.38	0.52
	SO_4^{2-}	0.22	0.42		0.31	0.82	0.72	0.73	0.58	0.45	0.65
	Ca^{2+}	-0.53	-0.53	-0.34		**0.04**	**0.01**	*0.06*	0.65	0.25	0.22
	K^+	-0.39	-0.10	-0.08	**0.63**		0.53	0.18	0.67	0.50	**0.02**
	Mg^{2+}	-0.19	-0.33	-0.12	**0.75**	0.21		**0.00**	0.45	*0.06*	0.88
	Na^+	0.19	0.11	0.12	*0.58*	0.44	**0.78**		0.23	0.21	0.85
	HCO_3^-	0.45	-0.02	0.19	0.16	-0.14	0.26	0.39		0.22	0.36
	pH	-0.21	-0.29	0.25	0.38	-0.23	*0.59*	0.41	0.40		0.22
	TC	**-0.62**	-0.22	-0.15	0.40	**0.70**	0.05	-0.06	-0.31	-0.41	

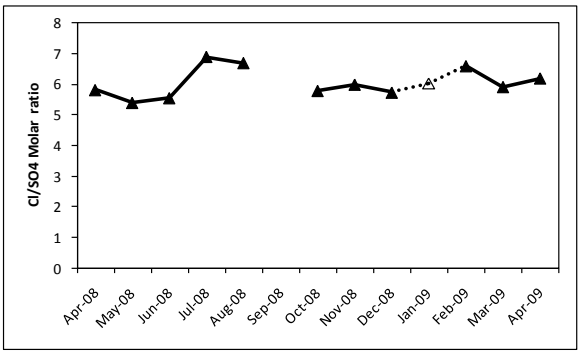
W20: Additional data

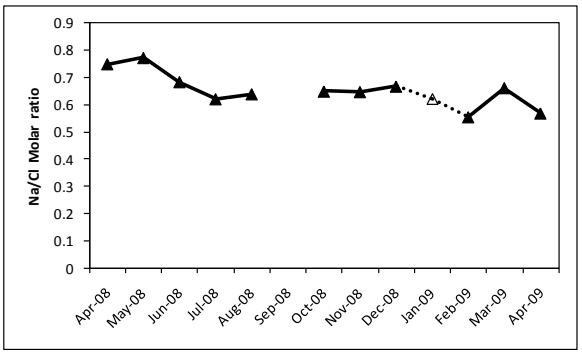












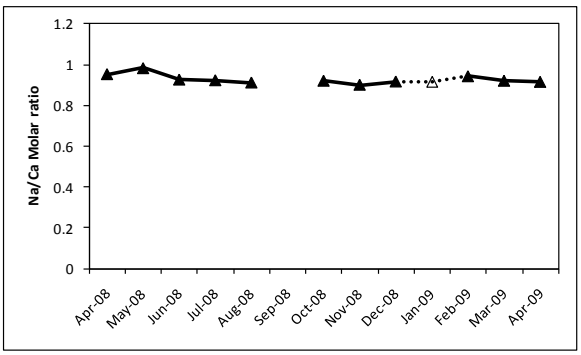
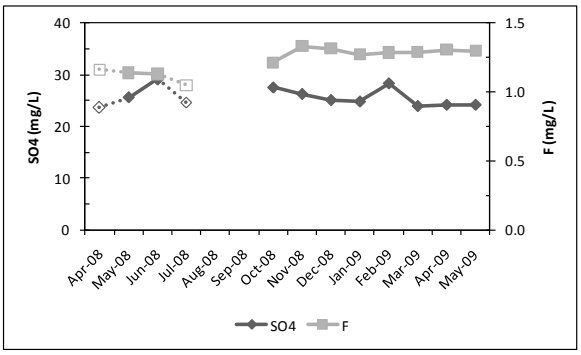


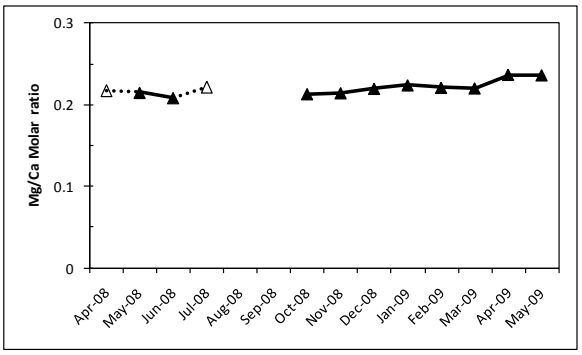
Table W20: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

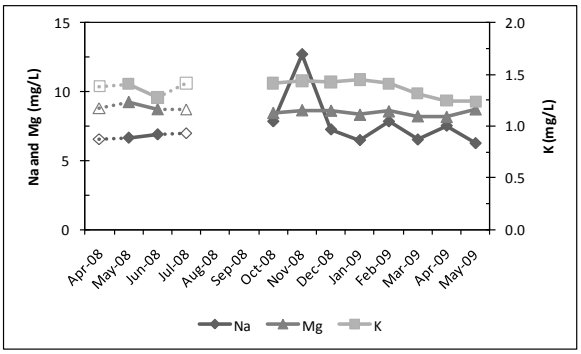
		p-values						
	Cl^-	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	pH
Cl^-		0.88	0.63	0.35	0.72	0.24	0.23	0.21
SO_4^{2-}	0.05		*0.05*	0.97	0.17	0.14	0.48	0.11
Ca^{2+}	-0.18	*-0.62*		0.50	**0.03**	**0.02**	0.26	0.76
K^+	-0.33	-0.01	0.24		0.68	**0.04**	**0.00**	0.76
Mg^{2+}	-0.13	-0.47	**0.70**	0.15		**0.04**	0.99	0.40
Na^+	-0.41	-0.50	**0.73**	**0.66**	**0.66**		**0.02**	0.21
HCO_3^-	0.42	0.25	-0.39	**-0.82**	-0.01	**-0.70**		0.74
pH	-0.43	-0.53	0.11	0.11	0.30	0.43	-0.12	

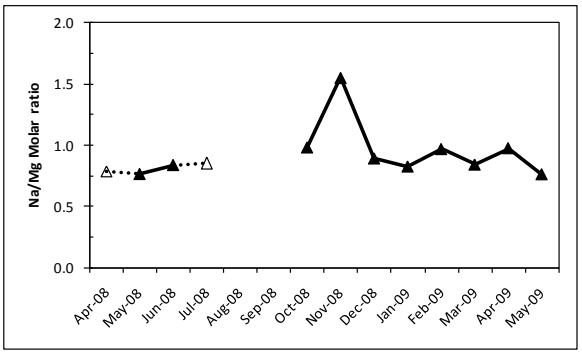
Coefficients of correlation

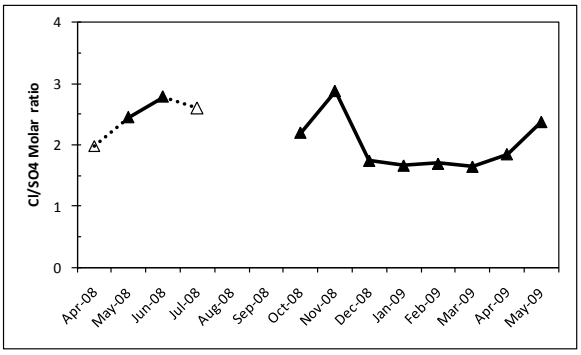
W22: Additional data

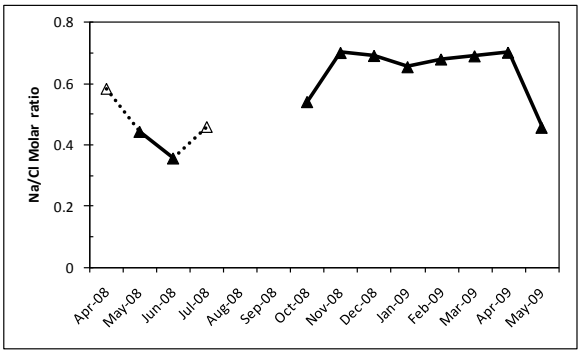












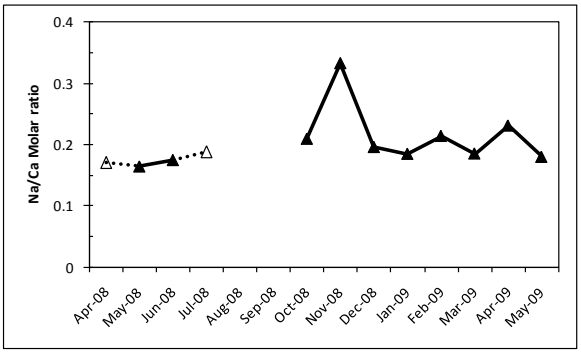
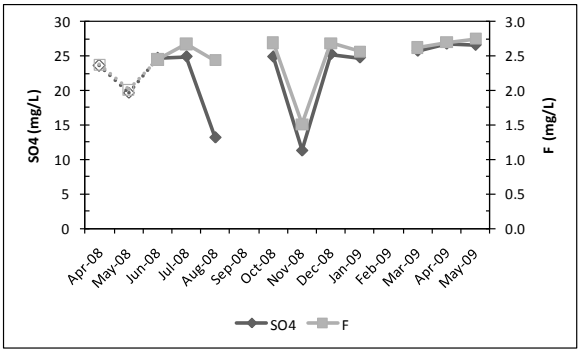
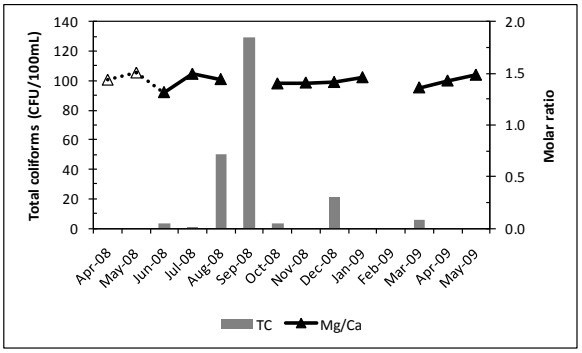


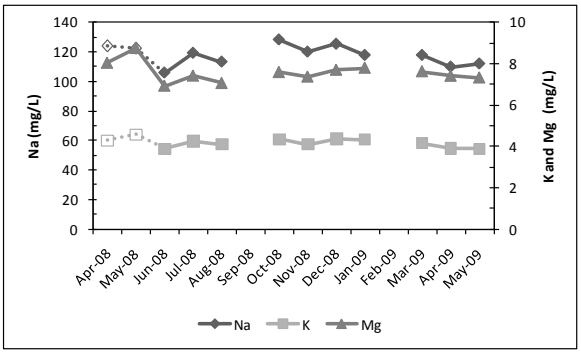
Table W22: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

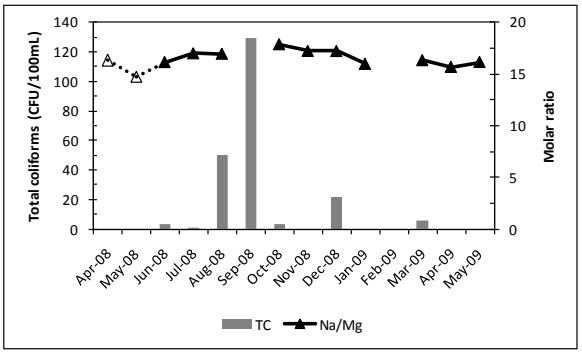
		p-values								
		F^-	Cl^-	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	pH
Coefficients of correlation	F^-		0.11	0.12	**0.03**	0.90	0.08	0.32	0.90	**0.01**
	Cl^-	-0.53		*0.06*	**0.03**	0.89	*0.06*	0.21	0.60	0.13
	SO_4^{2-}	-0.52	*0.62*		**0.05**	0.48	0.37	0.43	0.61	0.23
	Ca^{2+}	**-0.69**	**0.69**	**0.63**		0.21	**0.00**	0.60	0.76	**0.00**
	K^+	0.05	-0.05	0.25	0.44		0.58	0.28	0.92	0.41
	Mg^{2+}	-0.57	0.61	0.32	**0.81**	0.20		0.99	0.10	**0.05**
	Na^+	0.35	0.43	0.28	0.19	0.38	0.00		0.86	0.86
	HCO_3^-	-0.05	-0.19	0.19	-0.11	-0.04	-0.55	0.07		0.60
	pH	**-0.80**	0.52	0.42	**0.86**	0.29	**0.62**	-0.06	0.19	

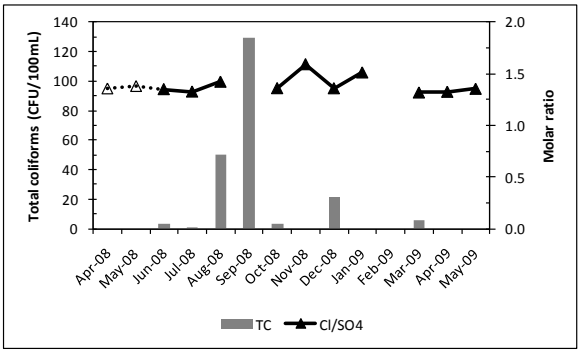
W23: Additional data

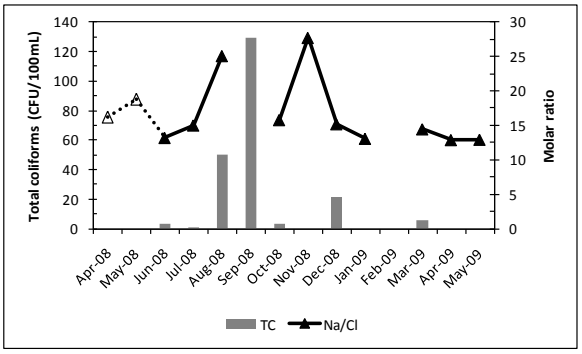












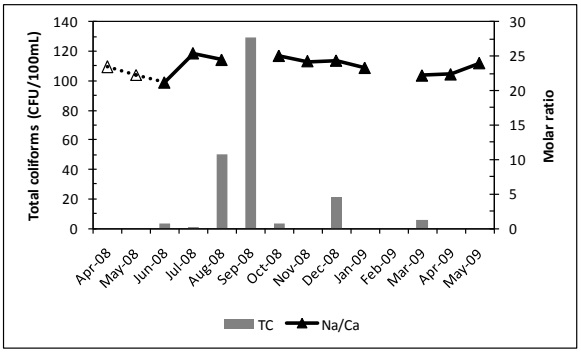
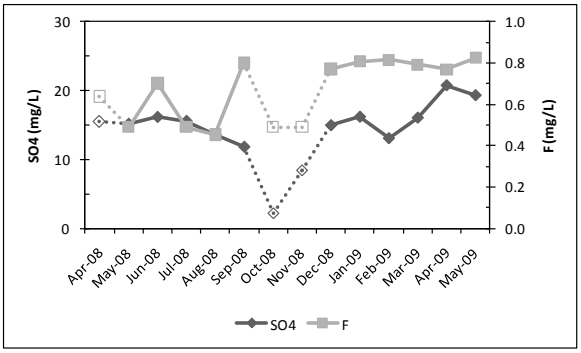
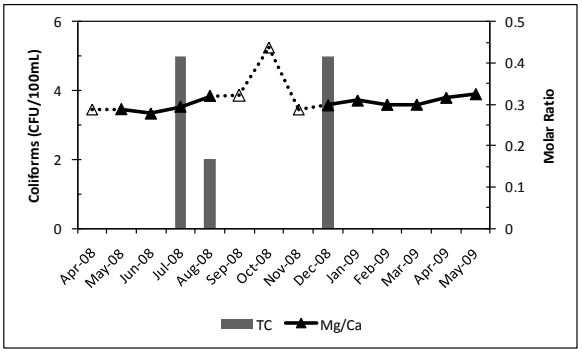


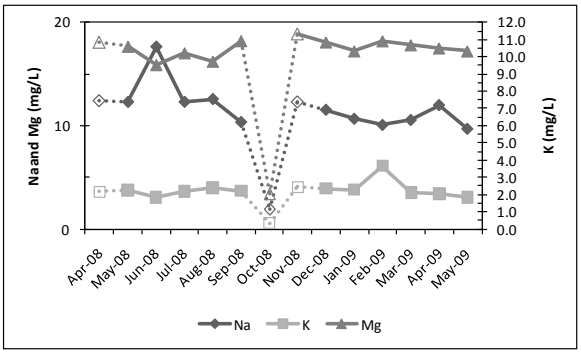
Table W23: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

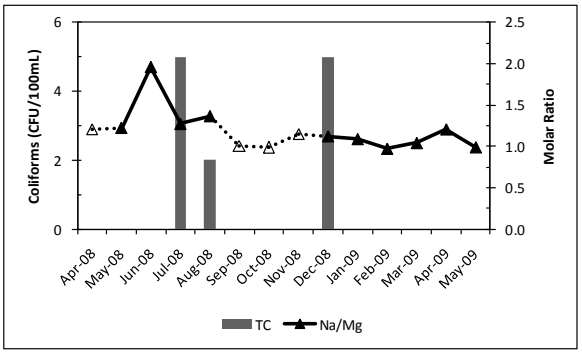
		p-values									
		F^-	Cl^-	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	pH	TC
Coefficients of correlation	F^-		**0.00**	**0.00**	**0.04**	**0.01**	**0.01**	**0.03**	**0.00**	0.35	0.28
	Cl^-	**0.88**		**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	0.29	**0.03**
	SO_4^{2-}	**0.91**	**1.00**		**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	0.25	**0.04**
	Ca^{2+}	**0.63**	**0.84**	**0.82**		**0.00**	**0.00**	**0.00**	**0.01**	0.17	0.17
	K^+	**0.73**	**0.89**	**0.85**	**0.85**		**0.00**	**0.00**	**0.01**	0.56	0.13
	Mg^{2+}	**0.77**	**0.94**	**0.92**	**0.88**	**0.97**		**0.00**	**0.01**	0.25	**0.04**
	Na^+	**0.65**	**0.82**	**0.79**	**0.83**	**0.97**	**0.94**		**0.05**	0.44	0.15
	HCO_3^-	**0.78**	**0.87**	**0.87**	**0.71**	**0.75**	**0.77**	**0.61**		0.59	0.08
	pH	-0.31	-0.35	-0.38	-0.45	-0.20	-0.38	-0.26	-0.18		0.34
	TC	-0.36	**-0.65**	**-0.62**	-0.45	-0.48	**-0.62**	-0.47	-0.55	0.32	

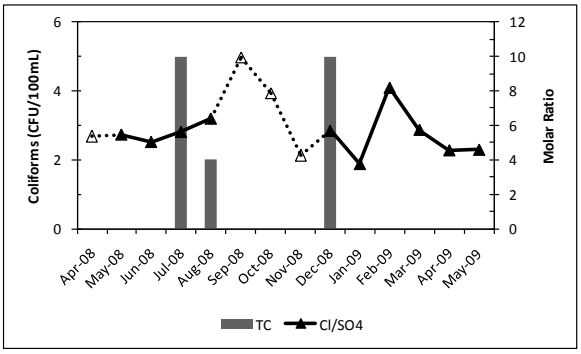
W24: Additional data

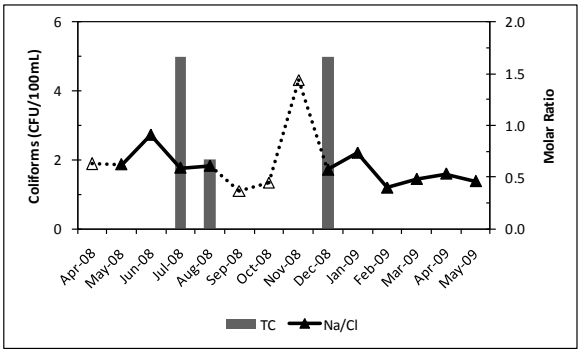












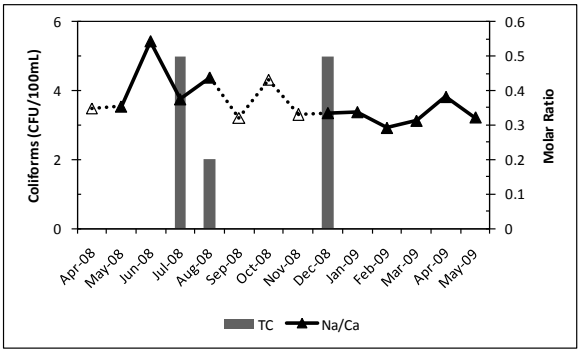
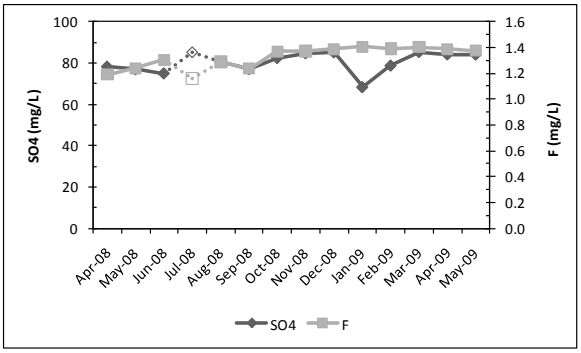
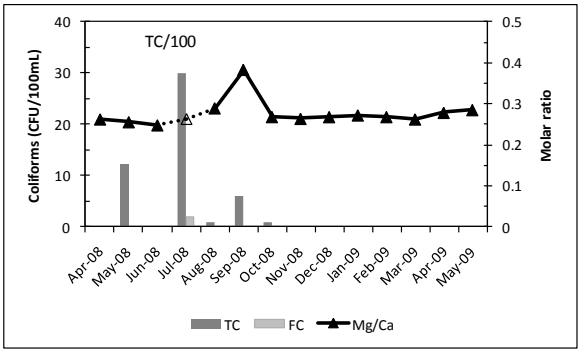


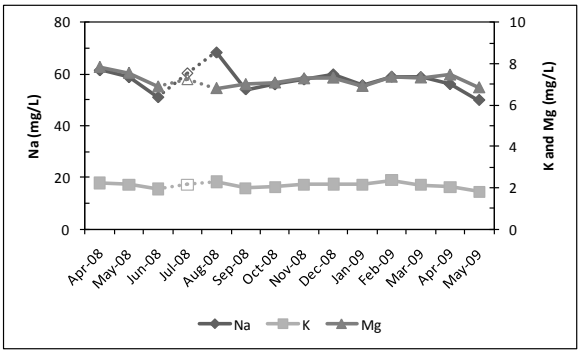
Table W24: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

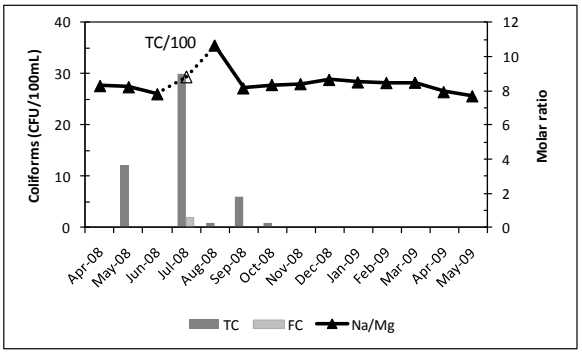
		p-values										
		F^-	Cl^-	NO_3-N	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	pH	TC
Coefficients of correlation	F^-		0.95	**0.04**	0.28	0.62	0.92	0.23	0.27	0.37	0.60	0.19
	Cl^-	0.02		0.88	0.80	0.59	0.28	0.38	0.67	0.46	0.73	0.94
	NO_3-N	**-0.65**	0.05		0.59	0.64	0.96	0.43	0.70	0.91	*0.07*	**0.03**
	SO_4^{2-}	0.38	-0.09	-0.20		0.42	**0.02**	0.91	0.89	0.62	0.32	0.35
	Ca^{2+}	0.18	0.19	-0.17	-0.29		0.30	**0.05**	0.93	0.72	*0.07*	0.98
	K^+	0.04	0.38	-0.02	**-0.71**	0.36		0.14	0.26	0.72	0.39	0.86
	Mg^{2+}	0.42	0.31	-0.28	-0.04	**0.64**	0.50		**0.02**	0.74	0.48	0.93
	Na^+	-0.38	-0.15	0.14	-0.05	-0.03	-0.39	**-0.73**		0.98	0.99	0.79
	HCO_3^-	0.32	0.26	0.04	0.18	-0.13	0.13	0.12	-0.01		0.97	0.40
	pH	0.19	-0.13	*-0.60*	0.35	*-0.59*	-0.30	-0.25	0.00	0.01		0.32
	TC	-0.45	0.03	**0.68**	-0.33	0.01	0.07	-0.03	0.10	0.30	-0.35	

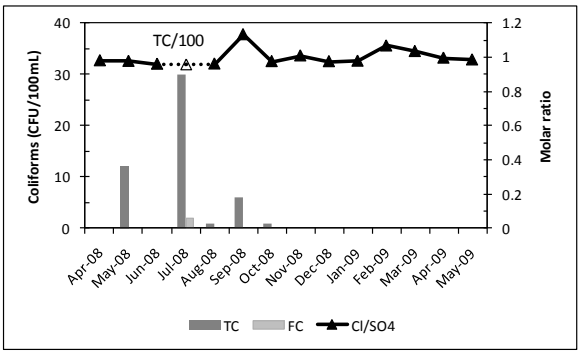
W25: Additional data

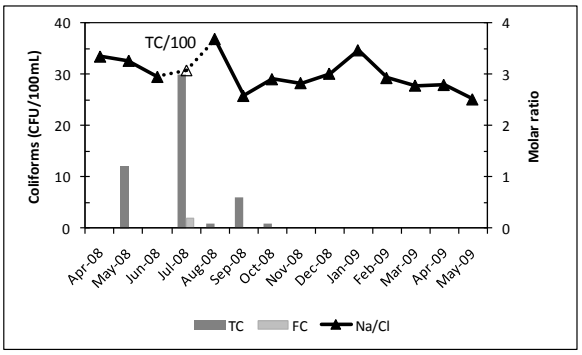












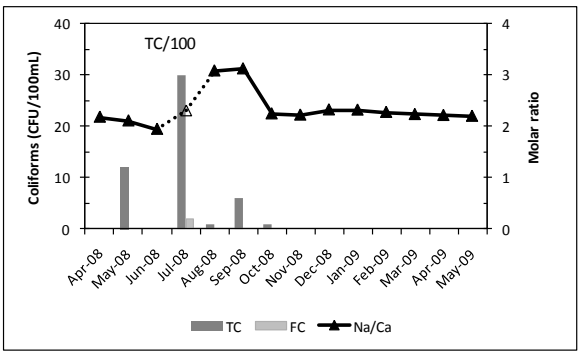
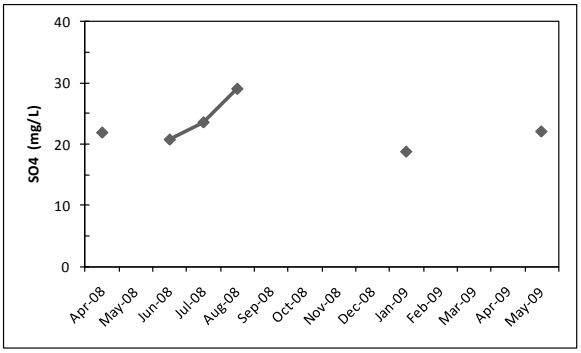
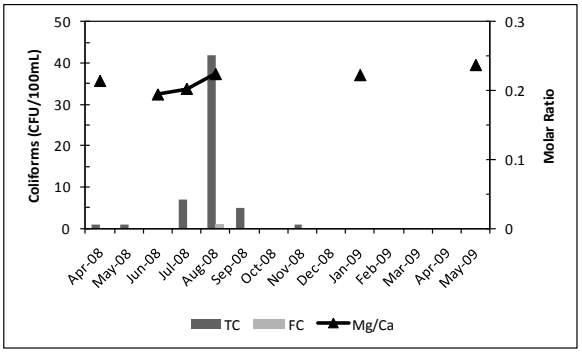


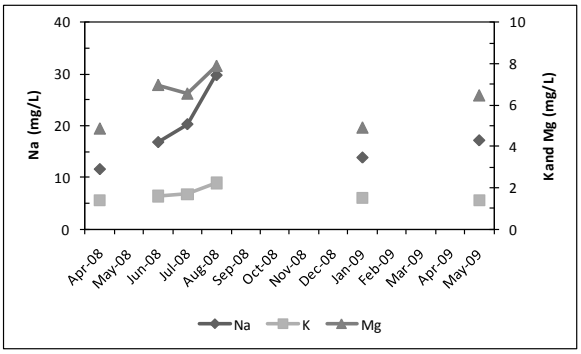
Table W25: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

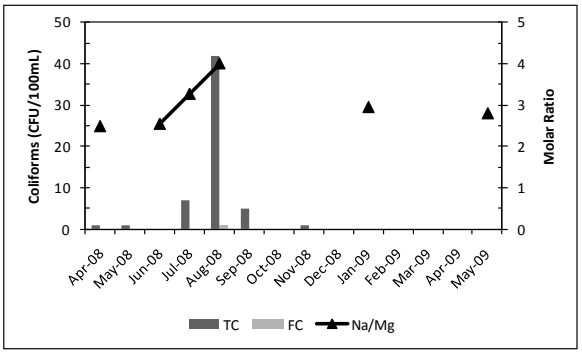
	p-values									
	F^-	Cl^-	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	pH	TC
F^-		0.75	0.57	0.78	0.84	0.26	0.53	0.18	**0.01**	*0.07*
Cl^-	0.11		**0.00**	0.36	0.86	0.66	0.91	0.13	**0.05**	0.83
SO_4^{2-}	0.19	**0.79**		0.83	0.80	0.67	0.62	0.57	**0.04**	0.65
Ca^{2+}	0.10	-0.31	0.07		0.27	**0.05**	0.54	0.10	0.72	0.33
K^+	-0.07	-0.06	-0.09	0.36		0.12	**0.00**	*0.07*	0.77	0.85
Mg^{2+}	-0.37	0.15	0.15	**0.61**	0.50		0.28	0.90	0.88	0.72
Na^+	-0.21	0.04	0.17	0.21	**0.86**	0.36		0.14	0.99	0.91
HCO_3^-	0.44	-0.49	-0.19	0.52	*0.57*	0.04	0.47		0.82	0.18
pH	**-0.73**	-0.60	-0.61	-0.12	-0.10	0.05	0.00	-0.08		*0.06*
TC	*-0.56*	0.07	-0.15	-0.32	-0.06	0.12	0.04	-0.43	*0.58*	

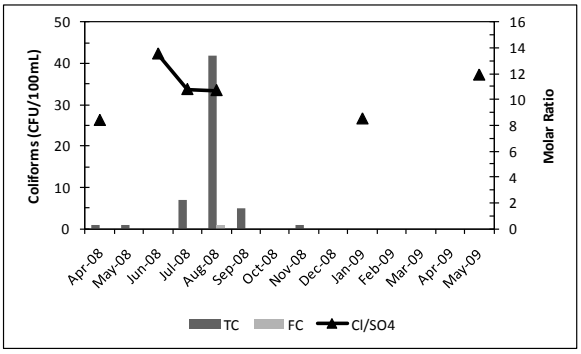
W26: Additional data

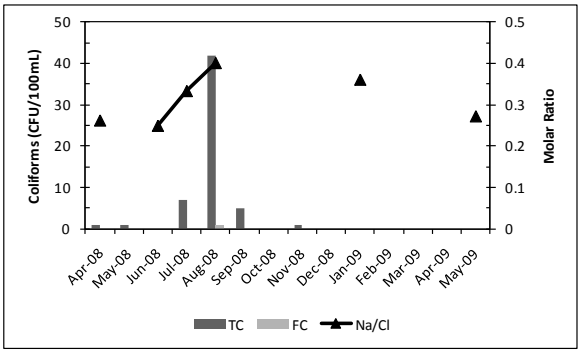












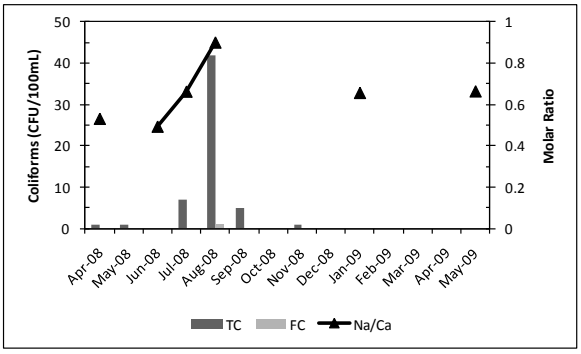
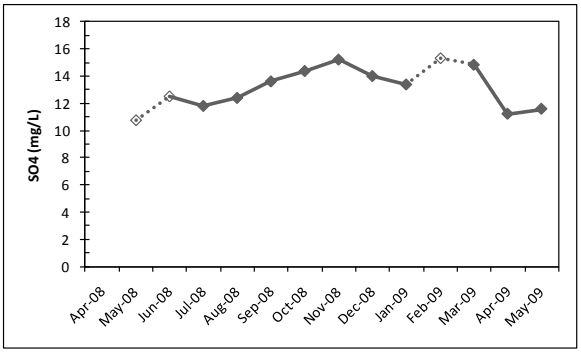
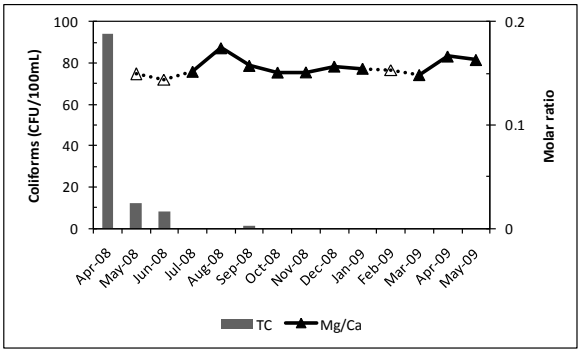


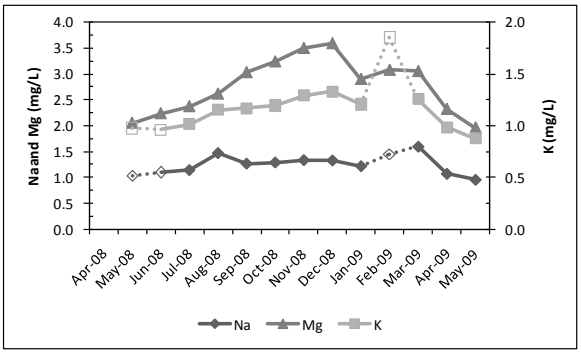
Table W26: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

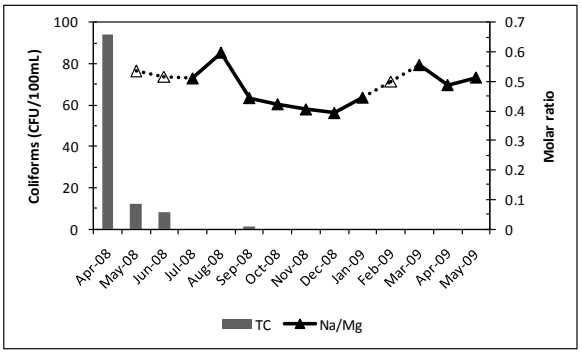
		p-values										
		F^-	Cl^-	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	pH	TC	FC
Coefficients of correlation	F^-		0.73	0.10	0.86	0.23	0.73	0.50	**0.02**	0.35	0.15	*0.06*
	Cl^-	0.18		0.12	**0.01**	0.21	**0.00**	**0.05**	0.52	0.76	0.29	0.29
	SO_4^{2-}	0.73	0.71		0.21	**0.05**	0.11	**0.04**	0.07	0.41	**0.01**	**0.03**
	Ca^{2+}	0.09	**0.93**	0.60		0.14	**0.01**	0.06	0.45	0.41	0.28	0.35
	K^+	0.58	0.60	**0.81**	0.68		0.10	**0.02**	0.08	0.21	**0.02**	**0.01**
	Mg^{2+}	0.18	**0.98**	0.72	**0.94**	0.72		**0.01**	0.48	0.69	0.21	0.19
	Na^+	0.35	**0.81**	**0.83**	*0.79*	**0.90**	**0.90**		0.32	0.57	**0.04**	**0.05**
	HCO_3^-	**0.89**	0.33	0.78	0.39	0.75	0.36	0.50		0.06	**0.05**	0.07
	pH	-0.46	-0.16	-0.42	-0.42	-0.60	-0.21	-0.30	-0.79		0.19	0.46
	TC	0.66	0.52	**0.92**	0.53	**0.90**	0.60	**0.83**	0.81	-0.62		**0.04**
	FC	*0.79*	0.52	**0.86**	0.46	**0.91**	0.62	**0.80**	0.77	-0.37	**0.83**	

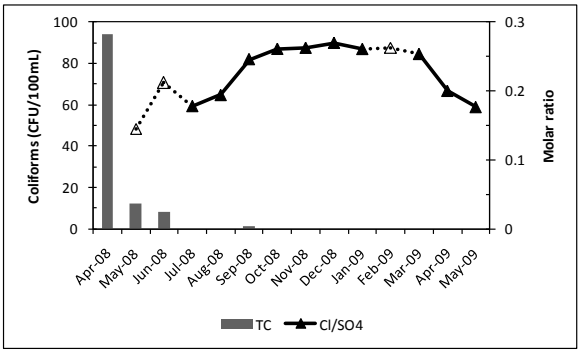
W27: Additional data

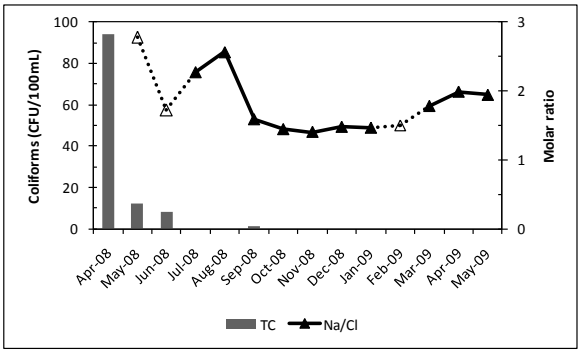












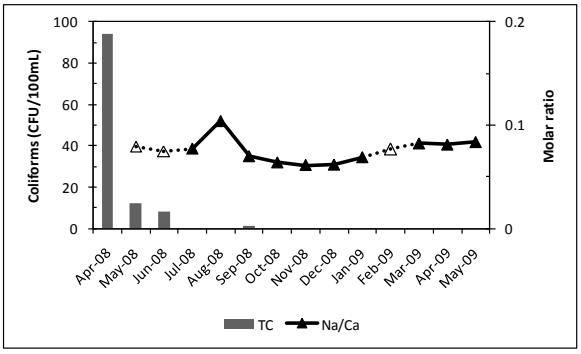


Table W27: Linear correlations using transform data. Significant correlation are in bold (p-value<0.05).

Coefficients of correlation	p-values									
	Cl^-	NO_3-N	SO_4^{2-}	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	pH	TC
Cl^-		**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.05**	**0.00**	0.60	0.69
NO_3-N	**0.81**		**0.01**	**0.01**	**0.01**	**0.02**	**0.06**	**0.02**	0.42	0.37
SO_4^{2-}	**0.95**	**0.77**		**0.00**	**0.00**	**0.00**	**0.02**	**0.00**	0.66	0.75
Ca^{2+}	**0.95**	**0.74**	**0.93**		**0.00**	**0.00**	**0.04**	**0.00**	0.40	0.74
K^+	**0.90**	**0.77**	**0.87**	**0.93**		**0.00**	**0.00**	**0.00**	0.62	0.86
Mg^{2+}	**0.93**	**0.71**	**0.91**	**0.98**	**0.96**		**0.02**	**0.00**	0.42	0.68
Na^+	**0.63**	**0.60**	**0.70**	**0.65**	**0.82**	**0.71**		**0.01**	0.93	0.93
HCO_3^-	**0.88**	**0.72**	**0.86**	**0.96**	**0.97**	**0.96**	**0.77**		0.54	0.93
pH	-0.19	0.29	-0.16	-0.30	-0.18	-0.29	0.03	-0.22		**0.00**
TC	0.15	-0.32	0.12	0.12	0.07	0.15	0.03	0.03	**-0.86**	

Table D2: Descriptive statistics of water chemistry for sampled wells

		Concentration (mg/L)									
		F	Cl	NO3-N	SO4	Ca	K	Mg	Na	HCO3-	pH
W1	Mean	0.7	30.3	0.5	42.8	68.6	2.0	25.6	26.3	284.4	7.2
	St dev	0.3	3.0	0.1	4.7	6.0	0.1	4.4	6.4	19.3	0.1
	Min	0.5	23.8	0.2	36.2	59.2	1.9	18.9	18.1	256.1	7.0
	Max	1.3	33.5	0.7	50.9	75.9	2.1	33.2	38.4	313.7	7.4
	C.V. (%)	36.1	9.9	27.9	10.9	8.8	4.3	17.4	24.3	6.8	2.0
W2	Mean	1.1	50.9	0.2	29.3	41.1	13.7	29.3	76.7	380.7	7.8
	St dev	0.3	12.7	0.1	13.0	28.8	1.7	4.8	6.3	103.3	0.5
	Min	0.5	20.5	0.1	6.9	5.6	11.4	22.4	66.0	227.9	7.4
	Max	1.5	63.8	0.5	47.5	88.7	15.6	37.5	84.5	578.0	9.1
	C.V. (%)	31.5	25.0	70.1	44.4	70.0	12.4	16.2	8.2	27.1	6.9
W3	Mean	1.5	8.1	0.1	32.8	54.4	3.2	10.7	39.1	238.0	7.2
	St dev	0.3	2.1	0.0	8.7	2.4	0.2	0.4	1.6	22.4	0.2
	Min	1.0	3.4	0.1	13.3	49.4	2.9	9.9	36.2	198.5	6.9
	Max	1.9	10.3	0.1	41.1	57.9	3.6	11.6	41.1	278.3	7.6
	C.V. (%)	19.3	25.8	0.0	26.6	4.4	6.4	4.0	4.0	9.4	2.6
W4	Mean	0.5	3.9	0.5	10.5	56.6	1.6	5.8	2.1	160.8	7.2
	St dev	0.0	0.6	0.1	1.7	2.4	0.1	0.3	0.2	10.6	0.1
	Min	0.5	2.7	0.3	5.9	52.3	1.4	5.4	1.9	140.2	7.0
	Max	0.5	4.8	0.6	11.6	59.8	1.6	6.4	2.5	177.7	7.4
	C.V. (%)	0.0	15.6	22.7	15.9	4.2	4.6	4.9	8.6	6.6	1.4
W5	Mean	0.5	18.9	1.2	22.1	49.5	2.1	8.9	12.7	150.2	6.8
	St dev	0.0	3.1	0.4	2.2	5.0	0.2	0.8	1.2	24.1	0.2
	Min	0.5	14.4	0.8	18.7	44.6	1.7	7.8	10.8	110.2	6.6
	Max	0.5	22.5	1.9	25.3	61.5	2.4	10.5	14.9	178.6	7.1
	C.V. (%)	0.0	16.3	29.8	9.9	10.0	11.0	9.5	9.3	16.0	2.3
W6	Mean	0.5	191.5	0.7	36.5	82.1	2.9	61.0	54.9	291.5	6.9
	St dev	0.0	67.7	0.2	7.7	15.4	0.6	13.8	11.3	49.9	0.2
	Min	0.5	47.4	0.2	11.9	40.2	1.3	23.2	22.5	145.4	6.4
	Max	0.5	263.4	1.0	41.5	98.4	3.7	74.8	66.2	360.6	7.2
	C.V. (%)	0.0	35.3	27.4	20.9	18.7	20.0	22.6	20.6	17.1	2.9
W7	Mean	0.6	55.9	0.7	29.7	75.5	1.9	11.3	16.0	184.1	7.1
	St dev	0.1	4.2	0.1	1.3	14.3	0.2	0.7	2.0	56.7	0.2
	Min	0.5	49.8	0.6	27.2	42.2	1.8	10.6	14.1	76.9	6.6
	Max	0.8	61.3	0.9	30.9	87.0	2.3	13.2	19.9	295.8	7.5
	C.V. (%)	17.0	7.6	12.6	4.2	19.0	8.4	6.4	12.5	30.8	3.2
W9	Mean	1.6	17.7	0.1	41.9	8.1	2.2	4.1	88.3	181.4	8.1
	St dev	0.1	2.5	0.0	2.1	0.4	0.2	0.2	4.3	15.9	0.3
	Min	1.5	13.6	0.1	39.4	7.3	2.1	3.6	81.4	158.2	7.4
	Max	1.7	20.4	0.1	45.3	8.5	2.7	4.3	95.6	211.5	8.5
	C.V. (%)	3.9	14.4	0.0	4.9	5.0	8.0	5.5	4.8	8.8	4.1

Table D2 (con't): Descriptive statistics of water chemistry for the sampled wells

		Concentration (mg/L)									
		F	Cl	NO3-N	SO4	Ca	K	Mg	Na	HCO3-	pH
W10	Mean	0.8	27.4	0.1	35.4	24.2	4.1	11.3	53.4	169.8	7.8
	St dev	0.1	0.8	0.0	1.0	0.8	0.1	0.5	2.0	24.2	0.5
	Min	0.7	26.1	0.1	33.8	23.2	3.9	10.6	49.9	148.7	6.9
	Max	0.8	28.8	0.1	36.6	25.7	4.3	12.3	56.6	232.2	8.5
	C.V. (%)	8.6	3.0	0.0	2.8	3.5	3.1	4.1	3.7	14.3	6.9
W11	Mean	0.5	13.3	0.1	15.9	37.6	1.1	8.3	7.0	123.0	6.7
	St dev	0.0	3.9	0.0	4.4	8.6	0.2	2.0	1.4	25.5	0.1
	Min	0.5	4.6	0.1	5.9	27.7	0.8	6.2	5.2	85.3	6.5
	Max	0.5	20.2	0.2	25.8	56.4	1.5	12.3	9.7	176.2	6.9
	C.V. (%)	0.0	29.2	32.1	28.0	22.8	20.4	23.6	19.7	20.7	2.0
W12	Mean	1.0	70.0	0.1	132.5	18.0	3.5	5.8	112.1	114.5	8.0
	St dev	0.2	7.5	0.0	26.2	1.5	0.2	0.6	13.3	14.3	0.5
	Min	0.7	56.9	0.1	80.1	15.8	3.2	4.7	89.9	93.7	7.3
	Max	1.5	80.5	0.1	164.0	20.8	3.7	6.8	129.5	147.0	8.7
	C.V. (%)	24.0	10.7	0.0	19.8	8.2	5.1	9.4	11.9	12.5	5.8
W13	Mean	0.5	57.5	2.4	106.4	111.3	2.3	10.5	23.5	214.7	7.1
	St dev	0.0	15.0	1.0	17.2	19.8	0.3	1.9	3.8	19.8	0.2
	Min	0.5	34.2	1.1	77.2	81.9	1.6	7.0	16.6	187.0	6.8
	Max	0.5	82.9	4.3	132.8	135.0	2.7	12.7	29.0	251.3	7.4
	C.V. (%)	0.0	26.1	44.1	16.1	17.8	15.1	18.4	16.2	9.2	2.5
W14	Mean	1.6	3.2	0.1	16.3	37.3	1.2	5.3	6.1	131.2	7.2
	St dev	0.2	7.5	0.1	2.1	3.4	0.1	0.6	6.5	15.8	0.4
	Min	1.3	0.6	0.1	13.1	31.4	1.0	4.1	2.9	112.5	6.8
	Max	2.0	25.9	0.4	19.6	41.3	1.4	6.2	25.4	159.0	7.9
	C.V. (%)	15.2	231.4	53.8	12.6	9.1	10.1	12.1	105.8	12.0	5.4
W15	Mean	0.9	91.4	0.5	99.9	121.6	1.5	8.5	47.3	249.8	7.1
	St dev	0.1	34.3	0.4	13.6	22.4	0.3	1.9	11.3	63.4	0.2
	Min	0.7	28.6	0.1	72.2	65.4	0.6	3.1	16.2	118.9	6.8
	Max	1.0	150.1	1.1	120.7	153.5	1.8	10.6	59.3	396.3	7.3
	C.V. (%)	11.1	37.5	65.4	13.6	18.4	19.5	22.6	24.0	25.4	2.3
W16	Mean	0.5	97.4	0.5	33.7	71.6	10.9	14.2	20.5	151.6	6.7
	St dev	0.0	17.1	0.2	8.8	15.8	4.7	1.8	5.1	46.5	0.2
	Min	0.5	68.0	0.1	20.8	50.2	3.5	11.6	14.3	89.1	6.4
	Max	0.5	122.3	0.7	45.8	90.6	18.7	16.4	28.9	215.1	7.1
	C.V. (%)	0.0	17.6	38.7	26.1	22.0	43.0	12.5	25.0	30.7	2.9
W17	Mean	1.3	1.3	0.1	65.6	47.0	0.5	4.7	36.2	181.8	7.3
	St dev	0.3	0.2	0.0	12.2	2.0	0.1	0.1	2.0	14.7	0.3
	Min	0.5	1.0	0.1	45.8	42.5	0.5	4.4	32.6	163.0	7.1
	Max	1.5	1.5	0.1	85.6	49.5	0.7	4.8	38.5	205.2	7.8
	C.V. (%)	23.2	14.8	0.0	18.7	4.2	11.8	2.9	5.6	8.1	3.8

Table 2 (con't): Descriptive statistics of water chemistry for the sampled wells

		Concentration (mg/L)									
		F	Cl	NO3-N	SO4	Ca	K	Mg	Na	HCO3-	pH
W18	Mean	0.5	167.8	0.7	92.0	70.1	3.1	11.2	158.9	303.1	7.2
	St dev	0.2	61.1	0.5	23.4	56.0	3.3	10.6	119.7	70.6	0.4
	Min	0.1	84.8	0.1	46.2	0.9	0.1	0.1	21.6	177.7	6.7
	Max	0.7	279.1	1.5	125.7	154.6	8.7	34.5	359.8	400.1	7.9
	C.V. (%)	34.0	36.4	72.6	25.4	79.9	105.1	94.6	75.3	23.3	5.0
W19	Mean	2.0	60.0	0.1	101.5	13.7	5.1	7.5	123.5	175.8	7.7
	St dev	0.1	5.5	0.0	8.7	1.0	0.4	0.5	10.7	21.8	0.4
	Min	1.7	51.5	0.1	84.9	11.9	4.4	7.0	107.7	143.5	7.1
	Max	2.1	69.6	0.1	117.6	15.0	6.1	8.3	136.5	212.2	8.2
	C.V. (%)	6.9	9.2	0.0	8.5	7.0	8.8	7.0	8.7	12.4	4.9
W20	Mean	0.5	66.0	0.1	29.5	52.4	3.5	12.8	27.9	141.9	7.4
	St dev	0.0	4.8	0.0	1.2	1.8	0.1	0.4	1.2	18.8	0.3
	Min	0.5	59.2	0.1	27.5	49.5	3.3	12.2	26.5	117.8	6.8
	Max	0.5	74.4	0.1	31.3	55.1	3.7	13.7	30.1	186.2	8.0
	C.V. (%)	0.0	7.3	0.0	3.9	3.4	3.8	3.5	4.2	13.3	4.4
W22	Mean	1.3	20.5	0.1	25.9	64.1	1.4	8.6	7.6	167.4	7.1
	St dev	0.1	5.4	0.0	1.9	4.2	0.1	0.3	1.9	13.6	0.2
	Min	1.1	14.6	0.1	23.9	56.9	1.2	8.2	6.3	140.2	6.9
	Max	1.3	30.0	0.1	29.1	70.9	1.5	9.2	12.7	185.7	7.5
	C.V. (%)	5.8	26.2	0.0	7.2	6.5	6.2	3.6	24.7	8.1	3.3
W23	Mean	2.5	11.6	0.1	22.8	8.6	4.1	7.4	116.9	312.8	8.0
	St dev	0.4	2.6	0.0	5.6	0.4	0.2	0.3	6.9	16.0	0.3
	Min	1.5	6.7	0.1	11.3	8.1	3.9	6.9	105.7	291.0	7.3
	Max	2.8	13.9	0.1	26.7	9.2	4.4	7.8	128.3	337.3	8.4
	C.V. (%)	14.6	22.2	0.0	24.6	4.6	4.6	3.7	5.9	5.1	4.1
W24	Mean	0.7	32.0	0.1	16.1	56.6	2.3	10.4	11.9	171.0	6.9
	St dev	0.2	4.3	0.0	2.4	3.5	0.5	0.5	2.2	15.4	0.1
	Min	0.5	22.5	0.1	13.1	50.1	1.8	9.5	9.7	142.6	6.6
	Max	0.8	39.5	0.2	20.7	60.7	3.7	10.9	17.7	199.8	7.1
	C.V. (%)	21.9	13.4	27.4	14.7	6.2	22.5	4.4	18.8	9.0	2.0
W25	Mean	1.3	29.4	0.1	79.3	43.0	2.1	7.2	57.5	157.0	7.4
	St dev	0.1	2.4	0.0	5.0	5.4	0.2	0.3	5.2	24.9	0.3
	Min	1.2	24.8	0.1	68.4	30.2	1.8	6.8	49.8	112.4	6.9
	Max	1.4	32.7	0.1	85.3	49.2	2.4	7.8	68.5	197.3	7.9
	C.V. (%)	5.8	8.2	0.0	6.3	12.5	7.6	4.6	9.0	15.9	4.3
W26	Mean	0.5	89.6	0.1	22.7	48.3	1.6	6.3	18.2	65.8	6.2
	St dev	0.0	21.7	0.0	3.5	10.0	0.3	1.2	6.4	14.0	0.3
	Min	0.5	59.0	0.1	18.8	36.6	1.4	4.9	11.5	50.5	6.0
	Max	0.5	115.1	0.1	29.1	59.2	2.2	7.9	29.9	89.2	6.8
	C.V. (%)	1.7	24.2	0.0	15.4	20.7	19.1	18.7	35.4	21.3	4.6
W27	Mean	0.5	1.1	0.7	13.2	30.1	1.1	2.9	1.3	83.7	6.7
	St dev	0.0	0.3	0.1	1.4	6.5	0.1	0.5	0.2	18.5	0.1
	Min	0.5	0.8	0.5	11.2	19.9	0.9	2.0	1.0	50.5	6.3
	Max	0.5	1.5	0.9	15.2	38.2	1.3	3.6	1.6	112.0	6.8
	C.V. (%)	0.0	25.6	19.8	10.7	21.4	12.7	18.6	14.9	22.0	2.2