HYDROGEOLOGICAL CONTEXT AND DISSOLVED TCE PLUME CHARACTERIZATION IN THE VALCARTIER AREA, QUEBEC, CANADA

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ABSTRACT
In the Valcartier area, a detailed characterization carried out in 2001 defines the hydrogeological context and delineates a dissolved 1,1,2-trichloroethene (TCE) plume. 65 Rotasonic boreholes were drilled to define the stratigraphy. More than 800 observation wells provided ≈2000 volatile organic compounds (VOC) analyses and ≈950 water levels. More than 200 direct push water-sampling profiles also allowed a 3D definition of the plume in a specific area. Hydraulic properties were determined on the basis of slug tests in 260 wells. In the area, a sandy marine paleo-delta overlies proglacial sand and gravel above till and bedrock. In the eastern part of the site, a semi-confining silty unit splits the deltaic sands in two. The dissolved TCE plume extends over 4.5 km with a width of about 650 m and an average thickness of 20 m. In 2001, concentrations ranged from values lower than 50 μg/L over 60% of the plume to maximum values between 1300 and 4500 μg/L in three source areas.

RÉSUMÉ
Dans le secteur Valcartier, une caractérisation détaillée a été réalisée en 2001 pour définir le contexte hydrogéologique et délimiter un panache de trichloro-1,1,2-éthène (TCE) dissous. 65 forages *Rotasonic* ont défini la stratigraphie. Plus de 800 puits d'observation ont permis l'obtention de ≈2000 analyses de composés organiques volatiles (COV) et la mesure de ≈950 niveaux d'eau. Plus de 200 échantillonnages par enfoncement ont fourni des profils de concentration en TCE dans l'eau et défini le panache en 3D dans un secteur. Les propriétés hydrauliques ont été mesurées par des essais de perméabilité dans 260 puits. Dans le secteur, un paléo-delta sableux repose sur une unité proglaciaire de sable et gravier. À l'est du secteur, une unité silteuse semi-confinante sépare l'unité deltaïque en deux. Le panache de TCE dissous s'étend sur 4.5 km avec une largeur d'environ 650 m et une épaisseur moyenne de 20 m. En 2001, la concentration allait de moins de 50 μg/L dans 60% du panache jusqu'à 1300 à 4500 μg/L à trois zones sources.

1. INTRODUCTION

This paper describes the characterization carried in 2001 to define the hydrogeological context and delineate a large dissolved TCE plume in the granular aquifer system of the Valcartier area (Lefebvre et al., 2003). The area is located 35 km north of downtown Quebec City (Figure 1). The study area comprises the Valcartier Garrison, research facilities of Defence R&D Canada (DRDC) Valcartier, the SNC TEC former industrial area and the municipalities of Shannon to the west and Quebec City to the east (former Val-Bélair). TCE source zones were found at DRDC-North and within the SNC TEC property. The area is mostly flat and is bounded to the west by the Jacques-Cartier River and to the east by the Nelson River. Mounts are found to the east and south. Municipal and private wells use groundwater as a drinking water supply at each end of the study area and the Valcartier Garrison also uses wells for its water supply. In 1997, TCE was found in groundwater at the site. The following studies led to a better understanding of groundwater flow (Martel et al., 2000). In December 2000 and early 2001, TCE concentrations often exceeding the guideline of 50 μg/L were found in private wells in Shannon (CCME, 1999). Filters were initially installed in private wells to treat the contaminated groundwater and later the Valcartier Garrison extended its water supply system to parts of Shannon.

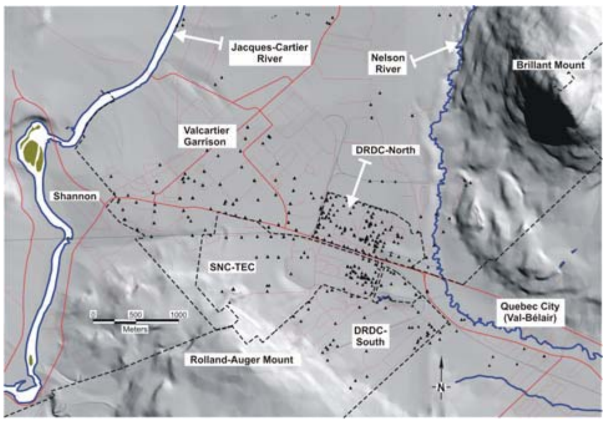

Figure 1. Location and physiography of the Valcartier area (borehole locations are indicated by dots)

2. CHARACTERIZATION PROGRAM

The characterization documented in this paper was carried out during the summer and fall of 2001 with some work completed in the winter of 2002. This program aimed to define the extent of the TCE plumes, to refine the understanding of the geological and hydrogeological contexts and to better identify potential TCE source zones. Table 1 summarizes the characterization data available in the study area both within and outside the Department of National Defence (DND) properties.

Table 1. Characterization data in the Valcartier area (Site 1 is the Valcartier Garrison and Site 2 is DRDC).

		DND Property					Others sectors	All
	Type of data	Site	Before fall 2001	During fall 2001	Total		Others sites	Total sector
Boreholes & wells	*Rotasonic boreholes*	1	0	27	27		N.A.	≥65
		2	0	38	38			
	Observation Wells	1	≈140	167	≈659		≈150	≈809
		2	105	247				
Hydrogeochemistry	*Water VOC analysis*	1-2	≈400	≈600	1000		≈1000	≈2000
	Geoprobe sampling station	1	0	1	1		29	212
		2	0	182	182			
Hydrogeology	*Water level*	1-2	≈200	≈600	≈800		≈150	≈950
	Slug test	1-2	28	260	288		N.A.	288

Prior to this study, the stratigraphy of the unconsolidated sediments found in the area had been partly defined above 20 m depth on the basis of double barrel core samples. During the fall of 2001, 65 boreholes were made using Rotasonic drilling that allowed the recovery of soil samples over most of the sediments thickness. Two-level observation wells were installed in these boreholes as well as in others drilled with conventional methods. The screen length varies among the wells, most wells having long screened interval to favor contaminant detection (between 1 and 6 m long, 3 m median screen length).

Hydraulic conductivity was determined with slug tests performed in 260 wells in 2001, thus providing a good control on hydraulic conductivity over much of the area. Groundwater levels were measured in about 800 locations to define groundwater flow patterns. Dissolved TCE concentrations as well as other VOCs were analyzed on about 2000 water samples both inside and outside the DND properties, thus allowing the delineation of the dissolved contamination plume. Also, more than 200 direct push water-sampling profiles allowed a more detailed vertical definition of the plume. Most of these samples were analyzed only for TCE using a fast field gas chromatography. Retardation factors of TCE in the deltaic sand and prodeltaic silty unit were measured using column tests (Section 5.5).

3. HYDROSTRATIGRAPHIC CONTEXT

Although the land surface is relatively flat, the underlying bedrock has a relief of about 50 m (Figure 2). It is characterized by a crescent-shaped buried valley that extends east-west. The valley is broader and deeper toward the west where it splits in north and south forks. A less defined buried valley extends north-south under the Jacques-Cartier River.

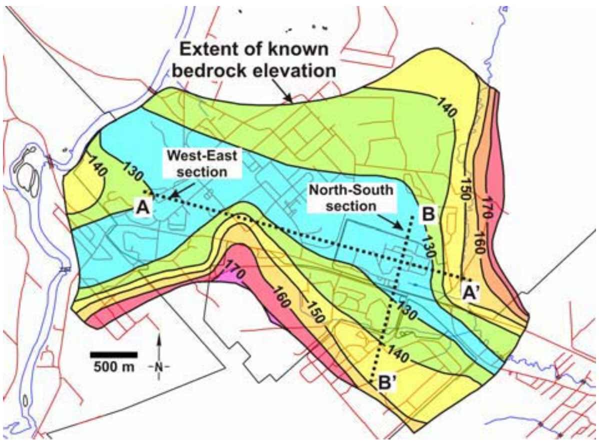

Figure 2. Bedrock topography under the study area

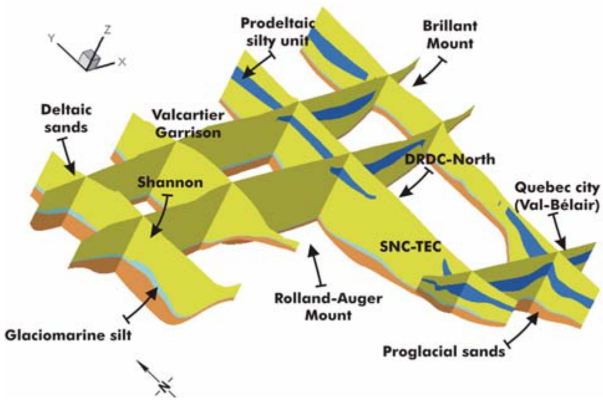

Figure 3. 3D geological model viewed from the southwest to the northeast

The stratigraphic control allowed the construction of a 3D gelological model of the study area (Figure 3). Six hydro-stratigraphic units were defined from bottom to top in the study area (Michaud et al., 1999; Martel et al., 2000; Lefebvre et al., 2003): till, proglacial sand and gravel, glaciomarine silts, deltaic sands, prodeltaic silts, and alluvial sands. The deltaic sand is the main aquifer unit filling the valley above the proglacial sand and gravel that covers the lower parts of the valley. The glaciomarine silt between these units is discontinuous and these units are thus mostly in hydraulic contact. The prodeltaic silty unit splits the deltaic sands in the eastern part of the area. Where present, this silty unit induces semi-confined conditions in the lower part of the deltaic sand and exerts an important control on groundwater flow.

4. HYDRAULIC PROPERTIES OF THE UNITS

4.1 Slug tests analysis

Slug tests were performed in 260 observation wells in the fall of 2001 to define the hydraulic conductivity. With repeats in the same well, a total of 698 tests were completed. Compressed air was used to generate drawdowns in wells (Levy and Pannell, 1991). The slug tests were performed in three different units: deltaic, proglacial and prodeltaic. The hydraulic conductivities obtained from the slug tests are presented in Table 2.

Table 2. Hydraulic conductivity *K* from slug tests.

Hydrostratigraphic Units	Nb. of values	Mean (m/s)	Median (m/s)
Deltaic	234	3.4×10^{-4}	3.0×10^{-4}
Proglacial	21	1.9×10^{-4}	4.3×10^{-5}
Prodeltaic	5	1.6×10^{-5}	1.5×10^{-5}
All combined	260	3.2×10^{-4}	2.6×10^{-4}

4.2 3D distribution of hydraulic conductivity

A regional trend in hydraulic conductivity *K* was recognized in the deltaic sands where *K* is generally lower in the eastern part of the study area (Boutin et al., 2002). The deltaic sands are finer grained in the east where there is a transition between deltaic sands and the prodeltaic silty unit. This silty unit is actually made up of alternating layers of fine sand and silt. Zones of hydraulic conductivity were used in a numerical model based on slug tests (Boutin et al., 2004; Boutin, 2004).

Further work was done to better define the 3D distribution of lithofacies and relate it to the distribution of *K*. About 60 slug tests were performed in *Rotasonic* wells within the deltaic unit. These measurements indicate a decreasing trend in hydraulic conductivities from west to east (Figure 4a). It is believed that much more continuous information related to hydraulic conductivities could be obtained through stratigraphic descriptions acquired in *Rotasonic* boreholes drilled in the deltaic unit. Detailed stratigraphy was described using a facies code developed by the Geological Survey of Canada (CGQ abbreviated code). All descriptors using this code observed in drill logs were ranked according to their relative grain size. For every borehole, CGQ codes were converted in hydraulic conductivity ranks that could then be plotted (Figure 4b). It is interesting to note that fine-grained facies tend to be associated with lower hydraulic conductivity values to the east. Further efforts still need to be carried to understand the link between measured *K* and facies. This should allow a better prediction of the spatial distribution of *K*. These results should first help better understand the quaternary sedimentology. These results will also be used to refine the hydraulic conductivity distribution in the numerical model to provide more representative groundwater flow and TCE mass transport modeling.

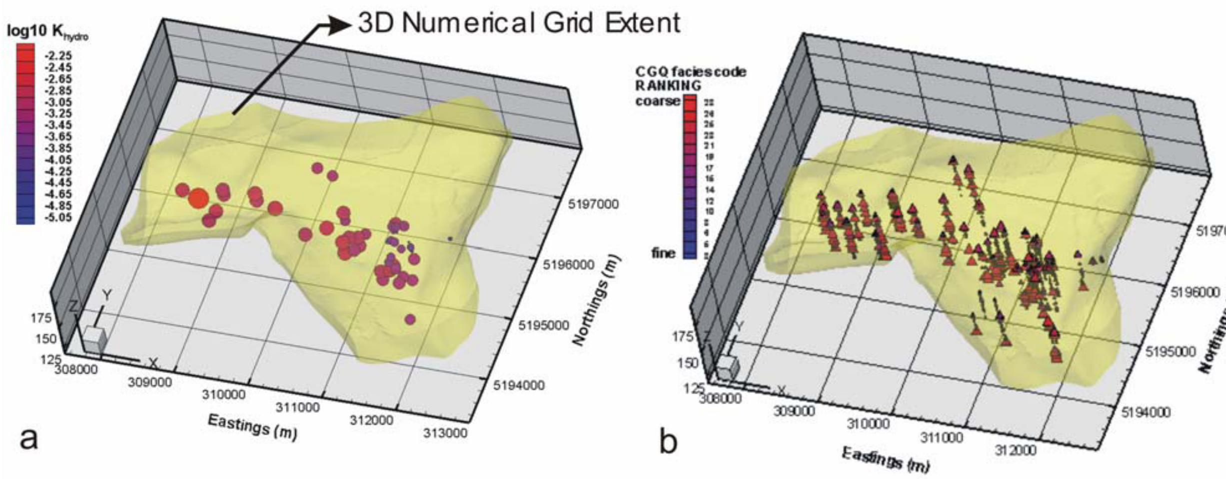

Figure 4. Spatial distribution of hydraulic conductivity measurements (a) and sedimentary facies (b) for the deltaic unit.

5. GROUNDWATER FLOW AND TCE PLUME

5.1 Groundwater flow regime

Hydrostratigraphic cross-sections show the hydraulic conditions prevailing in the study area (Figure 5, locations on Fig. 2). Section B-B' runs north-south across the buried valley in the eastern part of the area where some TCE source zones are located. Section A-A' is drawn west to east along the main axis of the buried valley. The deltaic sand is the main aquifer unit but the prodeltaic silty unit splits it in two parts in the eastern part of the study area. Unconfined conditions are found above the silty unit and where it is absent whereas semi-confined conditions are present under the silty unit. The vertical hydraulic gradient across the silty unit varies from 0.1 m/m to 0.3 m/m and flow is downward. The silty unit is thought to have controlled TCE migration from the sources zones located above it in the eastern part of the study area.

Figure 6 shows the water table elevation for the unconfined conditions present over the entire study area, including a regional unconfined aquifer where the prodeltaic silty unit is absent as well as above that silty layer in the eastern part of the site. Groundwater flow converges from the north and south to the center of the piezometric valley in the eastern part of the area. The dotted line on the map represents the groundwater divide in the unconfined aquifer. East of this line, water flows to the east and on the west side of the line, water flows towards the west to the Jacques-Cartier River. There is a high horizontal hydraulic gradient at the western edge of the silty unit. This is an adjustment of the water level that is higher above the silty unit than in the underlying deltaic sand. Groundwater velocities are highly variable: on the order of 100 m/y adjacent to hill slopes and on the order of 10 to 100 m/y in the center of the buried valley in the western part of the area. In the eastern part of the area, the velocities are smaller because of the finer grain size and locally lower horizontal gradient. Groundwater flow velocity is also very small where flow converges from the north and south to the center to the east of the buried valley (between DRDC-North and SNC TEC properties).

Figure 7 presents the features of groundwater flow in the semi-confined aquifer underlying the silty unit. The aerial distribution of the TCE plume and the main source zones are also indicated on this map. In the western part of the site, the prodeltaic silty unit is absent, thus the water elevations are identical to the regional unconfined aquifer (Figure 6). Under the silty unit, groundwater flow is similar to the unconfined conditions but with a more pronounced western direction. The TCE plume is superposed to the semi-confined flow conditions as most of the migration occurs under the silty unit. The plume actually provides further indications of groundwater flow directions from the source zones and it shows that the buried valley topography influences flow directions.

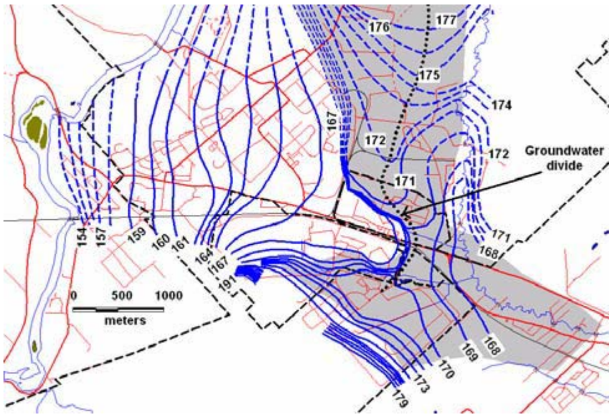

Figure 6. Piezometric map of the unconfined aquifer (the gray area shows where the prodeltaic silty unit is present)

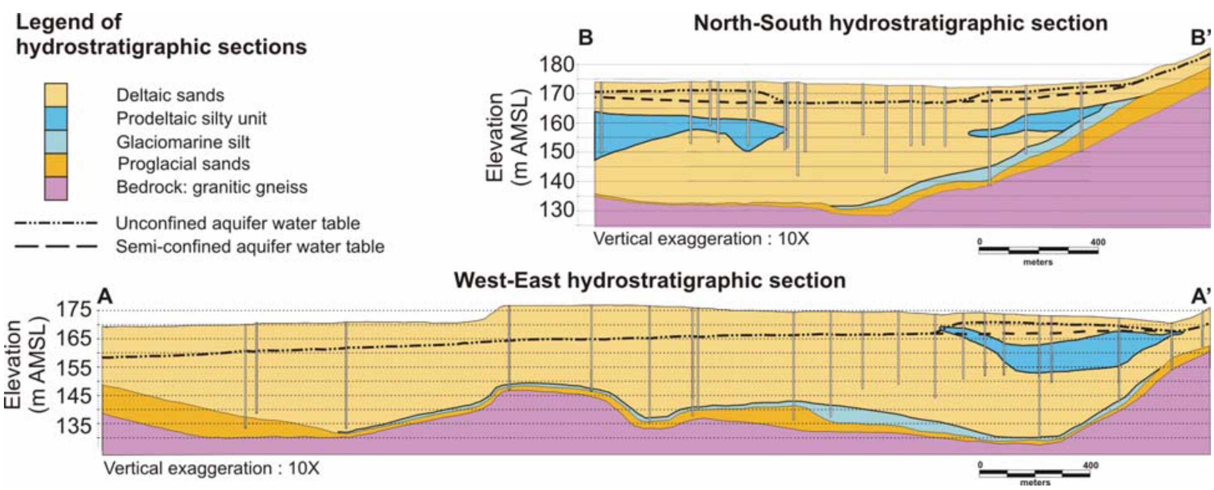

Figure 5. Hydrostratigraphic cross-sections showing the hydraulic conditions (locations shown on Figure 2)

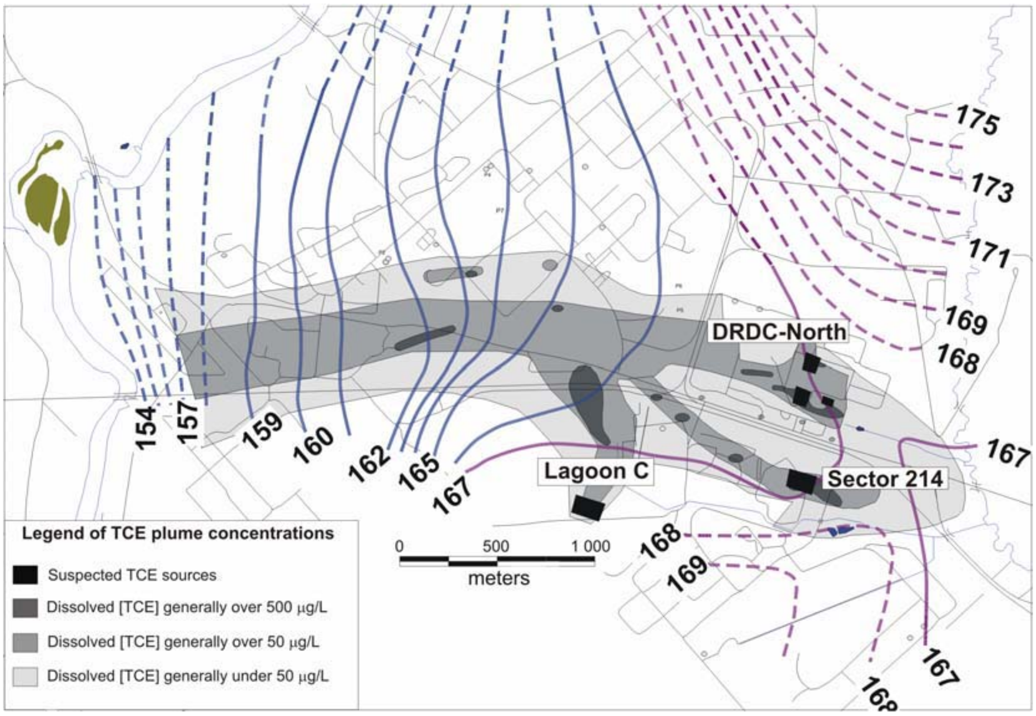

Figure 7. Dissolved TCE plume over unconfined piezometry in the west and semi-confined piezometry in the east

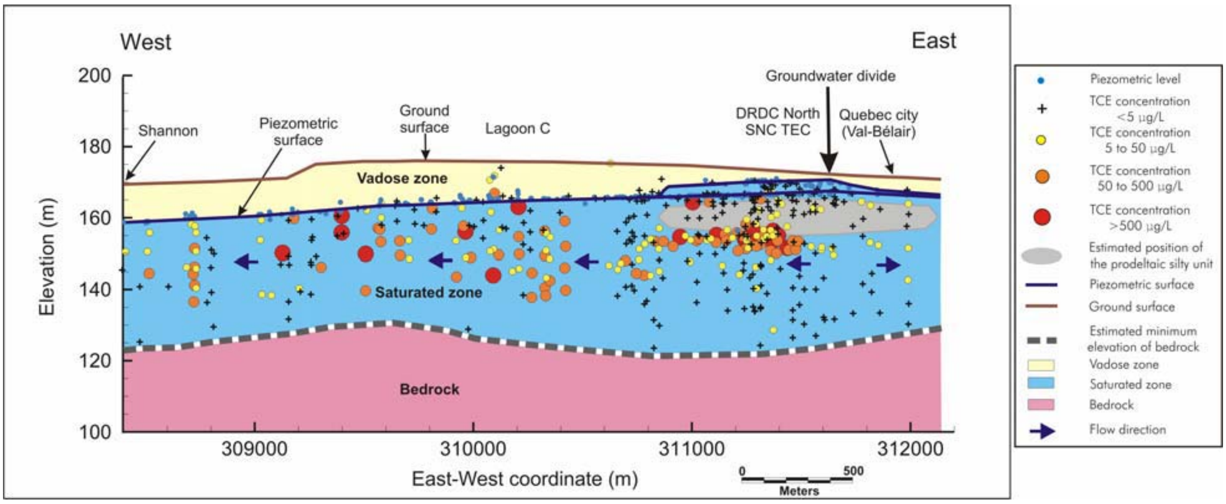

Figure 8. Vertical distribution of dissolved TCE concentrations along a west to east section

5.2 Regional dissolved TCE plume delineation

In the Valcartier area, no free or residual DNAPL were detected in observation wells or in soil samples on DND properties. TCE was found dissolved in groundwater. As mentioned in Section 2, the distribution of dissolved TCE was delineated by a combination of conventional observation wells in most parts of the study area combined with direct push water sampling mostly in DRDC-North. The 3D distribution of TCE in DRDC-North is discussed in Section 5.4.

Based on the available data the extent of the plume can be defined and the total area in which TCE is detected within the aquifer is about 3.16 km^2 (Figure 7). The TCE plume is about 4.5 kilometers long and 650 meters wide at its western limit. The average thickness of the plume is about 20 m (Figure 8).

Three TCE concentration zones were drawn to define the TCE plume (Figure 7). The first zone represents areas where TCE is generally detected but at concentration lower than 50 μg/L. The second zone is where TCE concentrations are generally between 50 and 500 μg/L. The third zone indicates where TCE concentrations generally exceed 500 μg/L, mostly closer to the suspected source zones. The maximum acceptable concentration for TCE in Canada is presently 50 μg/L (CCME, 1999). These zones were defined on the basis of concentrations obtained both from observation wells and direct push sampling, which tend to provide minimal and maximal concentrations, respectively. Thus some concentrations above or under these limits can be found in the zones.

TCE concentrations are variable aerially and vertically (Figure 8). There is a limited extent TCE plume with some concentrations above 50 μg/L in the upper unconfined aquifer where the prodeltaic silty unit is present within DRDC-North (Figures 8 and 10). However, most of the TCE is found directly under the silty unit in the eastern part of the area whereas it is found over a wider vertical width in the western part of the area where the silty unit is absent (Figure 8). The total mass of dissolved TCE in the plume outside the source zones was estimated to be about 1 600 kg (Lefebvre et al., 2003).

5.3 Source zones

Three main TCE source zones were identified in the area. Two known source zones are located south within SNC TEC: Sector 214 and Lagoon C (Fig. 7). Northeast of the site, three TCE sources are suspected within DRDC-North: Buildings 98 and 67 and the “Blue Lagoon” (Figures 7 and 10). The highest TCE concentrations found in 2001 were 4500 μg/L next to Sector 214, 1600 μg/L was found down gradient of Lagoon C, and 1300 μg/L was associated to DRDC-North source zones.

Dissolved TCE migration from each source zone converges to the center of the buried valley to form a wide plume. Source zones located to the east (Sector 214 and DRDC-North) are partly straddling the groundwater divide so that TCE migration occurs both to the east and west from these source zones, although TCE migration occurs predominantly to the west. TCE migration from the Lagoon C source zone makes a 90° turn to the west after an initial migration to the north. Most of the dissolved TCE emitted west from DRDC-North to the regional plume comes either from under the silty layer in the semi-confined aquifer or at the edge of the silty layer (Figure 10). TCE is emitted west mostly directly in the deltaic sand from the source zones within SNC TEC. TCE migration to the east is more poorly defined but it has a more limited extent due to lower hydraulic gradients as well as lower hydraulic conductivity. Modeling provided indications of the relative contribution of the sources to the formation of the plume (Boutin et al., 2004). A pump-and-treat system is operating in Sector 214 and the content of Lagoon C was excavated down to bedrock. Control and remediation actions are under evaluation for the DND properties.

5.4 3D TCE plume delineation in DRDC-North

The distribution of dissolved TCE was delineated by a combination of conventional observation wells in most parts of the study area combined with direct push water sampling mostly in DRDC-North and in some parts of SNC TEC. More detailed direct push water sampling was done in DRDC-North because TCE distribution was poorly known and because numerous potential TCE sources were located in that area.

Direct push sampling helped identify the overall extent of TCE contamination within DRDC-North and guided the location of conventional observation wells. The direct push system used was limited to a maximum depth of about 26 m under the conditions found. Figure 9 is a section of TCE concentration profiles obtained from direct push sampling. Using these profiles, the extent of TCE above, within and under the silty unit could be defined and mapped in 3D (Figure 10). The plume underlying the silty unit could also be further defined and related to potential source zones. Figure 10 shows that TCE migration may have occurred through the silty layer from the B98 source whereas TCE was emitted beyond the edge of the silt from the B67 and Blue Lagoon sources.

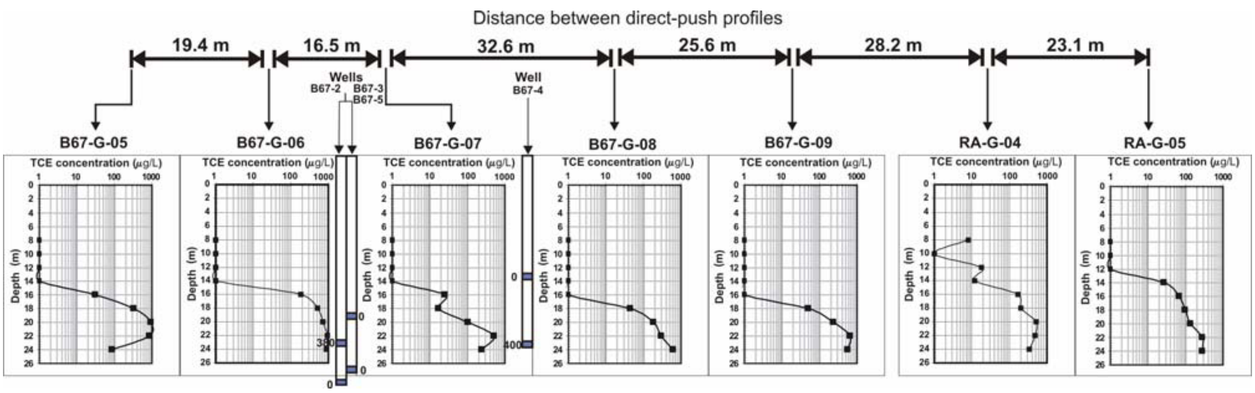

Figure 9. Section C-C’ of direct-push profiling of dissolved TCE concentration in DRDC-North (location on Fig. 10)

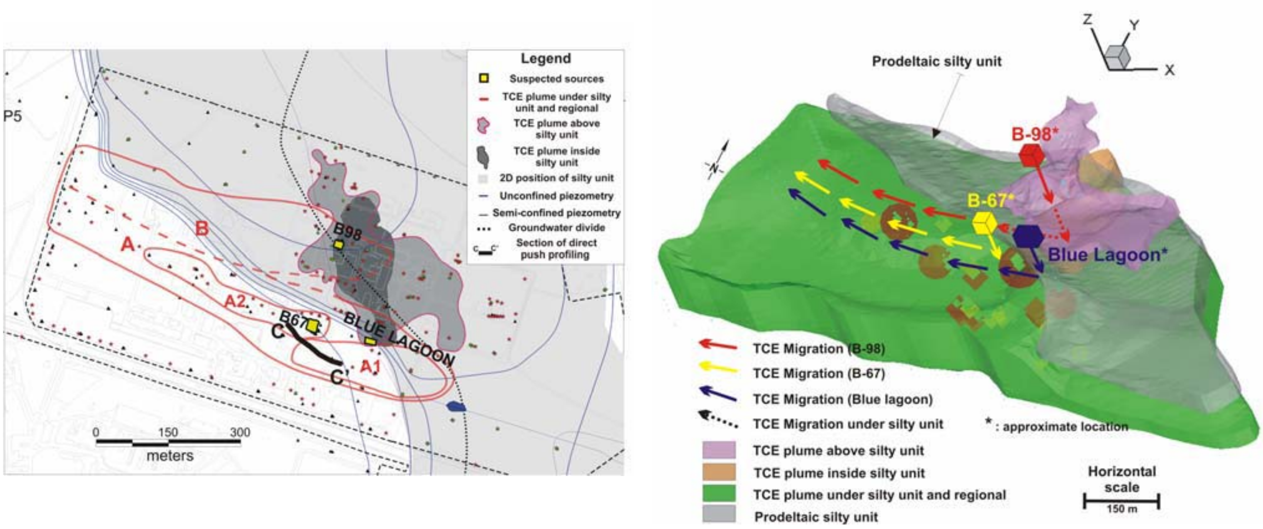

Figure 10. Aerial (left) and 3D (right) distribution of dissolved TCE within DRDC-North. The extent of dissolved TCE contamination above, within and under the silty unit is shown on both figures. The left figure schematically shows the presumed relationship between parts of the TCE plume (A and B) under the silty unit and 3 suspected source zones

5.5 Dissolved TCE transport

Preliminary evidence points to a loss of TCE mass in the groundwater plume based on TCE distribution, as seen down gradient of the DRDC-North western property limit. Daughter products of TCE degradation such as dichloroethene (DCE) and vinyl chloride (VC) were detected in the area (Lefebvre et al., 2003). A large part of the DCE found is 1,2 cis-DCE, which can only form by the degradation of TCE. However, the aerial distribution of these components does not form patterns easily explained by the progressive degradation of TCE from the source zones. Numerous parameters related to the degradation of chlorinated solvents were measured on water samples. The biodegradation index proposed by Weidmeyer et al. (1998) was calculated based on the available parameters (Lefebvre et al., 2003). The results indicated either poor or limited biodegradation. More work is needed to understand the TCE natural attenuation potential and the eventual applicability of biodegradation technologies.

The retardation of TCE relative to groundwater flow could result from its adsorption to the soil particles, mostly organic matter. Two column tests were carried to estimate the retardation factor of TCE on the deltaic sand and on silt from the prodeltaic silty unit. Figure 11 shows that TCE breaks through the column along with the conservative bromide tracer in the deltaic sand but it is retarded by 1.7 pore volumes in the silt. This can be explained by the very small total organic carbon (COT) concentration present in the deltaic sand (0.04%) compared to the silt (0.16 %) (Lefebvre et al., 2003). Based on indications of the low biodegradation potential of TCE and its insignificant retardation on the deltaic sand, the modeling of TCE mass transport was carried without taking into account biodegradation or retardation (Boutin et al., 2004).

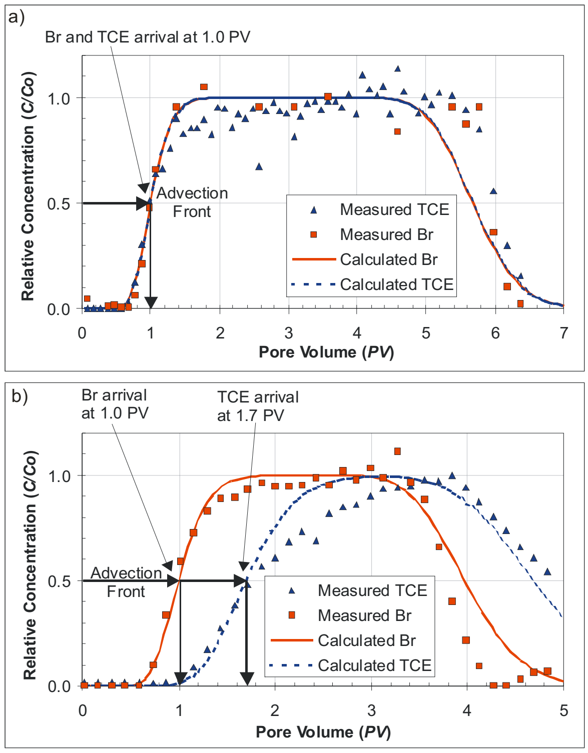

Figure 11. Retardation factor estimation from tracer tests in columns for the deltaic sand (top) and silty unit (bottom)

6. CONCLUSION

Understanding a regional groundwater contamination plume is challenging and requires an extensive characterization. In the Valcartier area, the means used for the characterization included conventional methods such as destructive drilling and observation wells but also more sophisticated approaches such as Rotasonic drilling and direct push water sampling. The data provided by the application of all these methods allowed the definition of the geological and hydrogeological contexts of the area, the delineation of the extent of the TCE plume, and the determination of the magnitude of dissolved TCE concentrations. The data also allowed the identification of the suspected main source zones at the origin of the TCE contamination.

The TCE contamination distribution in the Valcartier area is relatively complex. The hydrogeological context involves a deltaic sand aquifer locally separated by a silty prodeltaic unit with converging flow to the center of a buried valley. There are multiple TCE source zones at the origin of the contamination and TCE migration from these source zones combines to form a wide extent plume that is 4.5 km long with a width of about 650 m and an average thickness of 20 m. TCE migration also occurs in two opposite directions from a groundwater divide. TCE concentrations are often lower than 50 μg/L and maximum values in three source areas were between 1300 and 4500 μg/L in 2001. The detailed definition of the hydrogeological context also formed the basis for the development of a groundwater flow and TCE transport model providing insights on the relative importance of the source zones and on the role of the hydraulic conditions on the development of the TCE plume observed in the Valcartier area (Boutin et al., 2004).

7. ACKNOWLEDGMENTS

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