NUMERICAL MODELING OF GROUNDWATER FLOW AND MASS TRANSPORT IN INTERCONNECTED GRANULAR AND ROCK AQUIFERS AT THE VILLE MERCIER DNAPL-CONTAMINATED SITE, QUEBEC, CANADA

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ABSTRACT
Contamination by DNAPL and dissolved organic contaminants at the Ville-Mercier site has been present for 30 years. The DNAPL and dissolved organic compounds migrated from disposal lagoons through a sand and gravel unit that is locally in contact with the underlying rock aquifer through windows in the till overlying the bedrock. The problem was controlled with a pump-and-treat system intercepting the dissolved contaminant plume, and by defining an area within which groundwater pumping is prohibited. A 3D model was used to simulate groundwater flow under partially saturated and steady state conditions as well as simplified mass transport. The results allow a better understanding of present day and the original hydraulic conditions and give a simple simulation of contaminant migration. This model will be used to guide the choice of technologies that could efficiently replace the aging pump-and-treat system presently in place.

RÉSUMÉ
La contamination au site de Ville-Mercier par des contaminants organiques immiscibles denses et dissous existe depuis près de 30 ans. À l'origine la migration des liquides organiques et des contaminants dissous émis par des lagunes d'entreposage s'est faite dans l'unité de sable et gravier et à travers des fenêtres dans le till recouvrant le roc. Pour contrôler la contamination, un système de pompage et de traitement des eaux contaminées a été mis en place et une zone a été délimitée dans laquelle le pompage est interdit. Un modèle 3D en conditions partiellement saturées et en régime permanent a été réalisé pour permettre une meilleure compréhension des conditions hydrauliques actuelles et anciennes, et effectuer une première évaluation du transport de contaminants. Ce modèle servira de base pour évaluer les technologies potentiellement efficaces pour le remplacement du système de pompage et traitement âgé actuellement en place.

1. INTRODUCTION

The town of Ville-Mercier is located 20 km to the south-west of Montreal (Figures 1 and 2.a). In the 1970's, storage lagoons for organic liquids were excavated in a gravel pit within a fluvio-glacial sand formation Marine clay is present all around the pit, and overlies the sand and gravel unit which is in turn underlain by two different till units (Lasalle, 1980 The rock unit underlying the till units is a fractured sedimentary sandstone and a dolomite (Globensky, 1986). Windows exist in the till, enabling direct hydraulic exchange between the underlying bedrock and the overlying sand and gravel unit (CNFS, 1993). The original migration of DNAPL and dissolved organic compounds occurred through the sand and gravel fluvio-glacial system and contamination reached the bedrock through windows in the till. These contaminants then reached neighbouring private wells. The ministère de l'Environnement du Québec (MENV) controlled contamination by installing a pump-and-treat system to intercept the dissolved contaminant plume. The MENV also extended the municipal water distribution system to the affected domestic wells and delineated an area within which groundwater pumping is prohibited or limited.

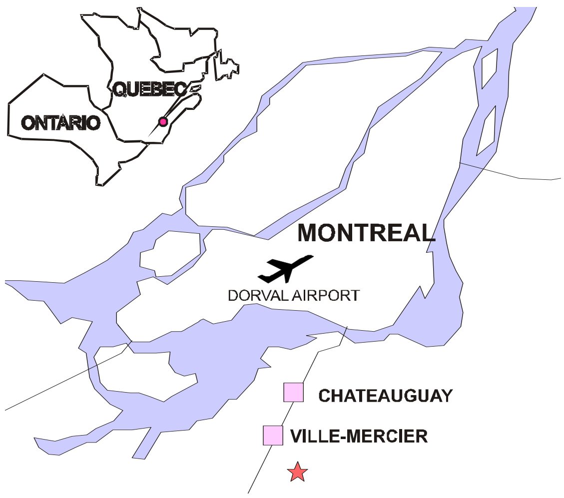

Figure 1.Schematic location map

This paper presents a 3D groundwater flow model developed in order to better understand the groundwater system and to help in the selection and design of a replacement technology for the pump-and-treat system.

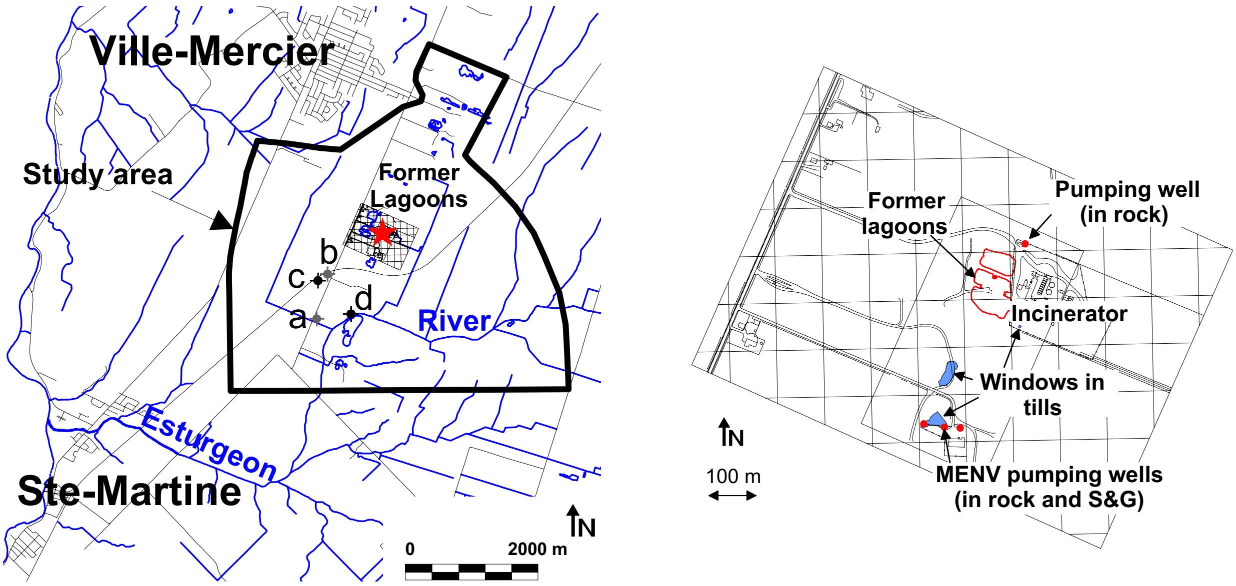

Figure 2. a) Map of the study area showing the extent of the numerical model and the location of the contaminated site and selected observation wells (a: 03097051, b:03097031, c: 03097041, d: 03097201). b) Close up of the contaminated area showing the former lagoons, the windows through the tills and the main wells of interest

2. GEOLOGY

The rock aquifer is made up of fractured Cambrian and Ordovician sedimentary rock (Globensky, 1986). The Cambrian rocks are represented by a sandstone of the Postdam Group whereas sandstone, dolomite and shale of the Beekmantown Group represent the Ordovician rocks. Tectonic events induced a succession of regional faults as well as large amplitude and low angle anticlines and synclines. Structural studies show two major sub vertical fracture families oriented N120 and N30 in decreasing order of density (GREGI, 1993; Denis, 1991).

Wisconsinian glacial events deposited two tills on the bedrock units (Lasalle, 1980). The basal till is very compact and dense while the upper till is reworked and more permeable (Parent, pers. comm.). Local studies show that windows (Figure 2b) exist in the tills and enable direct hydraulic exchanges between bedrock and the overlying sand and gravel unit (CNFS, 1993). An esker composed of fluvio-glacial sand and gravel esker covers and partially erodes the tills and outcrops as an 11 km long crest near Ville-Mercier. During the Champlain sea period, marine clay was deposited over both the fluvio-glacial formation and the tills.

3. HYDROLOGY

Average annual precipitation in the Ville-Mercier area is about 900 mm/year. Regional flow simulation estimated groundwater recharge at 50 mm/year (Pontlevoy et al., 2002). The Esturgeon River seems to play an important role on the groundwater system (Figure 4). The river is in contact with the rock aquifer to the south of the study area and drains the bedrock aquifer (Pontlevoy et al., 2002). The river is also in contact with the sand and gravel unit and drains part of the granular aquifer (Poulin, 1977). Four pumping wells pump are in use within the study area (Figure 2.b). Three wells open in both the sand and gravel and the rock aquifers pump to contain the contaminant plume (MENV pumping wells) while an incinerator uses a well open in the rock.

4. HYDROGEOLOGY

Previous studies concluded that the first 3 m of the rock aquifer are intensely fractured and constitute a good aquifer (Hydrogeo Canada, 1981; Poulin, 1977). More detailed studies showed that bedrock permeability is also important down to a depth of about 20 m (CNFS, 1993; Denis, 1991). The till and clay have a low permeability while the sand and gravel unit is one of the most permeable units of the region (McCormack, 1981).

Partial piezometric data prior to the emplacement of the hydraulic trap in 1984 is available but is of limited value. Observation wells a and b are open in the sand and gravel while c and d are open in the rock (Figure 2a). Figure 3 clearly shows a link between the water level data taken in the rock aquifer and those taken in the granular aquifer. This may result from a connection between these two aquifers but the stratigraphic information for these wells shows that from 6 to 20 m of till is present between the sand and gravel and the bedrock. Our interpretation is that the apparent link between the 2 aquifers is due to a poorly sealed installation of the observation wells. As a result, in our study, only the water level data from the granular aquifer were used to calibrate the flow model prior to the emplacement of the hydraulic trap. But as they were not numerous enough, these data were used as local calibration points. Detailed water level data were available to define the present-day groundwater flow conditions.

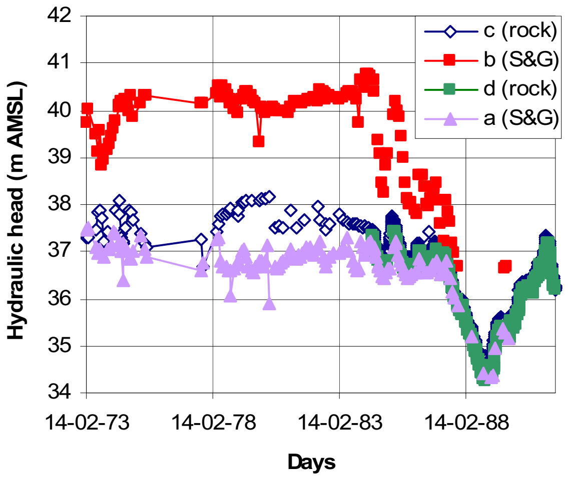

Figure 3. Water levels for observation wells in the rock and in the sand and gravel (S&G)

Figure 4 is a piezometric map of the rock aquifer under present-day pumping conditions. Groundwater generally flows from the east to the southwest. A piezometric depression to the southwest of the study area shows the impact of the Esturgeon River on the regional groundwater flow.

Figure 5 is a piezometric map of the sand and gravel aquifer under present-day pumping conditions.

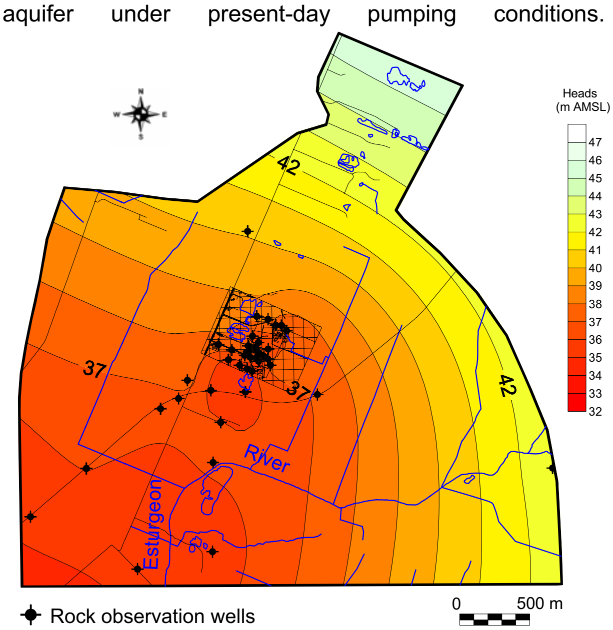

Figure 4. Piezometric map of the rock aquifer in 2001 with the pump-and-treat system in operation

Groundwater flows from the north to the south along the length of the esker. Groundwater flow converges to the Esturgeon River from each side and highlights its link to the sand and gravel aquifer. Poulin (1977) showed that the Esturgeon River was draining the granular aquifer but since the start of the pump-and-treat the flow seems to be reversed and the river now seems to feed the granular aquifer.

The main hydrogeological properties of the units are summarised in Table 1. For modelling purposes, the rock is considered isotropic with a mean hydraulic conductivity of 2.2×10^{-6} m/s. Many studies suggest 0,05 as rock porosity (CNFS, 1993; Denis, 1991; Poulin, 1977). The storage coefficient, measured by pumping tests, is generally on the order of 10^{-4}. In Table 1, the till unit regroups both the basal till and the reworked till and all the granular units are considered anisotropic in the model. The horizontal hydraulic conductivity and the vertical hydraulic conductivity of the till are about 1.7×10^{-8} m/s and 1.7×10^{-9} m/s respectively (Lefebvre, pers. comm.). These values correspond to the least permeable till unit. Till porosity is about 0.2 (CNFS, 1993) and the storage coefficient is about 10^{-4}. The sand and gravel horizontal and vertical hydraulic conductivities are about 2.1×10^{-4} m/s and 9.1×10^{-6} m/s, respectively (Lefebvre, pers. comm.). The sand and gravel porosity is 0.3 (Poulin, 1977) and the storage coefficient 10^{-4}. The clay unit presents horizontal and vertical hydraulic conductivities of 5×10^{-10} m/s (Hydrogéo Canada, 1978) and 10^{-11} m/s (Géomines, 1983), respectively, its porosity is about 0.5 (Hydrogéo Canada, 1978) and its storage coefficient is about 10^{-4}. The van Genuchten capillary parameters of each unit in Table 1 were adapted from the compilations of Carsel and Parrish (1988).

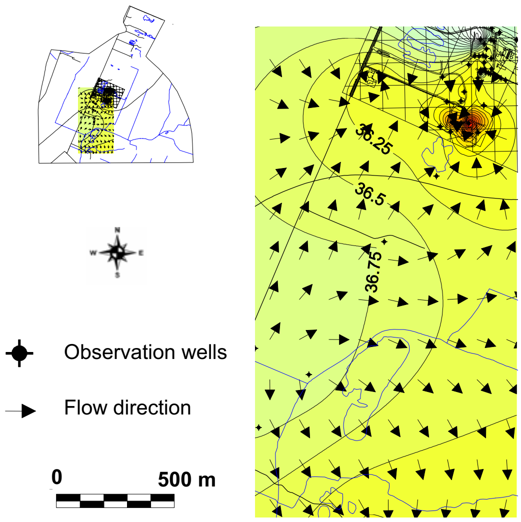

Figure 5. Piezometric map of the granular aquifer in 2001 with the pump-and-treat system in operation

Table 1. Initial and calibrated values for hydraulic properties

	Initial values				Calibrated values			
Parameter	Rock	Till	S&G	Clay	Rock	Till	S&G	Clay
n	0.05	0.2	0.3	0.5	0.05	0.2	0.3	0.5
$K_{x,y}$	2.2x10^{-6}	1.7x10^{-8}	2.1x10^{-4}	5x10^{-10}	4.2x10^{-6}	1.7x10^{-8}	4.1x10^{-4}	5x10^{-10}
K_z	2.2x10^{-6}	1.7x10^{-9}	9.1x10^{-6}	1x10^{-11}	4.2x10^{-6}	1.7x10^{-9}	1x10^{-6}	1x10^{-11}
S	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}
S_{wr}	0.012	0.07	0.061	0.07	0.012	0.07	0.061	0.07
α	14.5	0.5	10	0.5	14.5	0.5	10	0.5
β	2.68	1.09	2.08	1.09	2.68	1.09	2.08	1.09
γ	0.62	0.08	0.52	0.08	0.62	0.08	0.52	0.08

5. MODEL DESCRIPTION

5.1 Extent and boundary conditions

The piezometric map of the rock aquifer was used to determine the extent of the numerical model (Table 2). The eastern side of the model corresponds to a piezometric line and a constant head is imposed to the rock (Figure 6). The eastern part of the limit to the north corresponds to a groundwater divide of the granular aquifer where a constant head was imposed to the rock. A constant head was imposed to the western part of the southern limit in order to represent the effect of the Esturgeon River on the bedrock aquifer. The eastern part of the southern limit, the western limit and the western part of the northern limit were considered no-flow limits drawn perpendicular to the piezometric lines. A constant head was imposed at the Esturgeon River at the contact with the sand and gravel unit.

Table 2. Boundary conditions

Limit	Initial head (m)	Calibrated head (m)
East rock	42	39
North rock	43	40
South rock	From 37 to 34.5	Unchanged
Esturgeon Riv.	36.5	Unchanged

5.2 Numerical grid

The model covers almost 19 km^2. The 2D numerical grid of the region consists of 4 688 nodes and 9 308 elements (Figure 7). The grid was refined in areas of interest: near the wells, the windows in the till, the contaminated site and the contact between the Esturgeon River and the sand and gravel aquifer. The 3D numerical grid consists of 196 896 nodes and 381 628 elements.

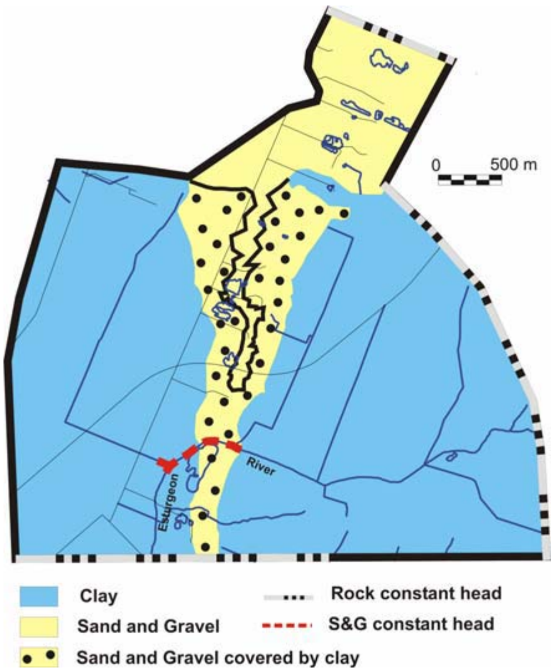

Figure 6. Extent and boundary conditions

5.3 3D Geological model

We consider that the groundwater flow is active over a thickness of 100 m. The rock aquifer is considered as an equivalent porous medium since fractures are dense enough to avoid representing discrete fractures. GMS 3.1 (BYU, 2000) was used to build the 3D geological model (Figure 8). The sand and gravel is thickest at the centre of the study area but has lower east-west lateral extensions.

The till is thinner and may be absent under the thickest portion of the sand and gravel unit. The rock was subdivided into 18 layers, the till into 19 layers where the sand and gravel unit is thick but only into 4 layers in the area of the three known windows. The sand and gravel unit overlying the till is subdivided into 15 layers and finally, the overlying clay was represented by 4 layers.

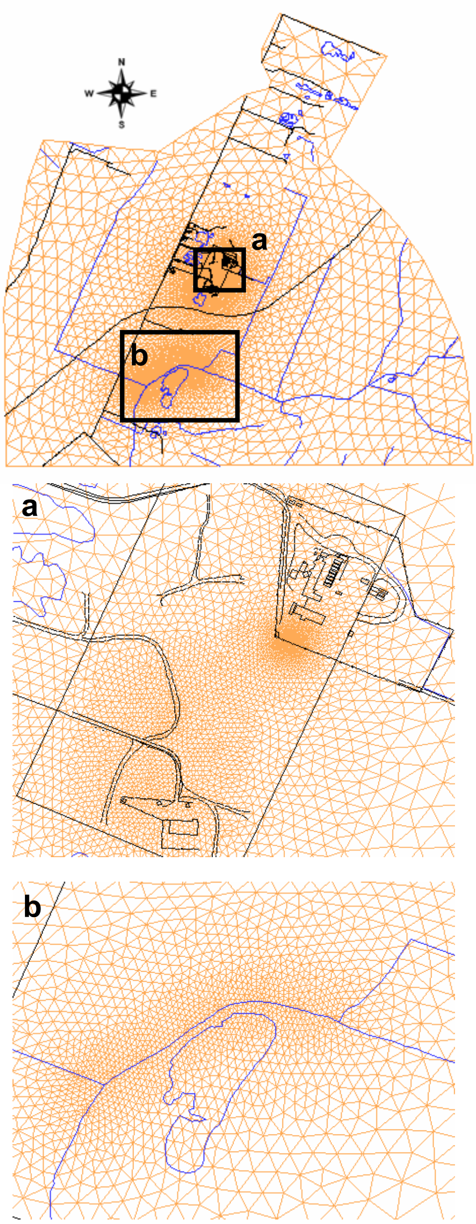

Figure 7. 2D numerical grid

5.4 Groundwater recharge

The spatial distribution of recharge depends on the sediments present at the surface and on their contact with the aquifers. Table 3 summarises the infiltration values selected for each exposed unit within the study area and the total recharge applied (Pontlevoy et al., 2002).

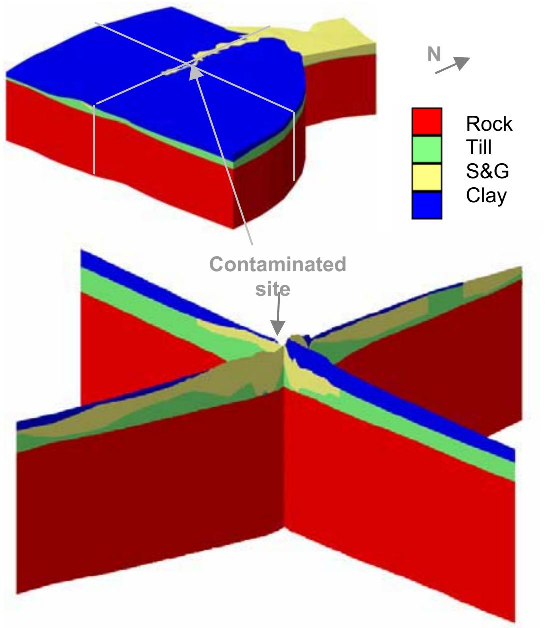

Figure 8. 3D geological model

Table 3. Recharge values for the model

Unit	Area (km^2)	Recharge (mm/year)	
		Initial	Calibrated
Sand & Gravel	2.36	600	520
Clay	16.64	3	0
Total	19	77.2	64.5

6. SIMULATIONS

6.1 Calibration

FRAC3DVS (Therrien and Sudicky, 1996) was used to simulate groundwater flow under steady state and unsaturated conditions. The calibration of the model under pumping conditions and prior to pumping was accomplished by using a set of parameters allowing a match between simulated and observed heads. Results of the calibration are shown in Figures 8 and 9 and Table 1. A better calibration could have been obtained under pumping conditions as well as without pumping. A compromise had to be made to allow an acceptable match under pumping conditions and without pumping using the same set of parameters. Results of the calibration are considered satisfactory under and prior to pumping since the mean absolute error of 0.68 m is smaller than the mean regional annual water elevation variation. Calibration allowed us to refining some parameters such as recharge. The model recharge value of 64.5 mm/year used in the model is close to the estimated value for regional recharge (50 mm/year). The constant head imposed on the north and east limits of the rock had to be reduced in order to decrease a water inflow in the model. Updated values are summarized in Tables 2 and 3.

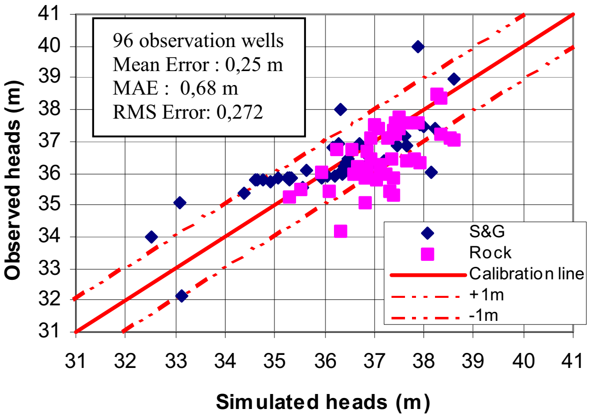

Figure 9. Simulated versus observed heads under present-day pumping conditions

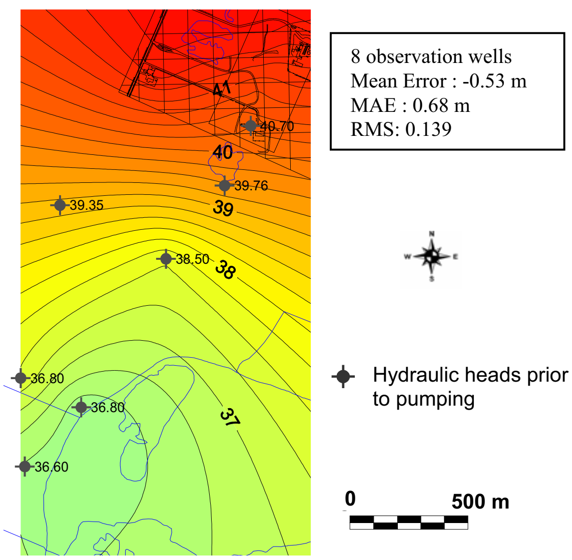

Figure 10. Simulated heads without pumping

6.2 Impact of the till Windows and water balance

Simulated vertical flow through the windows is shown in Figure 11 where positive values indicate upward flow and negative values downward flow. The operation of the pump-and-treat system reversed the situation and now the rock aquifer is feeding the granular aquifer (Figure 11a). At the pump-and-treat wells, the water pumped from the rock aquifer reaches the wells in two ways: directly from the rock or by flowing first into the sand and gravel through the windows in till then into the wells. Since the model gives us an estimation of fluxes through the windows, a water balance can be done on the pump-and-treat wells to estimate the flow pumped from the rock aquifer and from the sand and gravel. Almost 14 % of the water pumped comes from the rock (553 m^3/d over a total rate of 3888 m^3/d) of which 6 % is pumped directly in the rock and 8 % flows from the rock through the windows into the sand and gravel where it is capture by the wells. The rest (86%) is pumped directly in the sand and gravel aquifer.

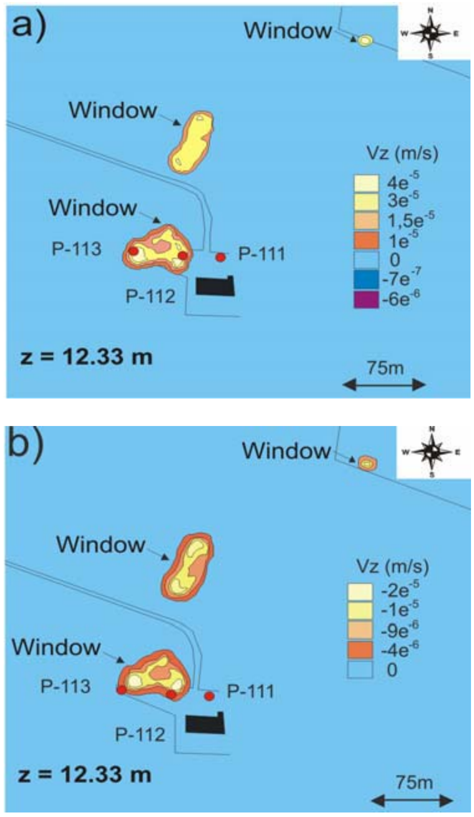

Figure 11. Vertical velocity simulated for pumping conditions (a) and prior to pumping (b)

6.3 Particle tracking

Particle tracking in the rock and in the granular aquifers shows that the pump-and-treat system is efficient and creates a good hydraulic trap limiting the migration of dissolved contaminant away from the source area (Figures 12 and 13). The source zone and the windows in the tills are totally included in the zone of contribution of the pump-and-treat wells. Particle tracking also allowed the estimation of ground water flow velocity. Groundwater velocity in the sand and gravel is about 300 m/year near the pump-and-treat wells while groundwater velocity in the rock aquifer is about 12 m/year. In the sand and gravel aquifer, it takes almost 1 year for groundwater to go from the source zone to the pumping wells.

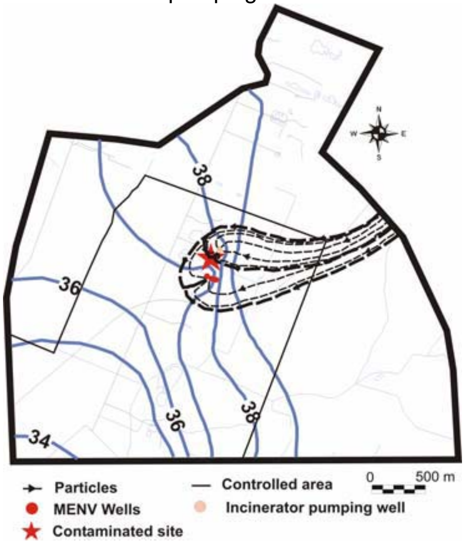

Figure 12. Particle tracking in the rock aquifer

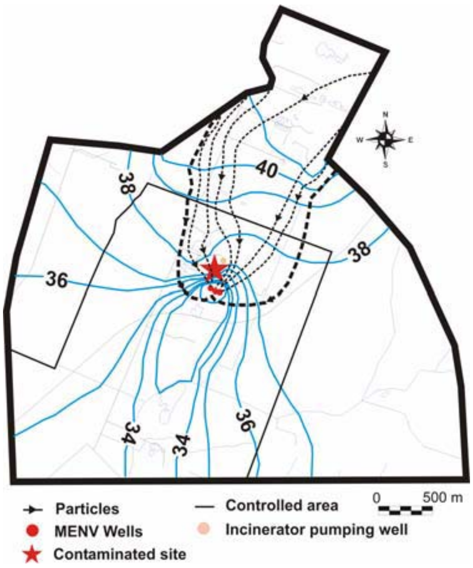

Figure 13. Particle tracking in the granular aquifer

7. TRANSPORT SIMULATION

Advective-dispersive transport was simulated for steady-state flow conditions with and without the pump-and-treat, to better understand contaminant migration from the source zone. Solute retardation and degradation were not accounted for. Figures 14 and 15 show the simulated plumes in the rock and in the granular aquifer without pumping before the start of the pump-and-treat. The simulated plume reaches the Esturgeon River in the granular aquifer after 16 years but remains close to the contaminated site in the rock. Figure 16 shows the simulated plume in the sand and gravel under present-day pumping controlling the plume, highlighting the impact of the pump-and-treat system.

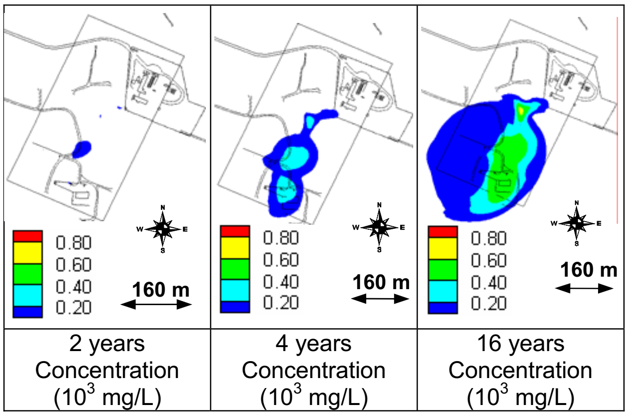

Figure 14. Simulated migration of the contaminant plume in the rock before start of the pump-and-treat

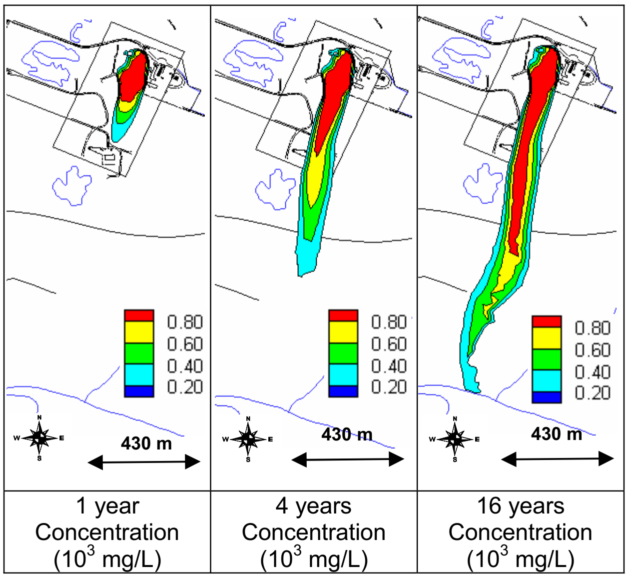

Figure 15. Simulated migration of the contaminant plume in the granular aquifer before start of the pump-and-treat

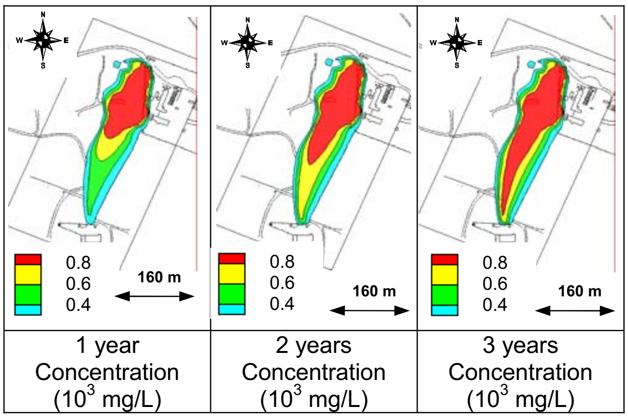

Figure 16. Simulated migration of the contaminant plume in the granular aquifer under present-day pumping

8. CONCLUSION

The 3D partially saturated flow model developed provides a better understanding of the hydraulics of the aquifer system. The model calibration is satisfactory with and without operation of the pump-and-treat. The pump-and-treat system is efficient both in the granular and the rock aquifers to control dissolved contaminant migration. The model highlights the important role played by windows in the till that control groundwater exchange between bedrock and granular aquifers. Simulations show that the pump-and-treat system has reversed the flow between the bedrock and the granular aquifer with the rock now feeding the granular aquifer. Thus, the role of windows cannot be neglected in the choice of a future control systems that could efficiently replace the aging pump-and-treat system. The model shows that almost 14 % of the water pumped comes from the bedrock, with 8 % crossing the windows prior to reaching the wells via the granular aquifer. Particle tracking shows that groundwater travels from the source zone to the pump-and-treat wells in 1 year. Simplified transport simulations were done under simulated flow conditions with and without pumping. Without pumping, contaminant migration leaves the source zone in the granular aquifer but there is limited migration in the rock aquifer. In the sand and gravel under pumping, the control exerted by the pump-and-treat system is confirmed.

9. ACKNOWLEDGEMENTS

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10. SYMBOLS AND UNITS

Symbol	Parameter	Unit
n	Porosity	-
$K_{x,y}$	Horizontal hydraulic conductivity	LT^{-1}
K_z	Vertical hydraulic conductivity	LT^{-1}
S	Storage coefficient	-
S_{wr}	Residual water saturation	-
α	Fitting parameter of the van Genuchten function	L^{-1}
β	Fitting parameter of the van Genuchten function	-
γ	Fitting parameter of the van Genuchten function	-
V_z	Vertical velocity	LT^{-1}

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