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Regional hydrogeological mapping project of the St. Lawrence Lowlands of southwestern Quebec: hydrogeological characterization work 1999–2000

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Abstract

The GSC is carrying out a regional hydrogeological mapping project of fractured rock aquifers in the St. Lawrence Lowlands of southwestern Quebec. The regional aquifer consists of Paleozoic fractured sedimentary rocks. This aquifer is mostly confined with clay and silt sediments at lower altitudes whereas over topographic heights it becomes a water-table aquifer. This paper presents the fieldwork and results of the hydrogeological characterization based on 361 constant-head injection tests, 4 large-scale pumping tests, 4 pulse tests, and 3 step pumping tests, as well as slug tests performed in 23 boreholes and 10 observation wells. The first results indicate that *carbonate and sandstone rocks are the most exploitable regional aquifers in the region. The average transmissivity shows a weak decreasing trend with depth. When present, the deep sandy gravel layer overlying the top of fractured aquifers is believed to be the major conduit for groundwater flow.*

Résumé

La CGC poursuit actuellement des travaux de cartographie hydrogéologique régionale des aquifères fracturés dans les basses terres du Saint-Laurent du sud-ouest du Québec. L'aquifère régional est situé dans des roches sédimentaires fracturées du Paléozoïque. Cet aquifère, largement captif, est contenu en grande partie dans de l'argile et du silt a de basses altitudes, et devient un aquifère libre au-dessus des hauteurs topographiques. Le présent article résume les travaux de terrain et les résultats de la caractérisation hydrogéologique fondée sur 361 essais à charge constante, 4 essais de pompage à grande échelle, 4 essais à impulsion, 3 essais à paliers, et plusieurs essais de perméabilité réalisés dans 23 forages et 10 puits d'observation. Les résultats préliminaires indiquent que les roches carbonatées et les grès représentent la portion la plus productive du système aquifère de la région. La transmissivité moyenne de ces roches tend à diminuer faiblement avec la profondeur. Aux endroits où elle est présente, la couche profonde de gravier sableux qui recouvre les roches paléozoïques pourrait constituer le conduit principal de l'écoulement souterrain.

INTRODUCTION

The Geological Survey of Canada is carrying out a regional hydrogeological mapping project of fractured rock aquifers in the St. Lawrence Lowlands of southwestern Quebec. The main scientific collaborators of the project are INRS-Géoressources, Laval University, Environment Canada, and Queen's

University. The study area encompasses four regional county municipalities — Argenteuil, Deux-Montagnes, Mirabel, and Thérèse-de-Blainville. The project activities consist of collection of existing data, update of the bedrock and Quaternary geological maps, field hydrogeological tests and measurements, hydrogeochemical characterization, surface and borehole geophysics, data compilation, groundwater-flow modelling, and reporting (thematic maps, technical reports). The project specific objectives are aquifer delineation and characterization, mapping methodology development, as well as characterization and protection of the groundwater resource. The overall objectives of the GSC project include developing and testing field hydrogeological, geophysical, and geochemical techniques for determination of the hydraulic properties of fractured rock aquifers, designing tools for data management, providing technical protocols and guides for regional hydrogeological mapping of fractured bedrock aquifers, and finally, increasing public awareness of the importance for groundwater protection. A particular attention of the St. Lawrence Lowlands mapping project is paid to the study of spatial and vertical variation in hydraulic properties of bedrock aquifers using the results of conventional pumping, slug, and constant-head injection tests.

The applied methodology of hydrogeological characterization described in this report was initiated by the need to develop a complete model of the groundwater dynamics in the St. Lawrence Lowlands heterogeneous aquifers. In effect, in contrast to unconsolidated porous media generally characterized by a relatively small range in hydraulic properties, the properties of fractured rock aquifers may vary considerably. Identifying and characterizing the spatial heterogeneity of rock environments in a regional study, such as the St. Lawrence Lowlands project, and ensuring adequate borehole coverage to capture the variations of these properties is difficult. Often, available hydrogeological data are sparse for the surface as well as the volume of rock under consideration. Thus the St. Lawrence Lowlands project is based on a multidisciplinary approach including hydraulic testing and geophysical and geochemical surveys, which, in conjunction with stratigraphic, lithological, and structural mapping, reduce the uncertainty of interpolation between control points. This paper presents the description of the hydrogeological characterization work of the first two years, 1999–2000, of the project and some of the preliminary results with the objective of summarizing the present state of the knowledge on the study area.

DESCRIPTION OF THE STUDY AREA

The study area is located in southwestern Quebec, northwest of Montréal, and includes approximately 1500 km^2 distributed in four regional county municipalities: Argenteuil, Deux-Montagnes, Mirabel, and Thérése-de-Blainville (**Fig. 1**). The boundaries of the study area are the Laurentians to the north-northwest, the Ottawa River and St. Lawrence River to the south, and the watershed of the Mascouche River to the east. Elevations range from 25 m a.s.l. near the St. Lawrence River to more than 80 m a.s.l. in the vicinity of the du-Nord River.

A lower Paleozoic rock succession composes most of the solid substrate in the study area. The succession consists in generally flat-lying sedimentary strata with (in ascending order) Cambrian siliciclastic rocks of the Potsdam Group (Covey Hill and Cairnside formations); Lower to Middle Ordovician carbonate rock of the Beekmantown Group, a succession of mostly dolostone, limestone, quartzose carbonate, and subordinate siltstone and shale; the Beekmantown Group (Thérèsa and Beauharnois); and finally, limestone of the Chazy, Black River, and Trenton groups. The sedimentary strata are underlain by Precambrian Grenvillian crystalline rocks that outcrop as Laurentian highlands to the north-northwest, and Oka and Saint-André hills to the south, pushed up by Cretaceous intrusions.

The rock succession in the study area is covered by unconsolidated Quaternary units. They include glacial deposits, mostly till of variable thickness (0–15 m), overlain by clayey and occasionally sandy marine deposits from the Champlain Sea. The thickness of these deposits can reach 100 m where the rock surface forms depressions and along the centrelines of ancient pre-glacier valleys. Evidence of fluviatile sand and gravel at depth ovelying fractured rock has also been found at several sites.

Two major rivers and their tributaries drain the surface waters in the study area, du Nord River to the west and Mascouche River to the east. The central area is drained by the du Chêne River. The surface waters are discharged into the Ottawa River and des Deux Montagnes Lake (prolongation of the St. Lawrence River).

EXISTING DATA

The St. Lawrence Lowlands mapping project started with the compilation of the available hydrogeological data such as thematic maps (geology, pedology, topography, hydrological units), drillers logs, transmissivity, storativity and specific capacity, pumping and discharge, water chemistry, hydrographs, etc. Existing data produced the first preliminary hydrogeological description of the studied area and indicated zones where additional information was necessary. The compiled existing data directly assisted in the planning and execution of the fieldwork. The major sources for these data were the Quebec Ministry of Environment, the Quebec Ministry of Transport, the Quebec Ministry of Natural Resources, Natural Resources Canada, Environment Canada, Hydro Québec, consulting firms, and municipal authorities.

Because of the uneven quality and reliability of the data from various sources, these data were first subjected to a rigorous screening and quality control procedure. It consisted, first of all, in the verification of the location points (UTM co-ordinates, elevation, address, etc.) and of the intercepted lithology. The comparison was conducted with verified nearby borehole logs in order to allow continuous interpretation of the stratigraphy. The verification process is still ongoing and to date the compilation includes more than 4600 borehole logs: 3619 driller logs from the the Quebec Ministry of Environment water well database, 205 from the Quebec Ministry of Natural Resources database, and 782 from the the Quebec Ministry of Transport database. These data give information on the intercepted Quaternary deposits and stratigraphic logs of Paleozoic rocks.

A total of 30 pumping tests performed in the rock units (6 in limestone, 15 in dolostone, 7 in sandstone, and 2 in metamorphic rock), and 8 in the Quaternary deposits were reported by consulting firms. Most of these tests have been conducted for water-productive wells for the municipalities. The interpretation of the tests was based in most of the cases on a single observation well. The results are summarized in **Table 1**.

DEVELOPMENT OF THE PRELIMINARY CONCEPTUAL MODEL

On the basis of the present knowledge of the geology in the study area and from the hydrogeological point of view, five main hydrostratigraphic units are recognized: 1) highly permeable surface sands; 2) low-permeability confining unit composed mostly of clay and silt deposits; 3) low to moderately permeable glacial tills; 4) highly permeable sandy gravel (when present) and fractured rock; and 5) moderate to low permeability rock. Among these hydrogeological formations, two aquifer units are identified. They are 1) surface fluvioglacial sands of local extent representing unconfined aquifers, and 2) uppermost part of the sedimentary rocks which represents the regional aquifer system.

A preliminary simplified conceptual model of the groundwater flow in the region is given on **Figure 2**. More than 90% of groundwater used in the region comes from the regional aquifer system (Savard et al., 2000). It is confined in most of the study area with the clayey confining unit. In topographic heights identified as recharge zones, the regional aquifer becomes a water-table aquifer. In this context, sedimentary rocks outcrop or are covered only with a till overburden of various thickness.

PIEZOMETRIC SURFACE OF THE FRACTURED ROCK AQUIFER

Fieldwork started with water-elevation measurements in wells intercepting rock formations. It was done with simple water-level meters at more than 570 wells evenly distributed over the study area. The potentiometric map of the study area (Fagnan et al., 2001), indicates that equipotentials follow closely the topography and that the regional groundwater flow is generally to the south. This map will be used for spatial delineation of the regional fractured aquifers and to identify the direction and gradients of groundwater flow.

A monitoring network for the measurement of long-term fluctuations in groundwater levels has also been established with 30 observation wells. Automatic data loggers have been installed in 13 of these wells, whereas in the others groundwater fluctuation is measured manually on a monthly basis.

DISTRIBUTION OF CONTROL POINTS FOR HYDRAULIC CHARACTERIZATION

The hydrogeological fieldwork addressed the characterization of the regional aquifer. A total of 23 boreholes were drilled in the uppermost 100 m of Paleozoic rocks (*see* **Fig. 1**). It is believed that this portion bears most of the groundwater flow in the fractured rock. The spatial and lithological distribution of the boreholes was carefully chosen in order to cover the studied area, to represent all the important hydrogeological formations, and to complete the hydrogeochemical and lithostratigraphic characterization. Three of the tested boreholes were drilled in limestone, twelve in dolostone, five in sandstone, one in the metamorphic rocks, two wells intercepted the dolostone and metamorphic rocks, and one well intercepted limestone and dolostone. Fifteen of the boreholes were drilled by air percussion hammer with 6" to 8" diameter, and eight 3" boreholes were drilled and cored with a diamond drill. The open part of the boreholes was subjected to a detailed hydrogeological analysis: 361 constant-head injection tests, 23 slug tests, 4 pulse tests, 3 step pumping tests, and 4 large-scale pumping tests. Core description, geophysical well logs, and borehole flow logs will be integrated with these data. Furthermore, composite and multilevel groundwater samples were collected for chemical analysis (Bourque et al., 2001). Borehole characteristics are given in **Table 2**.

The spatial and vertical extent and nature of the deep layer of sandy gravel overlying the top of the sedimentary rock is poorly known. Very limited information is available in the existing reports although its presence has often been identified during the drilling work. This layer was most probably deposed during the thawing of the glaciers in the region during the last glacial period (~15 000 years ago). The subglacial streams partially or completely flushed out the fine matrix of the till and deposited coarser sandy gravel materials. When intercepting this layer of relatively high permeability, the drillers had to inject high amounts of drilling mud to consolidate the borehole wall. Collecting samples of this unit by diamond drilling (split-spoon, coring) was extremely difficult as the recovery was very low, while the air percussion method was too destructive to allow any clear recognition of this layer. Furthermore, this unit along with other unconsolidated deposits is usually isolated by the well casing which prevents its hydrogeological investigation. To describe the hydrogeological properties of this layer, 2" PVC observation wells had to be installed (**Table 3**). These wells were equiped with 0.4 m to 3 m long screened sections and a filter sand pack placed against the contact of unconsolidated sediments with fractured rocks. The exception is the St-Vincent-2 observation well that was installed in the middle portion of the till layer.

LOCAL SCALE TESTING

Constant-head injection tests

A total of 23 boreholes were hydraulically profiled with constant-head injection tests (Zeigler, 1976). First, a sensitivity analysis of the tested interval length on the transmissivity was conducted in borehole R-3. Two test intervals were tested, 2 m and 4 m. The two transmissivity data sets showed a fairly good agreement and, for practical reasons, it was decided to continue transmissivity testing with the 4 m test interval with the perspective of a regional characterization (Nastev et al., 2000).

The transmissivity values show over four orders of magnitude variation in transmissivity with depth. This range of vertical variation in transmissivity was generally noted in all boreholes, although in some of the boreholes there appears to be a relatively uniform vertical transmissivity. Differences between neighbouring test intervals in many cases were up to three orders of magnitude. It is likely that these variations are related to differences in fracturing of the rock. In other words, the zones of high transmissivity ($>10^{-5}$ m^2/s) are likely dominated by fracture flow while zones of low transmissivity ($<10^{-7}$ m^2/s) are characterized by sparser fracturing or no fracturing. In one borehole, PE-2, lithological control of the permeability is suggested by the distinct change in transmissivity between the two rock formations (Beekmantown Group over Precambrian rocks).

A summary of obtained results is shown on Figure 3 where the transmissivity values are plotted against the open borehole depth, for carbonate rocks (dolostone and limestone), sandstone, and metamorphic rocks. The three boreholes drilled in the St-Eustache rock quarry are not considered in Figure 3, due to the possible effect of the excavation works on the fracturing pattern. The transmissivity variation with depth for all boreholes shows higher data dispersion for carbonate and Precambrian rocks (**Fig. 3a**, **c**). This is also confirmed with higher variance of ln(T) for these rocks (**Table 4**). For each open borehole depth, the logarithms of the obtained transmissivity values were averaged by the corresponding geometric mean. Although there is no apparent trend of the transmissivity variations with depth at this scale (up to 90 m open borehole depth), the vertical geometric mean variation shows a weak decreasing trend with depth. This conclusion, however, has to be taken with caution, keeping in mind the relatively low number of tested boreholes and often the presented geometric mean transmissivity at a given depth is based on a single measurement.

Overall, geometric mean transmissivity (T_G) for the three rock types ranges from 2.7 x 10^{-7} m^2/s to 2.7 x 10^{-6} m^2/s (Table 4). The T_G of the carbonate (dolostone and limestone) and sandstone is about one order of magnitude higher than that of Precambrian rocks. **Figure 3d** illustrates the relation between the logarithms of transmissivity values and the number of the observed data for the three rock types. The transmissivities span a range of 10^{-2} m^2/s to 10^{-10} m^2/s. Ninety per cent of transmissivities were measured within 10^{-3} m^2/s to 10^{-8} m^2/s.

The observed weak decrease of the transmissivity values with depth can be explained by the joint effects of the groundwater flow and chemical interactions of the groundwater with the hosting fractured rock. These processes, although extremely slow could, with years, widen the fracture apertures in the uppermost portion of the Paleozoic rocks. Another reasonable explanation could be found in thawing of the glaciers some 15 000 years ago. The thawing of 2 km thick glaciers could produce a release of the compressive stress in the upper portion of the Paleozoic rocks that again would result in fracture opening.

Slug tests

Slug tests were performed in all of the open boreholes in fractured rock and observation wells in granular deposits. Three different sizes of bailers were used to inject (withdrawn) the slug of water: 1.5" x 42" (1.2 L) for PVC 2" observation wells; 2.375" x 60" (4.3 L) for 3" boreholes; and 3.5" x 60" (9.5 L) for 6" and 8" boreholes. The test was repeated several times to obtain the most representative curve of water-level rise (fall) for the well. The interpretation of the tests was done by the Bouwer and Rice method for water-table aquifers, Cooper and Papadopulos method for confined aquifers, and with the Van der Kamp and Uffink method for aquifers with an oscillatory response.

The results of the slug tests are shown in **Table 5**. The total transmissivity computed as a sum of the discrete interval transmissivities of the constant-head injection tests for the corresponding wells is also presented in Table 5.

A graphical comparison of the two sets of data is depicted on **Figure 4**. A relatively good agreement of the results for most of the wells can be observed; however, for certain wells there are large discrepancies. In general, slug tests show higher transmissivity values. The uppermost portion of the open borehole was never tested with the constant-head injection test. In order to avoid any accident with the equipment, the upper inflatable packer for the first 4 m test interval was usually placed a few feet below the bottom of the steel casing of the well. In some cases, this portion may consist of so-called ‘altered rock’ which, although of limited thickness, may have a relatively high transmissivity. Also, the two testing methods do not examine exactly the same volume of fractured rock. Slug tests induced water-level rise (fall) of approximately 0.5 m. The head gradient induced by the constant-head injection test was in general 10 m and it was assumed that the corresponding radius of influence was 12 m.

The results of slug tests performed in the PVC 2" observation wells are given in Table 6. Because the length of the screen varied between 0.4 m and 3 m, the hydraulic conductivity is a more representative parameter for comparison. It spans a wide range from 1.4×10^{-6} m/s to 3.8×10^{-3} m/s. The higher conductivity values (>10^{-4} m/s) are likely representative for gravelly sediments while lower conductivities (<10^{-5} m/s) are characteristic for tills and finer matrix sediments. More field data are needed for the thickness, spatial extent, and hydraulic properties of the deep gravelly layer which, when present, seems to be a major conduit for the groundwater flow.

GROUNDWATER RECHARGE

Groundwater recharge in the region is being addressed by various, mostly indirect, estimation methods: global water balance for the region, regional groundwater flow modelling analysis, hydrograph analysis, infiltrometer test, and isolated pan lysimeters.

Particular attention was paid to the infiltration across the till layer in the recharge areas. This was tested at Foucault rock quarry (15 tests), Montée Lavigne (11 tests), Rang St. Vincent (8 tests), and Saint-Janvier (4 tests). Two test sites, Rang St. Vincent and Sablière, were instrumented with one deep open borehole well and a nest of three observation wells screened in the granular deposits. The deep wells were pumped during seven days. The drawdown of the local groundwater table, which was initially in the Quaternary deposits close to the ground surface, was monitored in the nearby observation wells. The objective of these tests was to quantify the hydraulic connection between the fractured rock and the Quaternary sediments. The installation of four pan lysimeters is planned for the beginning of November 2000.

INTERMEDIATE AQUIFER TEST STUDIES

Five intermediate aquifer test studies were realized in the scope of the project: Sainte-Anne-des-Plaines, Saint-Janvier (**Fig. 5a**), Sintra rock quarry, Saint-Eustache rock quarry, and Saint-Benoît (**Fig. 5b**). The main objective of these studies was to characterize aquifers on a local scale. Each detailed aquifer study consisted of at least one 3" borehole with coring for detailed description of the geology of the fractured aquifer and of the confining units, installation of observation wells, geophysical borehole logging, constant-head injection, pumping and slug tests, and collecting of composite and multilevel groundwater samples. The sites for these studies were chosen in order to cover the most important lithological units and to analyze aquifers in confined and unconfined conditions (**Table 7**). Prior to drilling, a preliminary hydrostratigraphic model for each site was developed and used to select the location and depth of the production and observation wells.

The production wells were completed in the fractured rock. The exception was the Saint- Benoît site, where the two pumping wells were completed in the gravelly layer underlain by low-permeability sandstone of the Potsdam Group. For Sintra and Saint-Eustache studies, the pumping of the groundwater inflow to lower the water table in the rock quarries were being used to estimate aquifer hydraulic properties. Here, the observed potentiometric surface is supposed to be in dynamic steady-state conditions.

The obtained field data are under interpretation. The drawdown curves will be interpreted with analytical models. A three-dimensional model of the aquifer and confining unit geometry will be integrated in the numerical modelling of the local groundwater flow for each intermediate study area. The intrinsic vulnerability of the aquifer and its vulnerability to specific contaminants will also be evaluated.

CONCLUSIONS

The description of the hydrogeological characterization work of the first two years, 1999–2000, of the GSC regional hydrogeological mapping project in the St. Lawrence Lowlands and some of the preliminary results were presented. The objective was to summarize the present state of the knowledge of the study area. Five main hydrostratigraphic units are recognized: 1) highly permeable surface sands; 2) low-permeability clayey confining unit; 3) low to moderately permeable tills; 4) highly permeable washed till (sandy gravel) and fractured rock; and 5) moderate to low permeability rock. More than 570 measurements of the groundwater elevation were taken in order to reproduce the potentiometric surface of rock aquifer. A monitoring network of 30 wells for long-term groundwater fluctuations was installed with 13 wells equipped with automatic data loggers. The control points (23 open borehole wells, 10 PVC 2" observation wells) for hydraulic testing were carefully planned in order to have a good coverage of the study area, of all the lithological formations, and of the granular sediments. Hydraulic testing consisted of 5 pumping test, more than 350 constant-head injection tests, and 33 slug tests. Five intermediate aquifer test studies were conducted with the objective to characterize fractured aquifers on a local scale. Groundwater recharge was studied at two sites.

The first results indicate that carbonate and sandstone rocks are the most exploitable regional aquifers in the region. The vertical geometric mean variation shows a weak decreasing trend with depth. When present, the deep sandy gravel layer superimposing the top of fractured aquifers could represent the major conduit for groundwater flow.

ACKNOWLEDGMENTS

This work was supported in part by Economic Development Canada, Conseil régional de développement-Laurentides, ministère de l'Environnement du Québec, the Regional County Municipalities of Argenteuil, Deux-Montagnes, Mirabel, and Thérèse-de-Blainville, and the Association des Professionnels de Développement Économique des Laurentides. Part of the drilling was supported by the ministère des Transports du Québec. The technical assistance of all the students participating in the project is greatly appreciated. The authors thank A. Rivera for helpful review of this manuscript.

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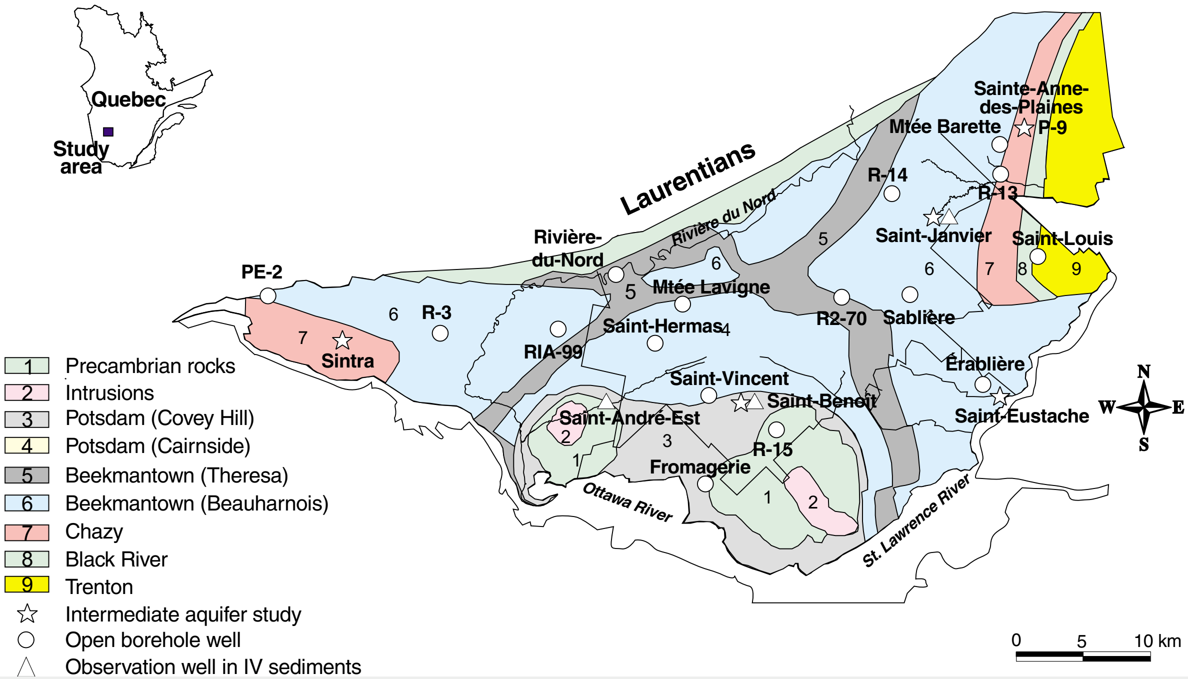

Figure 1. Study area and simplified geology. The location of rock boreholes, observation wells in Quaternary deposits, and intermediate aquifer test sites are also presented.

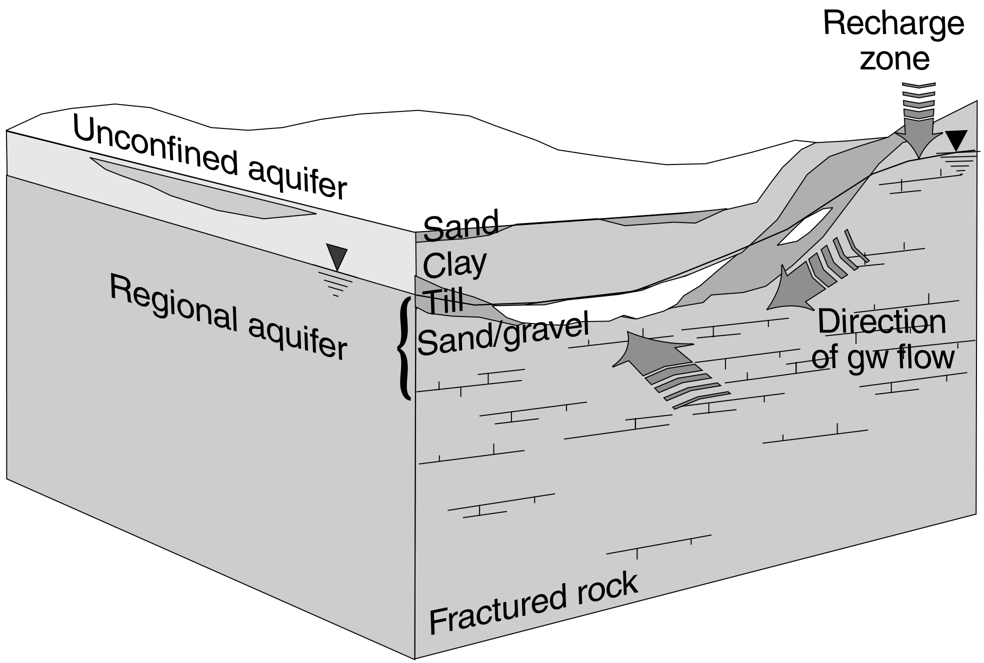

Figure 2. Schematic conceptual model of groundwater (gw) flow in the study area.

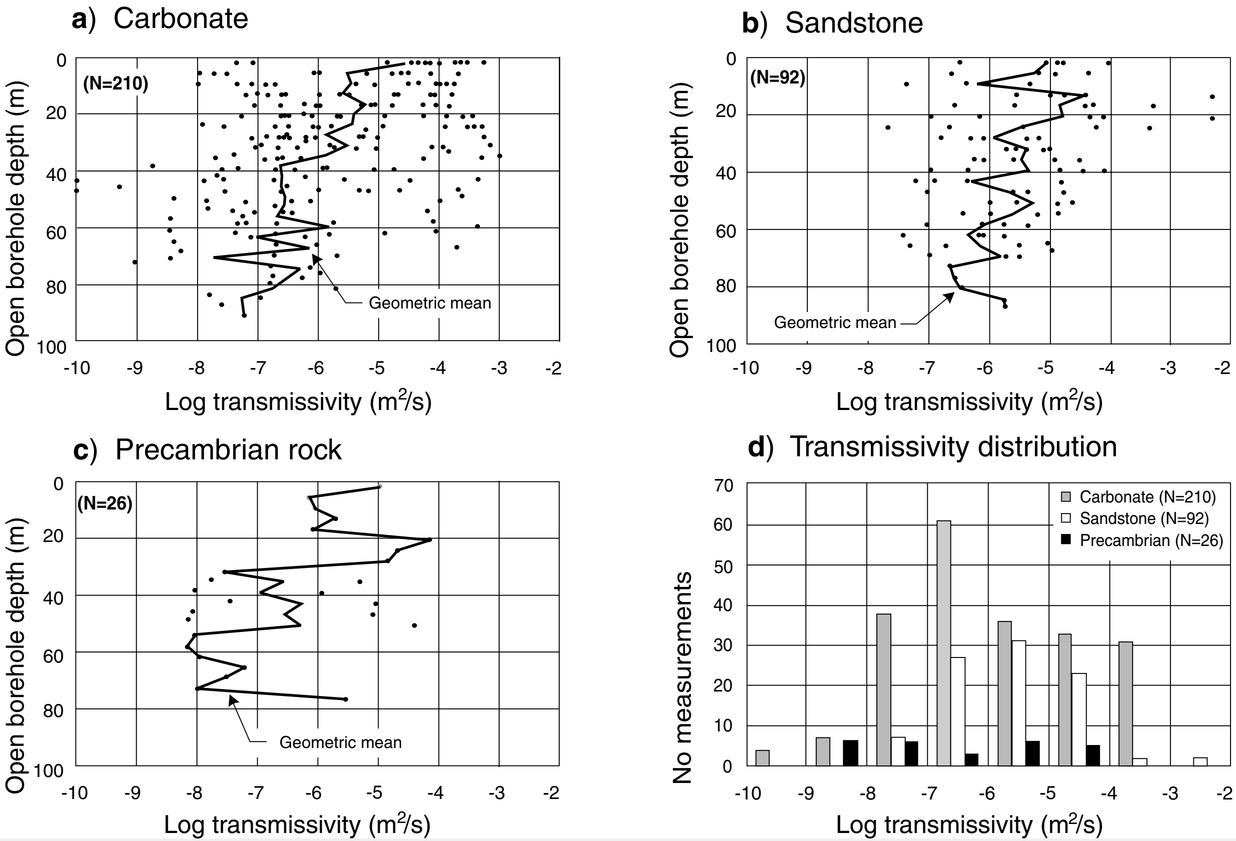

Figure 3. Summary of the constant-head injection test results. **a–c)** Transmissivity distribution with depth for the three main rock formations. Note that in this figure open borehole depth corresponds to the depth below top of rock. The corresponding geometric mean transmissivity for specific depths is also presented. **d)** Distribution of measured transmissivities.

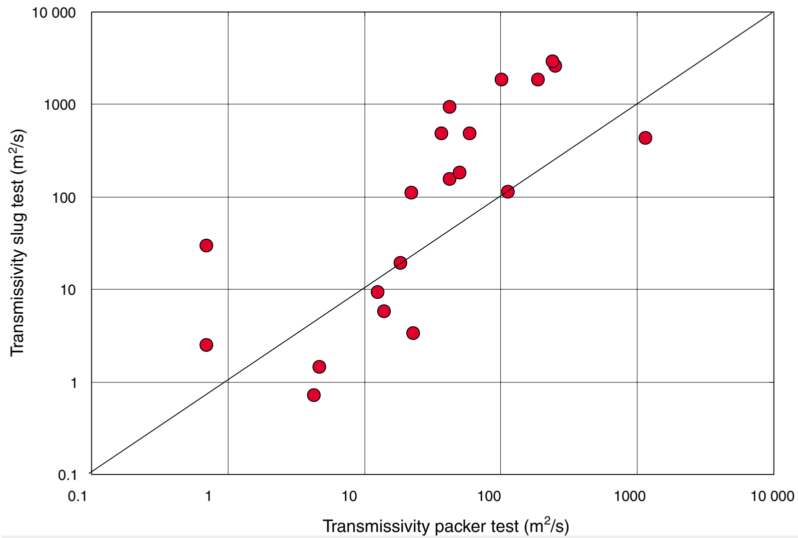

Figure 4. Comparison of the transmissivities obtained with constant-head injection and slug tests

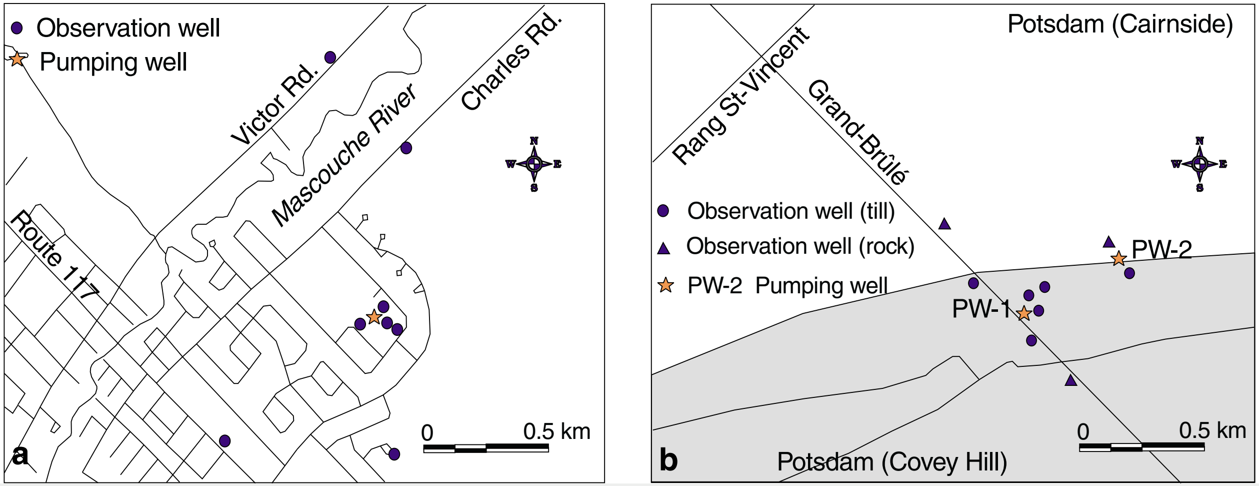

Figure 5. a) Saint-Janvier detailed aquifer test study. **b)** Saint-Benoît detailed aquifer test study.

Table 1. Results of existing pumping tests.

Aquifer lithology		Surface sands	Confined gravel and altered rock	Limestone	Dolostone	Sandstone	Precambrian rocks
# of pumping tests		**5**	**3**	**6**	**15**	**7**	**2**
Transmissivity (m^2/s)	min	$1.13x10^{-2}$	$1.04x10^{-3}$	$8.10x10^{-5}$	$2.43x10^{-4}$	$2.43x10^{-4}$	$2.31x10^{-5}$
	max	$6.50x10^{-2}$	$2.80x10^{-3}$	$8.67x10^{-3}$	$2.20x10^{-2}$	$4.24x10^{-3}$	$5.79x10^{-5}$
Storativity*	min	0.005	0.008	0.00006	0.00008	0.0001	-
	max	0.15		0.003	0.007	0.0008	-

* specific storage for confined aquifers, specific yield or effective porosity for unconfined aquifers

Table 2. Borehole information.

No.	Borehole	Rock group	Rock unit	Elevation (m a.s.l.)	Diameter cm (in)	Depth of well (m)	Depth to rock (m)	Depth to water (m)**
1	P-9*	Chazy	Laval	61.4	15 (6)	56.4	18.5	9.4
2	Saint-Louis	Trenton, Black River, Chazy		68	7.5 (3)	91.61	9.60	5.1
3	Sintra	Chazy, Beekmantown	Laval, Beauharnois	91.1	15 (6)	61.89	0.0	10
4	R-3*	Beekmantown	Beauharnois	73.3	15 (6)	91.5	20.4	21.1
5	R-13*	Beekmantown	Beauharnois	61.0	15 (6)	91.5	18.6	5.9
6	R-14*	Beekmantown	Beauharnois	68.6	15 (6)	48.8	2.7	4.8
7	Sablière	Beekmantown	Beauharnois	71	15 (6)	91.5	19.5	7.5
8	Érablière	Beekmantown	Beauharnois	42	15 (6)	94.52	0.30	40
9	Saint-Janvier	Beekmantown	Beauharnois	69.0	20 (8)	73.2	15.85	10.7
10	Saint-Eustache (3)	Beekmantown	Beauharnois	10.0	7.5 (3)	31	0.0	7.5
11	Montée-Barette	Beekmantown	Beauharnois	59.6	7.5 (3)	99.2	21.5	8.5
12	PE-2*	Beekmantown	Beauharnois/ Precambrian	72.0	20/15 (8/6)	85.6	24.4	5.6
13	RIA-99	Beekmantown	Thérèsa	79.0	7.5 (3)	94.2	9.6	5.0
14	R2-70*	Beekmantown	Thérèsa	72.5	20 (8)	47.2	8.2	2
15	Rivière-du-Nord	Beekmantown	Thérèsa	65	7.5 (3)	118.3	47.56	0
16	Saint-Hermas	Potsdam	Cairnside	48	7.5 (3)	91.6	47	0
17	Montée-Lavigne	Potsdam	Cairnside	87	15 (6)	81	10.8	6.9
18	Saint-Vincent	Potsdam	Covey Hill	58.0	15 (6)	110.3	20.8	10.2
19	Fromagerie*	Potsdam	Covey Hill	38.0	15 (6)	142	70.0	6.8
20	Saint-Benoît	Potsdam	CoveyHill	51	15 (6)	103.5	30.5	3
21	R-15*	Precambrian	Precambrian	68.2	15 (6)	91.5	4.6	8.3

* existing well
** as of August 2000

Table 3. Observation wells in Quaternary deposits.

No.	Observation well	Rock formation	Diameter of hole cm (in)	Depth of well (m)	Depth to rock (m)	Depth to water (m)	Screened deposits	Screened PVC 2" section
1	Saint-Benoît-1	Covey Hill	15 (6)	29.3	29.1	3.7	Sediments on top of rock	27.8–29.3
2	Saint-Benoît-2	Covey Hill	15 (6)	35.7	31.4	4.0	Sediments on top of rock	32.1–35.1
3	Saint-Benoît-3	Covey Hill	15 (6)	25.8	24.4	4.0	Sediments on top of rock	23.6–25.1
4	Saint-Benoît-4	Covey Hill	15 (6)	21.8	25	3.3	Sediments on top of rock	20.3–21.8
5	Saint-Benoît-5	Covey Hill	15 (6)	36.3	34.9	3.5	Sediments on top of rock	34.7–36.2
6	Saint-Janvier-3	Beauharnois	15 (6)	15.24	13.1	9.3	Sediments on top of rock	12.8–14.3
7	Saint-André-Est	Covey Hill	15 (6)	22.9	20.7	3.4	Sediments on top of rock	20.0–21.5
8	Sablière-1	Beauharnois	7.5 (3)	18.4	19.5	8.1	Sediments on top of rock	18.0–18.4
9	Saint-Vincent-1	Covey Hill	7.5 (3)	22	20.8	9.2	Sediments on top of rock	21.6–22.0
10	Saint-Vincent-2	Covey Hill	7.5 (3)	9.1	20.8	3.0	Middle of till layer	8.7–9.1

Table 4. Summary of transmissivity measurements for 4 m test intervals.

Rock type	N	T_{min} (m^2/s)	T_{max} (m^2/s)	T_G (m^2/s)	$\sigma_{ln(T)}$
Carbonate	210	$1x10^{-10}$	$1x10^{-3}$	$1.5x10^{-6}$	2.9
Sandstone	92	$4x10^{-8}$	$5x10^{-3}$	$2.7x10^{-6}$	1.9
Precambrian	26	$7x10^{-9}$	$7x10^{-5}$	$2.7x10^{-7}$	2.9

T_G: Geometric mean
σ_{ln}: Variance

Table 5. Results of the slug and constant-head injection tests in open boreholes.

No.	Borehole	Rock unit	Tested fractured rock thickness (m)	Hydraulic conductivity slug test (m/s)	Transmissivity slug test (m^2/s)	Total transmissivity Packer test (m^2/s)
1	P-9	Laval	38	$1.04x10^{-3}$	$3.95x10^{-2}$	$2.49x10^{-3}$
2	Saint-Louis		80	$8.68x10^{-8}$	$6.94x10^{-6}$	$4.28x10^{-5}$
3	Sintra	Laval, Beauharnois	51.9	$4.91x10^{-7}$	$2.55x10^{-5}$	$6.94x10^{-6}$
4	R-3	Beauharnois	72	$2.19x10^{-5}$	$1.57x10^{-3}$	$4.19x10^{-4}$
5	R-13	Beauharnois	72.9	$6.64x10^{-5}$	$4.84x10^{-3}$	$5.90x10^{-4}$
6	R-14	Beauharnois	43	$4.25x10^{-5}$	$1.83x10^{-3}$	$4.97x10^{-4}$
7	Sablière	Beauharnois	72	$2.57x10^{-4}$	$1.85x10^{-2}$	$1.86x10^{-3}$
8	Érablière	Beauharnois	56.1	$5.36x10^{-6}$	$3.01x10^{-4}$	$6.94x10^{-6}$
9	Saint-Janvier	Beauharnois	57.3	$1.61x10^{-4}$	$9.22x10^{-3}$	$4.20x10^{-4}$
10	Saint-Eustache	Beauharnois	23.5	$4.48x10^{-5}$	$1.05x10^{-3}$	$2.51x10^{-3}$
11	Montée-Barette	Beauharnois	80	$6.12x10^{-5}$	$4.90x10^{-3}$	$3.66x10^{-4}$
12	PE-2	Beauharnois/ Precambrian	60	$1.56x10^{-6}$	$9.38x10^{-5}$	$1.25x10^{-4}$
13	RIA-99	Thérèsa	84.6	$1.35x10^{-5}$	$1.15x10^{-3}$	$1.12x10^{-3}$
14	R2-70	Thérèsa	39	$7.52x10^{-4}$	$2.93x10^{-2}$	$2.37x10^{-3}$
15	Rivière-du-Nord	Thérèsa	72.9	$2.55x10^{-4}$	$1.86x10^{-2}$	$1.01x10^{-3}$
16	Saint-Hermas	Cairnside	47	$2.39x10^{-5}$	$1.12x10^{-3}$	$2.19x10^{-4}$
17	Montée-Lavigne	Cairnside	70	$6.20x10^{-5}$	$4.34x10^{-3}$	$1.15x10^{-2}$
18	Saint-Vincent	Cairnside	90	$1.54x10^{-7}$	$1.39x10^{-5}$	$4.63x10^{-5}$
19	Fromagerie	Covey Hill	72	$4.82x10^{-7}$	$3.47x10^{-5}$	$2.27x10^{-4}$
20	Saint-Benoît	CoveyHill	70	$8.27x10^{-7}$	$5.79x10^{-5}$	$1.39x10^{-4}$
21	R-15	Precambrian	83.2	$2.32x10^{-6}$	$1.93x10^{-4}$	$1.84x10^{-4}$

Table 6. Observation well information.

No.	Observation well	Screened PVC 2" section	Length of screen (m)	Transmissivity slug test (m^2/s)	Hydraulic conductivity (m/s)
1	Saint-Benoît-1	27.8–29.3	1.5	$6.45x10^{-4}$	$4.30x10^{-4}$
2	Saint-Benoît-2	32.1–35.1	3.0	$4.28x10^{-6}$	$1.43x10^{-6}$
3	Saint-Benoît-3	23.6–25.1	1.5	$9.26x10^{-5}$	$6.14x10^{-5}$
4	Saint-Benoît-4	20.3–21.8	1.5	$5.66x10^{-3}$	$3.78x10^{-3}$
5	Saint-Benoît-5	34.7–36.2	1.5	$1.59x10^{-3}$	$1.06x10^{-3}$
6	Saint-Janvier-3	12.8–14.3	1.5	$3.22x10^{-3}$	$2.15x10^{-3}$
7	Saint-André-Est	20–21.5	1.5	$3.23x10^{-4}$	$2.15x10^{-4}$
8	Sablière-1	18.0–18.4	0.4	$6.06x10^{-5}$	$1.52x10^{-4}$
9	Saint-Vincent-1	22.0–22.4	0.4	$4.86x10^{-6}$	$1.22x10^{-5}$
10	Saint-Vincent-2	8.7–9.1	0.4	$6.94x10^{-7}$	$1.74x10^{-6}$

Table 7. Description of intermediate aquifer test sites.

Location	Tested unit	Aquifer type	Pumping rate (m^3/h)	Observation wells
Sainte-Anne-des-Plaines	Chazy	Confined	83 *	9
Saint-Janvier	Beauhornois	Confined	21 *	6
Sintra rock quarry	Chazy	Unconfined	50–100	4
Saint-Eustache rock quarry	Beauharnois	Unconfined	157	3
Saint-Benoît (PW-1)	Gravel, altered rock	Confined	8 *	9
(PW-2)	Gravel, altered rock	Confined	9 *	9

* pumping duration: 7 days