Small scale study of groundwater flow in a fractured carbonate-rock aquifer at the St-Eustache quarry, Québec, Canada

Jean-Michel Lemieux · René Therrien · Donna Kirkwood

Abstract A small-scale hydrogeological study was conducted in a fractured carbonate-rock aquifer located in a quarry to relate groundwater flow to the fracture network. The field study in the St-Eustache quarry, which integrates structural surveys, well logging and hydraulic tests, showed that the most important features that affect groundwater flow in the sedimentary aquifer are high hydraulic conductivity horizontal bedding planes. Vertical fractures are abundant in the quarry and throughout the region, but they have a minor effect on groundwater flow. To have a significant impact on the flow regime and lead to vertical groundwater flow, the permeability of all vertical joints need to be enhanced compared to what was generally observed at the site. Such an increase in permeability could potentially occur where dissolution and fracturing is more intense or at stress release locations such as near the surface in the quarry.

Résumé Une étude hydrogéologique à petite échelle a été réalisée dans un aquifère carbonaté fracturé situé dans une carrière afin de comprendre la relation entre l'écoulement de l'eau souterraine et le réseau de fractures. Cette étude ponctuelle qui intègre des observations géologiques, diagraphiques et hydrogéologiques a permis de mettre en évidence l'importance des plans de litage diagénétiques horizontaux pour l'écoulement de l'eau souterraine dans l'aquifère sédimentaire de la carrière St-Eustache. Les fractures verticales, très abondantes à la carrière St-Eustache et dans l'ensemble de la région, ont une influence mineure sur l'écoulement de l'eau souterraine. Afin d'avoir une influence majeure sur l'écoulement et ainsi faciliter un écoulement vertical, la perméabilité des fractures verticales doit être beaucoup plus élevée que ce qui est observé sur le site. Une augmentation de la perméabilité significative de la perméabilité pourrait être possible là où la dissolution et la fracturation sont plus intenses ainsi qu'à l'intérieur de zones où les contraintes sont plus faibles, comme à la surface de la carrière.

Resumen Se llevó a cabo un estudio hidrogeológico en pequeña escala en un acuífero carbonatado fracturado localizado en una cantera con objeto de relacionar el flujo de agua subterránea con la red de fracturas. El estudio de campo en la cantera de San Eustaquio, el cual integra levantamientos estructurales, registro de pozos y pruebas hidráulicas, mostró que las características más importantes que afectan el flujo de agua subterránea en los acuíferos sedimentarios son planos de estratificación horizontal con alta conductividad hidráulica. Las fracturas verticales son abundantes en la cantera y en toda la región pero tienen efectos menores en el flujo de agua subterránea. Para que las fracturas verticales tengan un impacto significativo en el entorno de flujo y favorezcan el flujo vertical de agua subterránea es necesario estimularlas en comparación con lo que se observa generalmente en el sitio. Tal incremento en permeabilidad puede ocurrir potencialmente donde la disolución y fracturamiento es más intenso o en lugares con liberación de esfuerzos tal como cerca de la superficie de la cantera.

Keywords Fractured rocks · Sedimentary rocks · Carbonate-rock aquifer · Bedding planes

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Introduction

Fractured rock aquifers are used for groundwater supply in several regions of the world. Sound management of groundwater resources of these aquifers requires knowledge of their hydraulic properties, as well as groundwater flow dynamics and transport properties of potential contaminants. These properties may vary drastically depending on whether the rocks are of sedimentary, igneous or metamorphic origin.

In contrast to granular unfractured aquifers, fractured rock aquifers exhibit a stronger heterogeneity because of the large contrast in hydraulic properties between the high-permeability fractures and the surrounding rock matrix of lower permeability and also because of the contrast between different fracture types. Although significant knowledge has been gained towards understanding fluid flow and solute transport in fractured rock, mainly from research focusing on geologic repositories for nuclear waste, there are still unresolved issues concerning the small-scale characterization of fractured rock formations.

Very few detailed groundwater studies have been reported for fractured sedimentary aquifers and, more particularly, for fractured dolostone. Novakowski and Lapcevic (1988) show the important role of bedding planes in controlling groundwater flow in Silurian and Ordovician dolostones underlying Niagara Falls, Ontario, Canada. Michalski and Britton (1997) also show the role of bedding plane fractures for fluid flow in the Newark Basin, New Jersey, USA. Muldoon et al. (2001) correlate hydraulic conductivity with stratigraphy in a fractured dolomite in Wisconsin, USA. In these studies, different characterization methods are used to highlight features that control groundwater flow in fractured dolostones, with horizontal bedding planes identified as controls for fluid flow at the field and regional scales. Michalski and Britton (1997) emphasize the need to use several characterization methods to locate these horizontal bedding planes and to build a realistic conceptual model for fluid flow.

Presented here is a small-scale hydrogeological study of a fractured carbonate-rock formation. The study focused on the development of a conceptual model for fluid flow at the scale of a dolostone quarry. To build the conceptual model, it is important to determine the type of fractures most likely to conduct groundwater flow at the site scale because different types of fractures, and even different fractures of the same type, can act either as preferential flow paths or barriers to groundwater flow. Structural surveys, extensive logging and hydraulic testing have been combined to build a conceptual model of groundwater flow at the site. This conceptual model is further tested with a groundwater flow model to check its validity.

The work presented is part of a regional hydrogeological mapping project in the Saint-Lawrence Lowlands in Québec, Canada. The aquifers in the region are composed of sedimentary rocks that are fractured and from which groundwater is extensively abstracted. The main objectives of the regional project were to answer the needs of decisionmakers relative to the use and protection of the groundwater resource, set provincial guidelines for characterizing regional sedimentary fractured rock aquifers and quantify groundwater availability and quality in the region (Savard et al. 2000).

Structural Survey

The study was conducted at the St-Eustache quarry (Fig. 1), where the main rock unit is a well bedded, flat-lying Ordovician dolostone that belongs to the Beauharnois Formation of the Beekmantown Group. Globensky (1987) indicates that the Beauharnois Formation has a thickness of 305 m and is composed of a massive and laminated dolostone with interbedded dolomitic sandstone.

The excavation at the quarry, which was in operation during the project, is approximately 60 m deep and is maintained dry by pumping. Scanline mapping of the walls of the St-Eustache quarry consisted of measuring the position, length, direction, dip, termination and infill of all fractures intercepted by horizontal and vertical lines drawn on the quarry wall. Surveys were conducted on walls having different orientation to prevent bias induced by the orientation of the fractures relative to the walls (Terzaghi 1965). Fractures were also mapped on the quarry floor.

The fractures mapped include all discrete breaks in the rock mass where cohesion is lost (Ramsey and Huber 1987). The term fracture used here includes faults, that display observable offset parallel to the fracture surface, joints along which there has been imperceptible movement more or less perpendicular to the fracture surface (Davis and Reynolds 1996), sealed joints where fluids passing through the rock have partially or completely healed the fracture surface and joined the adjacent sides by deposition of crystalline material, and veins where a considerable thickness (>1 mm)

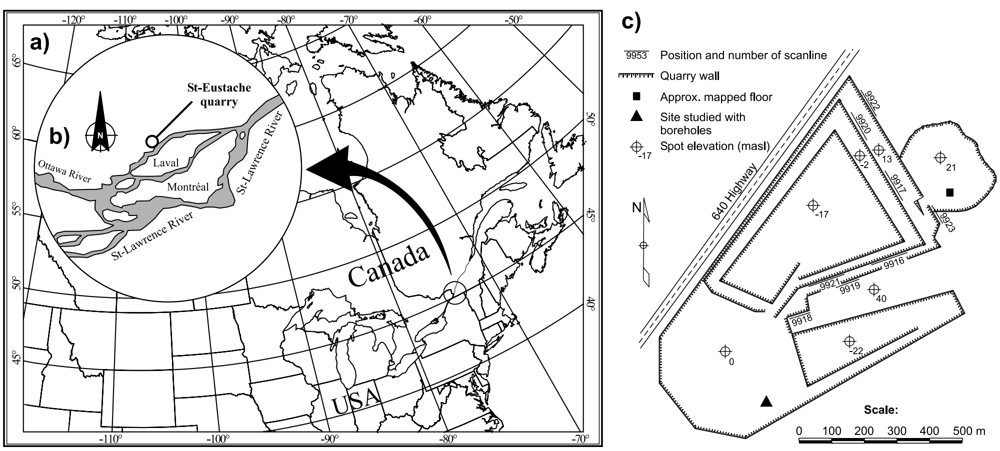

Fig. 1 **a** Localization of the study area in North America. **b** Regional map of the St-Eustache quarry location. **c** Plan view of the St-Eustache quarry

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of filling material occupies the space between the fracture walls (Ramsey and Huber 1987). Diagenetic dissolution planes or diagenetic stylolites (bedding planes), which are weak cohesion planes, are also included in the fracture definition used here.

Three types of fractures were identified in the dolostone at the quarry (Lemieux 2000). The first type consists of large vertical strike-slip faults. The length of these faults is greater than the dimensions of the quarry and their width varies between 10 and 50 cm. There are fewer than 10 of these faults in the whole quarry and none near the location of the boreholes. The second type of fracture is the most frequent and it consists of vertical straight joints of varying orientation that usually terminate on horizontal bedding planes. Horizontal diagenetic dissolution planes, or bedding planes, constitute the third fracture type. Hundreds of these bedding planes were mapped. They are characterized by a high content of insoluble minerals and organic matter and they delimit the various dolostone beds on the quarry wall, with a spacing between 5 and 100 cm. The bedding planes do not form regular planar features but are irregular rough surfaces of variable aperture, ranging from zero where both sides of the fracture are in contact, to values between a few millimeters and about two centimeters where the fracture sides are not in contact. Because the dolostone beds in the quarry are near horizontal, bedding planes are laterally continuous at the scale of the quarry. Sustained groundwater seepage originating from the deepest bedding planes was observed on the quarry walls, suggesting that some of the bedding planes act as hydraulic drains in the fractured rock mass.

A statistical analysis of the orientation of vertical joints indicates that they can be grouped in four different sets (Table 1) that have mean orientations equal to N2°, N80°, N150° and N30°, listed in order of decreasing number of fractures. Depending on the set, the spacing of the vertical joints follows either a log-normal or an inverse exponential distribution with a median value between 0.5 and 2 m. Since these probability distributions are skewed, the median value is a better descriptor of the center of the distribution than the mean, as suggested by Narr and Suppe (1991) for lognormal distributions. The vertical trace length of the joints is log-normally distributed, with a median between 29 and 35 cm for the 4 sets. This median vertical trace length corresponds to the median spacing of the horizontal bedding planes equal to 0.4 m, which is expected since the vertical joints do not usually extend beyond a single dolostone bed.

Experimental variograms of fracture spacing suggest very little spatial correlation for the fracture location (see Lemieux 2002). However, calculation of the correlation coefficient introduced by Odling et al. (1999) using the fracture spacing suggests that the fractures are slightly grouped instead of being randomly distributed.

Odling et al. (1999) suggest a simple classification for fracture networks according to their scaling properties. The classification is based on lithological layering with the following two end-members: non-stratabound and stratabound. Non-stratabound networks are found in plutonic or metamorphic rocks. In such cases, fractures are not limited by mechanical layering and their length can vary over several orders of magnitude. The stratabound networks are generally found in sedimentary rocks where bedding planes are well developed. In these networks, vertical joints terminate on bedding planes, as observed at the St-Eustache quarry. According to this classification, the dolostone studied here would fall into the stratabound category. Odling et al. (1999) indicate that fracture spacing in stratabound networks is regular and a representative elementary volume (REV) for the fractured rock mass would be one to two orders of magnitude larger than the mean fracture spacing. Considering all fractures, the REV for the St-Eustache quarry would thus be on the order of 5 to 50 m in length, or 25 to 2,500 m^3 in volume. The dimensions of the site fall in that interval, such that the entire rock mass could be considered homogeneous if all fractures are assumed to have similar hydraulic properties and if the relationship given by Odling et al. (1999) for defining the size of the REV is valid here.

Table 1 Summary of fracture network characteristics

Characteristic	Value
Main features	
Geometrically well connected	
Stratabound system	
“Purely” fractured media	
Faults	
None in the study area	
Vertical joints	
Number of sets	4
Type	Discontinuous
Orientation of sets	N2°, N80°, N150°, N30°
Median spacing	0.5–2 m
Vertical extension	29–35 cm
Spacing distribution	Lognormal/inverse exponential
Horizontal bedding planes	
Type	Continuous
Median spacing	40 cm
Spacing distribution	Lognormal

From the statistical analysis of fracture properties and from the visual observation at the quarry, a conceptual model is proposed for the fractured dolostone. The conceptual model, schematically illustrated in Fig. 2 and described in Table 1, includes the two main fracture types: the vertical joints and the horizontal bedding planes. The structural survey suggests that the fracture network is geometrically well connected since there are four sets of vertical joints, with different orientations, that intersect each other in the rock mass. Moreover, each vertical joint is usually connected to at least two horizontal bedding planes that have a large horizontal extent. Although not measured, the matrix porosity and permeability are assumed to be very small based on visual observation and the rock mass may thus be considered a “purely” fractured medium. The hydraulic properties of the rock mass are therefore controlled by the hydraulic properties of the individual fractures composing

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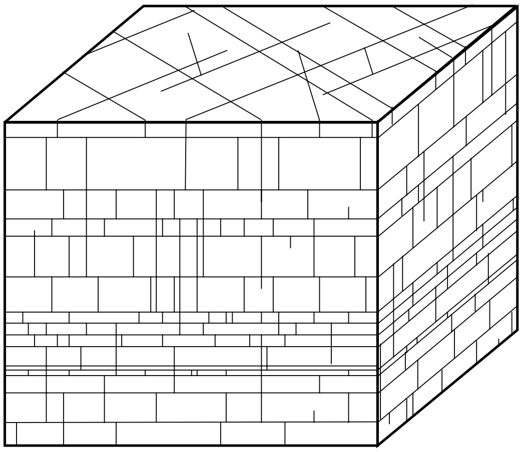


Fig. 2 Conceptual model of fracture geometry in the St-Eustache quarry. The sides of the block are approximately 5 m long

the well-connected network, which have been investigated to the extent possible by geophysical and hydraulic tests in vertical boreholes.

Well Logging

Three vertical boreholes were diamond-drilled directly on the quarry floor for hydraulic and geophysical testing. The three boreholes (SE4, SE5 and SE6 in Fig. 3) with a diameter of 76.2 mm have been drilled to a depth of approximately 35 m. The water table in the wells was at a depth of approximately 6 m below ground surface. Although inclined boreholes were initially planned in order to intercept as many vertical fractures as possible, inclined drilling was impossible since the drilling company selected for the work did not have the proper equipment.

Excellent recovery during drilling allowed a direct description of the cores. No vertical joints were observed, which is obviously expected for vertical boreholes. The main structural feature observed in the cores are bedding planes outlined by stylolites, similar to those observed on the quarry walls. The spacing of the bedding planes mapped in the cores varies between 10 to 20 cm, whereas the median spacing of the stylolites on the quarry walls is 40 cm. This difference in spacing is attributed to the more detailed scale of observation when logging the cores compared to mapping of the quarry walls, as well as the discrete nature of several stylolitic planes in the cores. It is assumed that similar discrete stylolitic planes are also present on the quarry walls but they were not observed during mapping because of the absence of weathering, enhancing the presence of organic rich layers and their identification as bedding planes. These small stylolites not mapped on the quarry walls are assumed to play a minor role for fluid flow.

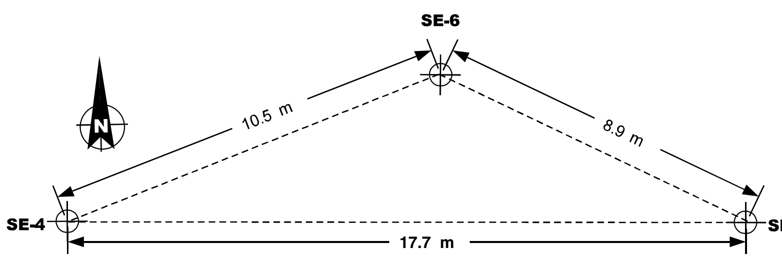
The following geophysical logs were conducted in each borehole: caliper, natural gamma, fluid resistivity, single-point resistance, normal resistivity, acoustic waveform, acoustic televiewer, optical televiewer, and electromagnetic flowmeter (see Etienne 2002, for details). During well logging, the quarry was dewatered with pumps located in a ditch approximately 10 m from the nearest borehole, which perturbed the groundwater flow. As a result, several geophysical measurements, such as fluid resistivity, could not be interpreted and are not shown here. On the other hand, this perturbation provided ideal conditions for the electromagnetic flowmeter, which indicates that the boreholes intersect two major features that create opposite vertical flow directions along the boreholes (Fig. 4a). These two features, located at depths of 13 and 24 m below ground surface, also correspond to changes in borehole diameter as measured with the caliper (Fig. 4b). The two features correspond to two distinct stylolitic bedding planes, as confirmed by the natural gamma, optical televiewer and description of the cores. The profile shown in Fig. 4a is for well SE-6, but similar results not shown here have been observed for the other two wells.

Hydraulic Tests

The hydraulic tests conducted at the site include constant injection tests in individual boreholes, as well as pumping and pulse interference tests between boreholes.

A total of 31 constant injection tests with inflatable packers was performed to obtain a vertical profile of transmissivity within the three boreholes (Fig. 4c–e). A 2-m interval between the packers was selected for the tests and a 1-m interval was also used in well SE5 (not shown). Time and equipment constraints did not allow for a smaller packer interval. The transmissivity profiles in the three wells are similar and show two zones of higher transmissivity. The first zone corresponds to the upper part of the aquifer, from the water table to a depth of 13 m, where the mean transmissivity is approximately 1×10^{-3} m^2/s. The second high transmissivity zone corresponds to a single packed interval. It is located at a depth of 24 m, which is the same elevation as the bedding plane that induced a change in the velocity of the water in the wells during testing with the electromagnetic flowmeter (see Fig. 4a). All other

Fig. 3 Relative position of the wells in the quarry



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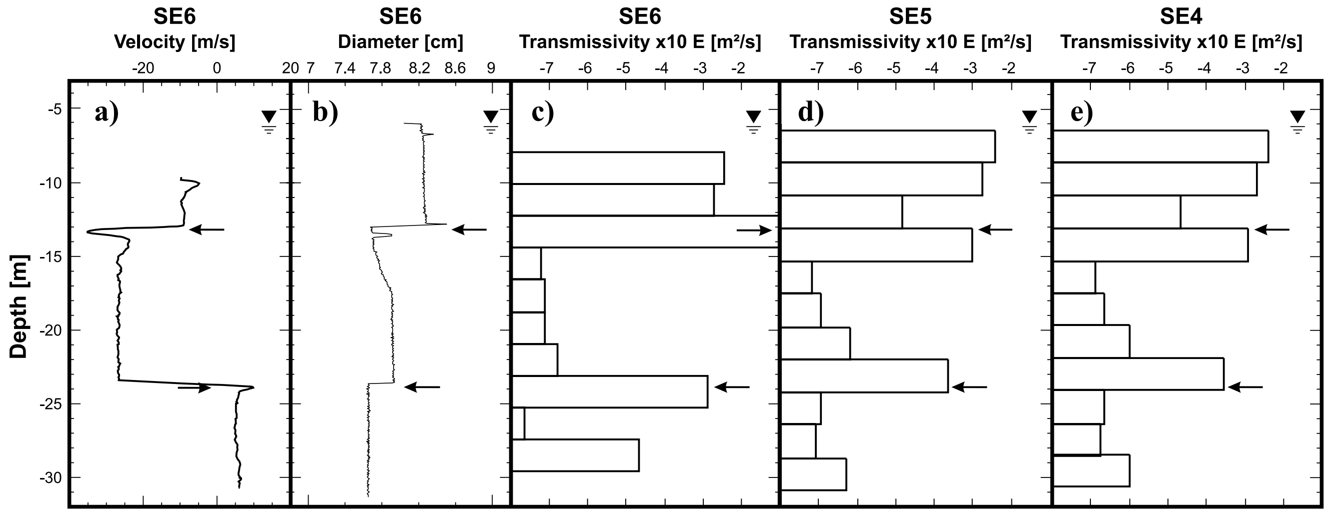

Fig. 4 Well logs and transmissivity profiles. **a** Velocity profile obtained by the EM Flowmeter in borehole SE-6 (negative values of velocity indicate downward flow in the borehole and positive values indicate upward flow). **b** Caliper log in borehole SE6. **c–e** Transmissivity profiles in borehole SE6, SE5 and SE4, respectively. *Arrows* indicate positions of open fractures

transmissivity values measured in the boreholes are at least three orders of magnitude lower than those of the two conductive zones.

Further hydraulic testing included pumping and pulse interference tests in the three boreholes, with one well pumping or injecting water and the response measured in the other two wells. The two observation wells were equipped with inflatable packers to isolate the two conductive bedding planes located at depths of 13 and 24 m (Fig. 5), as well as other intervals. The pumping well was also equipped with inflatable packers to isolate the pumping or withdrawal interval, which was either the upper or lower bedding plane. The intervals were numbered from 1 at the bottom to 5 at the top (Fig. 5). Four tests were conducted by pumping either SE5-2, SE5-4, SE6-2 or SE6-4 and monitoring in the other intervals. The discussion here is restricted to the test that consisted in pumping the deepest bedding plane in well SE6 and observing the response at various intervals in wells SE4 and SE5.

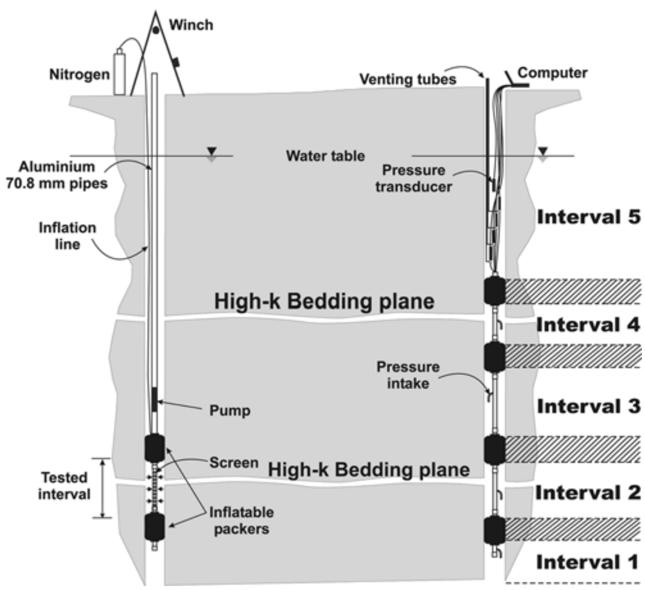

Fig. 5 Hydraulic testing set-up

The drawdown response was initially analyzed with analytical solutions for a porous medium, assuming one of two types of aquifer-aquitard systems to represent the fractured dolostone. Results are summarized in Table 2. The first aquifer-aquitard system considers the deepest fracture as a confined aquifer, with transmissivity and storativity calculated with the Theis (1935) or the Cooper and Jacob (1946) method. The second system assumes that the deep fracture acts as a leaky aquifer, with drainage from an overlying aquitard and its analysis was performed with either the Walton (1962) method, the Hantush (1956) inflection point method, or the Hantush (1960) type curves. The last two methods allow calculating the hydraulic conductivity and storativity of the aquitard (Lemieux 2002).

The transmissivity values obtained by the different methods are similar and are on the order of 1×10^{-4} m^2/s. The storativity values are also similar for the various methods, with a geometric mean of 2.3×10^{-4} obtained from the analysis of 10 drawdown curves. The average hydraulic conductivity and storativity of the aquitard are 1.9×10^{-7} m/s and 1.8×10^{-4}, respectively. The reliability of these values is unknown since the analytical methods used are based on the equivalent porous medium concept, which may not be consistent with the presence of two main horizontal fractures in the domain. Furthermore, the bottom of the aquifer, which is the lower bedding plane, might not be impermeable. To evaluate the validity of the assumptions in the analytical solutions, the hydraulic tests were also simulated with a discrete-fracture numerical model. Results from these simulations are presented later.

Tests were also performed by pumping the upper horizontal fracture located at a depth of 13 m. Unfortunately, dewatering at a variable rate was still conducted by the pumping in the ditch near the pumping well, making the

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Table 2 Summary of pumping test analysis. *T* and *S* are transmissivity and storativity of the aquifer (i.e. the fracture). *K′* and *S′* are the hydraulic conductivity and storativity of the aquitard

Solution	Aquifer type	Well	T (m^2/s)	S (–)	K' (m/s)	S'(–)
Hantush	Leaky	SE4	7.9×10^{-4}	2.6×10^{-4}	1.5×10^{-7}	–
Inflexion point		SE5	8.7×10^{-4}	4.0×10^{-4}	2.3×10^{-7}	–
Hantush	Leaky	SE4	6.2×10^{-4}	2.5×10^{-4}	–	1.5×10^{-4}
Type curves		SE5	7.4×10^{-4}	3.4×10^{-4}	–	2.2×10^{-4}
Walton	Leaky	SE4	1.7×10^{-5}	6.2×10^{-6}	–	–
		SE5	7.7×10^{-4}	1.9×10^{-4}	–	–
Theis	Confined	SE4	7.7×10^{-4}	2.6×10^{-4}	–	–
		SE5	7.0×10^{-4}	2.7×10^{-4}	–	–
Cooper—Jacob	Confined	SE4	6.3×10^{-4}	5.8×10^{-4}	–	–
		SE5	5.5×10^{-4}	7.8×10^{-4}	–	–
Geometric mean			4.9×10^{-4}	2.3×10^{-4}	1.9×10^{-7}	1.8×10^{-4}

interpretation of these tests extremely difficult. However, massive pumping in the ditch (10 m depth) provided unexpected information on the connectivity of the packed-off intervals, because it caused drawdown only in upper intervals 4 and 5 (Fig. 5) and not in the lower intervals. This suggests that the upper intervals are connected by vertical fractures but they are isolated from the deeper intervals.

In addition to the pumping tests, eight pulse interference tests were performed in bedding planes to confirm their lateral extent and connectivity between the wells. A pulse interference test consists of measuring the pressure response in one or more observation zones after introducing an instantaneous slug of water in a nearby well (Lapcevic et al. 1998). The tests were conducted twice and consisted of injecting water in intervals 2 and 4 of boreholes SE5 and SE6 (Figs. 3 and 5) and monitoring the response in the remaining intervals in the other boreholes.

Injection in the upper bedding plane (interval 4) produced a very weak or no response in the observation wells. Potential reasons for the lack of response might be that the injection head is too small, a single fracture was not isolated in the observation interval, or there is poor connection between the wells for the intervals tested. On the other hand, injection in interval 2, corresponding to the lower bedding plane at a depth of 24 m, produced a clear response in the observation wells. For all tests performed in interval 2, the hydraulic head response was analyzed using both the curve-fitting program TCINV (Piggott et al. 1995) and the graphical method proposed by Novakowski (1989) and the geometric mean of the transmissivity thus obtained is equal to 5.64×10^{-4} m^2/s and 2.33×10^{-4} m^2/s, respectively. Both methods provide very similar results for transmissivity.

Revised Conceptual Model

The initial structural survey of the quarry shows that vertical joints are confined to individual beds limited by bedding planes (Fig. 6a). Four sets of vertical joints intersect horizontal bedding planes, resulting in a high fracture connectivity in the rock mass. A characterization of the rock mass by fracture mapping only would thus suggest that fluid flow in the dolostone, at the scale of the quarry, would not be restricted to a few permeable features but would rather occur almost anywhere in the rock mass. However, this initial conceptual model can be improved by incorporating results from hydraulic tests and downhole geophysical measurements.

The geophysical logs provide insight into the variation of the rock and fracture properties with depth. Although fracture mapping from core analysis and borehole televiewer could reveal mostly the presence of horizontal bedding planes, geophysical well logs indicate two zones of higher hydraulic conductivity and two zones of low hydraulic conductivity (Fig. 4c–e). These zones are illustrated schematically in the well log model in Fig. 6b, updated from the fracture network model (Fig. 6a), which shows that although there are numerous horizontal bedding planes, high hydraulic conductivity bedding planes are concentrated in the upper part of the rock mass and a single high hydraulic conductivity bedding plane is located at depth.

Water level monitoring and pumping tests further helped refine the model. In addition to confirming the high hydraulic conductivity of some horizontal bedding planes, hydraulic testing suggests that the upper part of the aquifer acts as a surficial aquifer, while the deepest bedding plane has a high hydraulic conductivity but is not well connected to the surficial aquifer (Fig. 6c).

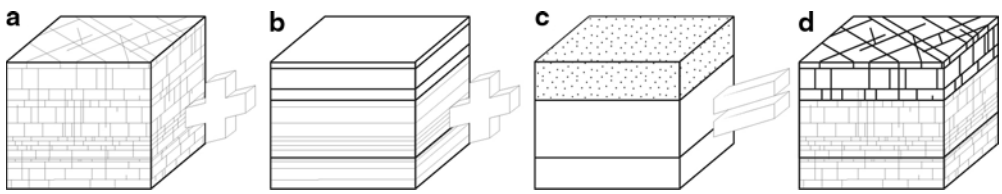

Fig. 6 Evolution of the conceptual model for the fractured dolostone. **a** Fracture network model. **b** Well logging model. **c** Hydraulic testing model. **d** Revised conceptual model. *Bold lines* are for high hydraulic conductivity fractures and *hairlines* are for potentially conductive fractures. All block sides are approximately 5 m long

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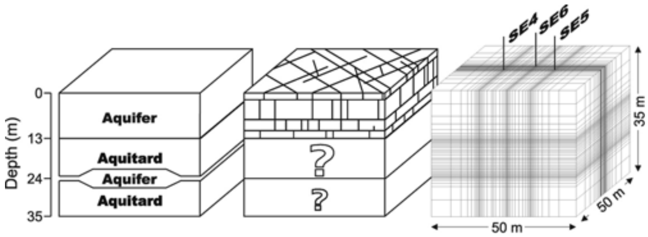

Fig. 7 Conceptual model and corresponding numerical grid

Combining all data acquired with the different field methods produces the updated conceptual model for fluid flow in the fractured dolostone at the scale of the study (Fig. 6d). The fractured dolostone is a multi-layered system where the aquifers are represented by the high hydraulic conductivity bedding planes. The bottom of the system corresponds to the maximum depth reached by the boreholes in the quarry and it corresponds to a fractured rock mass of low hydraulic conductivity. This low-permeability rock mass is overlain by a single high conductivity horizontal fracture, or bedding plane, that can be conceptualized as a confined aquifer. This horizontal fracture is overlain by a second low hydraulic conductivity fractured rock mass, which is in turn overlain by a more permeable fractured rock mass, which acts as a surficial unconfined aquifer. In this last zone, the vertical and horizontal fractures have high hydraulic conductivities while elsewhere, their contribution to flow is uncertain but most probably small.

Numerical Modeling

A numerical model that solves fluid flow in discretely-fractured porous media was used to reproduce the hydraulic tests and to verify the conceptual model obtained from the field characterization. The finite element model FRAC3DVS (Therrien and Sudicky 1996) solves the three-dimensional flow equation for discrete fractures embedded in a porous matrix. The model thus allows the representation of discrete fractures in the system, as well as the treatment of the dolostone as an equivalent porous medium corresponding to either the upper aquifer or the aquitards highlighted in Fig. 7. The properties of the aquitard were inferred from the analysis of the pumping tests. Details on the governing equations and the numerical methods used in the model are found in Therrien and Sudicky (1996).

A three-dimensional domain having a horizontal extent of 50 m in each of the *x*- and *y*-directions, and a vertical thickness of 35 m is used to represent the section of the dolostone tested (Fig. 7). The rock matrix is discretized with three-dimensional rectangular prisms, while the two conductive horizontal fractures are discretized with 2D planar elements. The three wells (SE4, SE5, SE6) are further represented by one-dimensional high conductivity elements, according to the formulation presented in Therrien and Sudicky (2000). The grid was refined horizontally near the three wells and vertically around the two horizontal high-permeability fractures (Fig. 7). Although the surficial aquifer is shown in Fig. 7, it was not implicitly considered in the simulations and the upper part of the model was assigned the hydraulic properties of the underlying aquitard, because it is assumed that the high hydraulic conductivity surficial aquifer does not influence drawdown in the deepest bedding plane aquifer.

The boundary conditions for the flow simulation are a constant head on each of the lateral sides, assuming no drawdown from pumping, and no-flow boundaries at the top and the bottom of the domain. The initial hydraulic head is assumed constant for the whole domain and fully-saturated conditions are also assumed. The simulation presented here reproduces the pumping test described in the hydraulic testing section, with the pumping well located at SE6-2 and observation wells at SE4-2 and SE5-2. A constant pumping rate equal to 4.66×10^{-4} m^3/s is imposed for a total duration of approximately 8 h. Variable time stepping was used for the simulation (Therrien and Sudicky 1996).

The properties which were varied to manually calibrate the model are the aperture of the deepest horizontal fracture and the hydraulic conductivity and storage coefficient of the aquitards. Although the two horizontal bedding planes were discretized in the model, the deepest plane has the greatest effect on flow and it was not necessary to adjust the hydraulic conductivity of the upper plane for calibration. The fracture specific storage was not included in this analysis since its influence on groundwater flow is negligible.

The best fits between the simulated and measured drawdown curves for all three wells are shown in Fig. 8. The corresponding fitted fracture aperture is equal to 7×10^{-4} m for the lower bedding plane, the hydraulic conductivity and specific storage of the aquitards are equal to 5×10^{-7} m/s and 1×10^{-3} m^{-1}, respectively (Table 3).

The hydraulic conductivity associated with the calibrated fracture aperture can be compared to the transmissivity value obtained from the pumping test analysis for the same fracture by applying the cubic law. Assuming the parallel plate model for a single fracture, the transmissivity T can be related to the fracture aperture b by (Bear 1993):

$$T = \frac{b^3}{12}\frac{\rho g}{\mu} \quad (1)$$

where ρ is water density, g is the gravitational acceleration and μ is the viscosity of water. Using that relationship, the geometric mean of the transmissivity obtained with the various analytical methods presented previously corresponds to an aperture of 9.6×10^{-4} m, which is of the same order

Table 3 Summary of calibrated properties

Properties	Value
Fracture	
Aperture, b (m)	7×10^{-4}
Specific storage, (m^{-1})	–
Matrix (aquitard)	
Hydraulic conductivity, k (m/s)	5×10^{-7}
Specific storage, S_s (m^{-1})	1×10^{-3}

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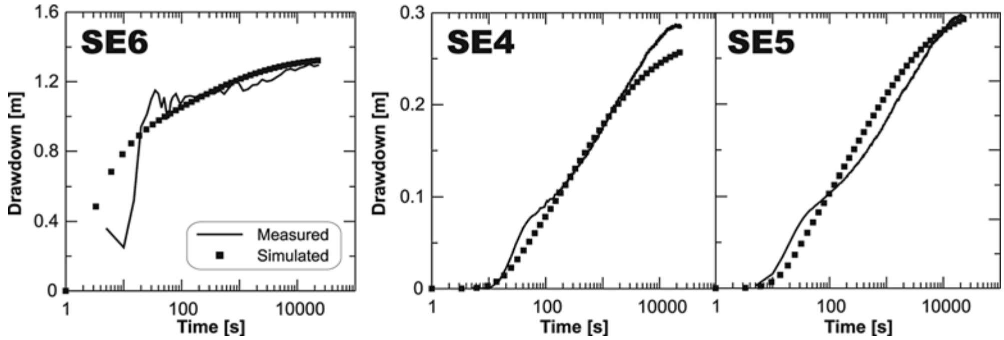

Fig. 8 Simulated and observed drawdown for pumping well (SE6) and observation wells (SE4 and SE5)

of magnitude as the value of 7×10^{-4} m obtained from the discrete-fracture model calibration.

The calibrated hydraulic conductivity of the aquitards is at the upper end of values reported for unfractured dolostone (UNESCO 1984) and is of the same order of magnitude as values obtained from constant injection tests in the aquitard. The calibrated hydraulic conductivity of the aquitard represents a bulk value for a low hydraulic conductivity dolostone that contains fractures. These fractures, however, have a lower hydraulic conductivity than the highly transmissive bedding planes.

Finally, the storativity of the aquitard obtained from the Hantush type curves method is 1.8×10^{-4}. The specific storage used for the calibration of the discrete-fracture model is 1×10^{-3} m^{-1} which correspond to a storativity of 1.1×10^{-2} when using the following relation: $S{=}S_s{\cdot}b$ where S is storativity, S_s is specific storage and b is the thickness of the aquitard, assumed to be 11 m. This calibrated value is two orders of magnitude higher than that obtained by the analytical methods. This discrepancy is expected since the Hantush analytical solution relies on assumptions that do not correspond with the test geometry, such as an impervious base for the aquifer. Also, the Hantush solution assumes that flow in the fracture can be simulated as porous medium flow, which is not necessarily the case. Finally, the value obtained with the analytical solution is based on the interpretation of one test and since the physical characteristics of the fracture network are probably variable in the quarry, the interpretation of additional tests would provide a more representative value of the specific storage of the aquitards.

Discussion

The characterization approach used here to build a conceptual model for fluid flow relies on a combination of geological, geophysical and hydraulic observations and measurements, as suggested by NRC (1996). The conceptual model developed for the fractured dolostone could not have been built using a single characterization method since, for example, geophysical measurements would not have given information about vertical fractures. Although hydraulic testing was done only with vertical boreholes and focused on horizontal fractures such as bedding planes, useful information on vertical fractures has also been gained using different investigation methods.

Horizontal bedding planes represent the most important feature for fluid flow, because of their high permeability and large lateral extent. A single horizontal high-conductivity bedding plane can significantly modify the flow regime. A single high-conductivity vertical joint will not have the same impact as conductive horizontal bedding planes since vertical joints in the quarry are of limited extent and do not usually cross more than one dolostone bed. To have a significant impact on the flow regime and lead to vertical groundwater flow, the equivalent permeability of all vertical joints would need to be enhanced as a whole, together with the properties of the horizontal bedding planes. Such increase in permeability could occur in zones of reduced stress such as near the surface, for fracture sets parallel to the principal stress direction, or when alteration has enhanced the aperture of the fractures.

Stress was not measured at the site. However, the effect of a given horizontal principal stress would be to enhance the hydraulic conductivity of the vertical fracture set oriented parallel to the principal stress direction. Even so, a more conductive vertical fracture set would not necessarily enhance the horizontal hydraulic conductivity since no connection is possible between fractures of the same set. Accordingly, impact on flow is assumed to be negligible. Furthermore, the only effect would be to enhance the vertical hydraulic conductivity locally since the vertical fractures are of limited extent and always terminate on horizontal bedding planes which, except for a few, have a low hydraulic conductivity.

Another observation can support the relation assumed between flow and fracture types. A first borehole was initially drilled at the lowest point on the quarry floor, to an absolute depth greater than that reached by boreholes SE4, SE5 and SE6. When drilling that first borehole, no water was seeping out of the well until the borehole reached a depth of 20 m below the quarry floor. At that depth, water began to freely flow out of the borehole during drilling and reached an elevation of 3 m above the quarry floor. The borehole most probably tapped into a high-permeability horizontal fracture at a depth of 20 m, where the hydraulic head was much greater than that near ground surface because vertical fractures have a low hydraulic conductivity, which produces strong vertical hydraulic gradients in the rock mass.

It is believed that the vertical fractures have a high hydraulic conductivity in the upper part of the aquifer.

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This would explain the hydraulic link between intervals 4 and 5 and between the high hydraulic conductivity bedding planes that were highlighted by the transmissivity profiles. On the other hand, it is not known whether this is due to decompression near the surface or due to an enhanced hydraulic conductivity by dissolution along the fracture planes. The regional study has shown that the first few meters of the rock aquifers, just below the contact with Quaternary deposits, are characterized by a much higher hydraulic conductivity than the underlying rock mass (Nastev et al. 2001). It is believed that this high hydraulic conductivity is related to a highly fractured and altered zone. At the St-Eustache quarry, hydraulic tests were undertaken on the quarry floor, which has only been exposed recently and where alteration and dissolution of the rock mass is not believed to have played a major role in enhancing the hydraulic conductivity. The stress release in all directions due to decompression is thus a much more probable phenomenon.

The vertical joints, in conjunction with the generally low hydraulic conductivity bedding planes, are believed to provide the storage capacity of the aquifer and permit leakage to the high conductivity bedding planes. As mentioned previously, Odling et al. (1999) suggest that an REV can be defined and the rock mass can be treated as an equivalent porous medium (EPM) approach when the REV is one to two orders of magnitude larger than the mean spacing of the fractures. For the St-Eustache quarry, the mean fracture spacing of each of the fracture sets is around 1 m but when all fractures are pooled, the spacing is around 0.5 m. Using the results from Odling et al. (1999), an EPM for the low hydraulic conductivity fractures could thus be attained for domains of 5 by 50 m sides, which corresponds approximately to the scale of the site. However, it has been shown here with the pumping test simulation that, although the fractured rock mass containing low-permeability vertical and horizontal fractures can be represented by an equivalent porous medium, the two high-permeability bedding planes need to be explicitly included in the discrete-fracture model to reproduce the hydraulic test results.

Since the fractures for all rock formations in the region have the same pattern as those observed in the quarry, field and regional studies can potentially be based on an EPM approach according to the Odling et al. (1999) criterion. On the other hand, the St-Eustache site study indicates the impact of single bedding planes on the flow regime. Thus, at the field scale, a high conductivity bedding plane may also exist and must be identified and considered in any groundwater flow study, while at the regional scale, the impact of such planes is not yet understood. The conceptual model at the St-Eustache quarry site could be applied to the regional scale, and would imply a layered aquifer system because of the presence of high conductivity bedding planes and zones of low hydraulic conductivity.

The horizontal fracture located at 24 m in the St-Eustache quarry site study has been observed in each of the three boreholes, which are less than 20 m apart. Although horizontal fractures are continuous at the scale of the quarry (1 km long), there is no data indicating that they maintain a high conductivity at that scale. Also, high hydraulic conductivity zones observed in single borehole tests during the regional project have not been tested for lateral extent, since these boreholes are too far apart. Novakowski et al. (1999) studied the hydraulic properties of a fractured dolostone in Ontario, Canada, in a sedimentary sequence similar to that studied here. They conclude that horizontal fractures constitute the preferred flow paths in the dolostone, similar to the present study, and they have identified five high-permeability horizontal fractures that are continuous over a distance of 125 m. Although no extrapolation of fracture trace lengths can be made over that distance, it is known that the bedding planes continue through interconnection over great distances.

Michalski and Britton (1997) also recognize the importance of bedding planes in the hydrogeology of sedimentary basins. They suggest using more than one characterization method to locate the bedding planes and build a realistic conceptual model. They also state that the mathematical models currently used to design remediation efforts in fractured sedimentary rock do not correctly account for heterogeneities. These models are based on an EPM approach, a two-aquifer EPM approach, or on a model with anisotropy due to subvertical joints. Michalski and Britton (1997) promote using a leaky multi-unit aquifer system, which is a set of bedding planes with high hydraulic conductivity separated by lower hydraulic conductivity aquitards. This is a model similar to that applicable at the St-Eustache quarry, where discrete major bedding planes form the aquifer units, with vertical joints that provide leakage between the main aquifers. Michalski and Britton (1997) illustrated, with a pumping test, that some bedding planes have a high hydraulic conductivity for distances of at least 500 m. These results suggest that the horizontal bedding planes may behave in a similar fashion in the region of our study. Results from field scale studies could thus be affected by such bedding planes and they therefore must be identified.

Conclusions

Two types of fractures influence the hydraulic properties of the rock mass at the St-Eustache quarry: vertical joints and horizontal bedding planes. The vertical joints terminate on the bedding planes to form a stratabound network. The use of more than one investigation method was crucial for building a strong conceptual model of groundwater flow in the St-Eustache quarry. This site scale study showed that the most important features to identify in the aquifer are the bedding planes. Some of the bedding planes have a high hydraulic conductivity, and because of their large extent, they represent major groundwater flow paths. Vertical joints and other horizontal bedding planes are well connected but exhibit a hydraulic conductivity value lower than that of the more permeable horizontal bedding planes. The matrix is considered impervious, so the rock mass can be classified as “purely” fractured. According to the scaling classification for stratabound systems proposed by Odling et al. (1999),

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the rock mass could be considered as an equivalent porous medium at a scale of at least 5 m.

Two high-permeability bedding planes have been identified at depths of 13 and 24 m. The conceptual model for the site suggests a layered aquifer system consisting of low hydraulic conductivity zones and high hydraulic conductivity bedding planes that show a contrast of three orders of magnitude in hydraulic conductivity. The bottom of the rock mass is a low hydraulic conductivity bedding plane zone up to a depth of 24 m. This bedding plane is overlain by a low hydraulic conductivity zone which is in turn overlain by a high hydraulic conductivity bedding plane located at 13 m. The upper part of the rock mass is an unconfined aquifer where both horizontal and vertical fractures have high hydraulic conductivity.

The vertical joints play a minor role for groundwater flow because of their limited extent. To provide a significant flow path in the rock mass, the bulk permeability of the vertical joints must be greater than that generally observed in the rock mass. Enhanced permeability of these joints could potentially occur where dissolution and fracturing is more intense, as seen in the first surficial meters of the bedrock everywhere in the region or at stress release locations such as near the surface in the St-Eustache quarry.

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References

Bear J (1993) Modeling flow and contaminant transport in fractured rocks. In: Bear J, Tsang C-F, de Marsily G (eds) Flow and contaminant transport in fractured rock. Academic Press, pp 1–37

Cooper HH, Jacob CE (1946) A generalized graphical method for evaluating formation constants and summarizing well field history. Am Geophysl Union Transa 27:526–534

Davis GH, Reynolds SJ (1996) Structural geology of rocks and regions, 2nd edn. John Wiley and Sons, New York, 776 p.

Etienne M (2002) Caractérisation in situ des milieux fracturés à l'aide de diagraphies géophysiques. [In situ caracterization of fractured media using well logging techniques] Master's thesis, Université Laval, Québec, Canada

Globensky Y (1987) Géologie des Basses-Terres du Saint-Laurent. MM 85-02, Ministère de l'Energie et des Ressources, Québec

Hantush MS (1956) Analysis of data from pumping tests in leaky aquifer. Trans Am Geophys Union 32:702–714

Hantush MS (1960) Modification of the theory of leaky aquifer. J Geophys Res 65:3713–3725

Lapcevic PA, Novakowski KS, Sudicky EA (1998) Groundwater flow and solute transport in fractured media. In: Delleur JW (ed) The handbook of groundwater engineering. CRC Press, pp 17–39

Lemieux J-M (2000) Caractérisation structurale locale et régionale des aquifères fracturés du Sud-Ouest du Québec. [Local and regional structural characterization of southwestern Québec fractured aquifers] B.Sc. thesis, Département de géologie et génie géologique, Université Laval, Québec, Canada

Lemieux J-M (2002) Caractérisation multiapproche à petite échelle de l'écoulement de l'eau souterraine dans un aquifère carbonaté fracturé et implications pour les changements d'échelle. [Small-scale study of groundwater flow in a fractured carbonate aquifer and implications for upscaling.] Master's thesis, Université Laval, Québec, Canada

Michalski A, Britton R (1997) The role of bedding fractures in the hydrogeology of sedimentary bedrock—Evidence from the Newark basin, New Jersey. Groundwater 35:318–327

Muldoon MA, Simo JAT, Bradbury KR (2001) Correlation of hydraulic conductivity with stratigraphy in a fractured-dolomite aquifer, northeastern Wisconsin, USA. Hydrogeol J 9:570–583

Narr W, Suppe J (1991) Joint spacing in sedimentary rocks. J Struct Geol 13:1037–1048

Nastev M, Savard MM, Lapcevic P, Paradis D, Lefebvre R, Martel R (2001) Investigation of hydraulic properties of regional fractured rock aquifers. In: 2nd Joint CGS-IAH Groundwater Speciality Conference, pp 1058–1066

Novakowski KS (1989) Analysis of pulse interference tests. Water Resou Res 25:2377–2387

Novakowski KS, Lapcevic PA (1988) Regional hydrogeology of the Silurian and Ordovician sedimentary rock underlying Niagara falls, Ontario, Canada. J Hydrolo 104:211–236

Novakowski K, Lapcevic P, Bickerton G, Voralek J, Zanini L, Talbot C (1999) The development of a conceptual model for contaminant transport in the dolostone underlying Smithville, Ontario. NWRI Contribution 99–250, National Water Research Institute

NRC (1996) Rock fractures and fluid flow: Contemporary understanding and applications. National Research Council, Committee on Fracture Characterization and Fluid Flow

Odling NE, Gillespie P, Bourgine B, Castaing C, Chilés J-P, Christensen NP, Fillion E, Gender A, Olsen C, Thrane L, Trice R, Aarseth E, Walsh JJ, Watterson J (1999) Variations in fracture system geometry and their implications for fluid flow in fractured hydrocarbon reservoirs. Petrol Geosci 5:373–384

Piggott AR, Huynh TNT, Lapcevic PA, Novakowski KS (1995) Automated analysis of hydraulic and tracer tests conducted in fractured rock. NWRI contribution 95-28, Nat Water Res Inst

Ramsey JG, Huber MI (1987) The techniques of modern structural geology, vol. 2. Academic Press

Savard MM, Nastev M, Lefebvre R, Martel R, Fagnan N, Bourque E, Cloutier V, Lauzière K, Gélinas P, Kirkwood D, Lapcevic P, Karanta G, Hamel A, Bolduc A, Ross M, Parent M, Lemieux J-M, Boisvert E, Salad Hersi O, Lavoie D, Girard F, Novakowski K, Therrien R, Etienne M, Fortier R (2000) Regional hydrogeology of fractured rock aquifers in southwestern Québec (St.Lawrence Lowlands). In 1st Joint CGS-IAH Groundwater Speciality Conference, pp 247–253

Terzaghi RD (1965) Sources of errors in joint surveys. Geotechnique 15:287– 304

Theis CV (1935) The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage. Am Geophys Union Trans 2:519–524

Therrien R, Sudicky EA (1996) Three-dimensional analysis of variably-saturated flow and solute transport in discretely-fractured porous media. J Contam Hydrol 23:1–44

Therrien R, Sudicky EA (2000) Well bore boundary conditions for variably saturated flow modeling. Ad Water Resou 24:195–201

UNESCO (1984) Guide to the hydrology of carbonate rocks. Stud Reports in Hydrol

Walton WC (1962) Selected analytical methods for well and aquifer evaluation. Ill State Water Sur Bulletin 49

DOI 10.1007/s10040-005-0457-2