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Developing conceptual hydrogeological model for Potsdam sandstones in southwestern Quebec, Canada

M. Nastev · R. Morin · R. Godin · A. Rouleau

Abstract A hydrogeological study was conducted in Potsdam sandstones on the international border between Canada (Quebec) and the USA (New York). Two sandstone formations, arkose and conglomerate (base) and well-cemented quartz arenite (upper), underlie the study area and form the major regional aquifer unit. Glacial till, littoral sand and gravel, and marine silt and clay discontinuously overlie the aquifer. In both sandstone formations, sub-horizontal bedding planes are ubiquitous and display significant hydraulic conductivities that are orders of magnitude more permeable than the intact rock matrix. Aquifer tests demonstrate that the two formations have similar bulk hydrologic properties, with average hydraulic conductivities ranging from 2×10^{-5} to 4×10^{-5} m/s. However, due to their different lithologic and structural characteristics, these two sandstones impose rather different controls on groundwater flow patterns in the study area. Flow is sustained through two types of fracture networks: sub-horizontal, laterally extensive fractures in the basal sandstone, where hydraulic connectivity is very good horizontally but very poor vertically and each of the water-bearing bedding planes can be considered as a separate planar two-dimensional aquifer unit; and the more fractured and vertically jointed system found in the upper sandstone that promotes a more dispersed, three-dimensional movement of groundwater.

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Résumé Une étude hydrogéologique a été entreprise dans les grès de Potsdam, sur la frontière entre le Canada (Québec) et les Etats-Unis (New York). Sous le secteur d'étude, deux formations gréseuses, les arkoses et conglomérats (base) et les arénites quartzeuses cimentées (sommet), forment une unité aquifère majeure à l'échelle régionale. Les moraines glaciaires, les sables et graviers littoraux, et les argiles et silts marins recouvrent l'aquifère de manière discontinue. Dans les deux formations gréseuses, les litages sub-horizontaux sont omniprésents, et présentent des conductivités hydrauliques significatives, supérieures de plusieurs ordres de grandeur à celles de la matrice rocheuse intacte. Les pompages d'essai démontrent que les deux formations ont des propriétés hydrologiques apparentes comparables, avec notamment des conductivités hydrauliques comprises entre 2×10^{-5} et 4×10^{-5} m/s. Cependant, du fait de leurs lithologies et de leurs caractéristiques structurales contrastées, ces deux formations gréseuses imposent des contrôles différents sur les écoulements souterrains dans le secteur d'étude. L'écoulement est soutenu par deux types de réseaux de fractures : des fractures latéralement extensives sub-horizontales dans les grès de base, où la connectivité hydraulique est très bonne horizontalement mais médiocre verticalement, et où chacun des plans aquifères peut être considéré comme une unité aquifère isolée plane bidimensionnelle, et un système fissuré verticalement et plus fracturé situé dans les grès supérieurs, qui favorise des écoulements souterrains tridimensionnels et plus dispersés.

Resumen Se realizó un estudio hidrogeológico en las areniscas Potsdam sobre el límite internacional entre Canadá (Quebec) y Estados Unidos de América (Nueva York). Dos formaciones de arenisca, arkosa y conglomerado (en la base) y arenita de cuarzo bien cementada (en la cima), componen el área de estudio y forman la principal unidad regional de acuífero. Conglomerado glacial, grava y arena litoral, y arcilla y limo marino sobreyacen discordantemente el acuífero. En ambas formaciones de arenisca existen abundantes planos de estratificación subhorizontales que muestran conductividades hidráulicas significativas que son varios órdenes de magnitud más permeables que la matriz de roca intacta. Las pruebas de acuífero demuestran que las dos formaciones tienen propiedades hidrológicas globales similares, con conductividades hidráulicas promedio que varían de

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2×10^{-5} a 4×10^{-5} m/s. Sin embargo, debido a diferencias litológicas y características estructurales, estas dos areniscas imponen controles muy distintos en los patrones de flujo de agua subterránea en el área de estudio. El flujo es sostenido a través de dos tipos de redes de fracturas: fracturas subhorizontales lateralmente extensivas en la arenisca basal, donde la conectividad hidráulica es muy buena horizontalmente pero muy pobre verticalmente y cada uno de los planos de estratificación acuíferos puede ser considerado como una unidad acuífero en 2 dimensiones plana y separada; y el sistema de fracturas verticales que se encuentra en la arenisca superior que promueve un movimiento de agua subterránea más disperso en 3 dimensiones.

Keywords Canada · Sedimentary rocks · Conceptual models · Geophysical methods

Introduction

The study area coincides with the lateral extent of the Potsdam sandstones in southwestern Quebec (Canada) and encompasses Covey Hill, which spreads over the international border with the USA, and the Rocher Plateau extending northward toward the Chateauguay River (Fig. 1). It is bounded along the contact between two distinct physiographic provinces: from the southern margin of the St. Lawrence Lowlands platform to the north-western margin of the Champlain Lowlands, and then to the north-eastern piedmont of the Adirondack uplands.

Covey Hill is an elongated E−W morphological feature approximately 20 km long and 10 km wide. It comprises rocky outcrops of relatively flat-bedded sandstone forming a series of sub-horizontal terraces or irregular masses of glacial debris (Clark 1966; Globensky 1987). The maximum altitude of Covey Hill is 340 masl. To the north and east, the terrain descends relatively abruptly with slopes reaching more than 10% in the direction of the St. Lawrence and Champlain plains. To the south, the relief is more subdued and evolves from undulating to mountainous. The Rocher Plateau is a circular belt of discontinuous rock outcrops of horizontal sandstone pavement eroded by the glaciers and meltwater. The regional drainage forms part of the radial drainage

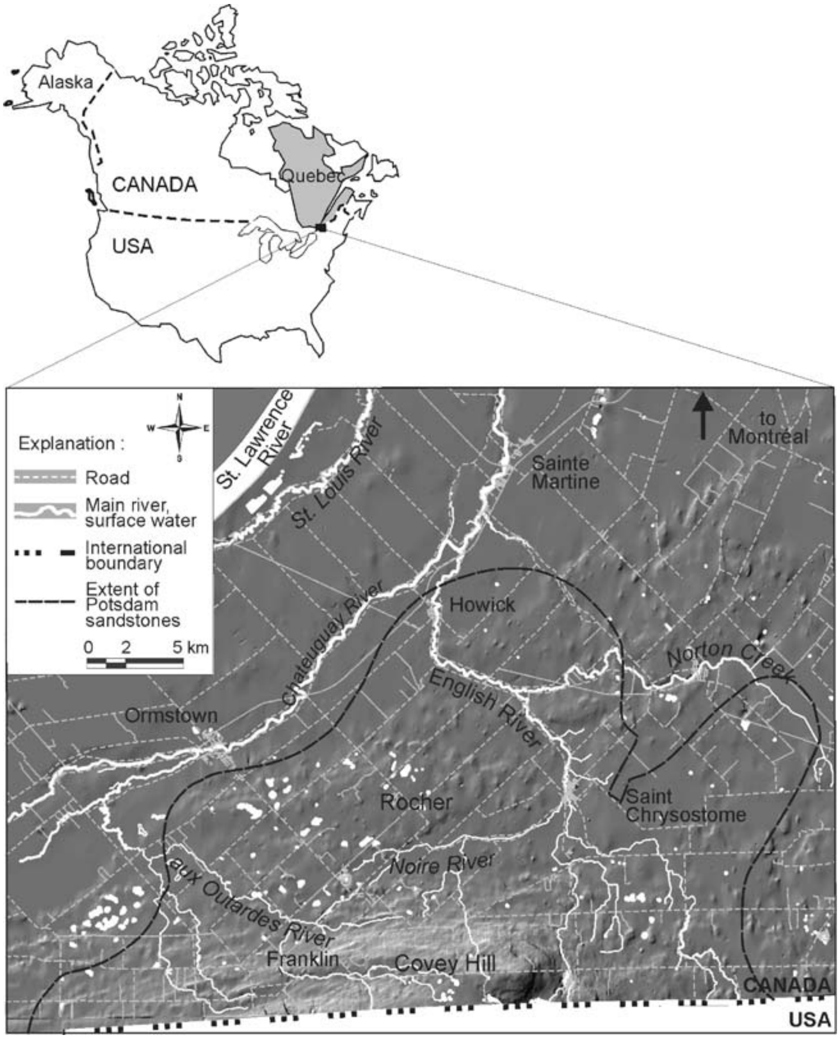

Fig. 1 Location of the study area. The *black bold dashed line* indicates the surficial extent of the Potsdam sandstones

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network originating at the Adirondack Uplands. This drainage system is relatively sparse on Covey Hill proper, where coarser unconsolidated sediments at the surface (reworked till) seem to have a high capacity to accumulate precipitation waters. With few exceptions, the drainage of surface water occurs mainly by infiltration and subsequent sub-surface runoff and groundwater flow. On the Rocher Plateau, numerous lakes and wetlands are disposed at altitudes ranging primarily between 60 and 80 masl. They provide a surface expression of the intense runoff and discharge processes taking place at Covey Hill (Nastev et al. 2004).

With an approximate population density of 10–20 persons per km^2, the study area represents a relatively sparsely populated, rural region that depends entirely on groundwater for its source of potable water. Although unfit for large-scale farming, this stony region is ideally suited for apple orchards and sugar-maple groves. Other agricultural activities include mainly dairy and livestock farming, equine centers, and vegetable and small fruit growing (Dagenais and Nastev 2005). The intensive application of fertilizers, herbicides and pesticides to fruit trees may potentially contribute to the alteration of the groundwater quality. The increasingly popular planting of dwarf apple trees, perfectly adapted to the shallow soils and rock outcrops, represents an additional stress on groundwater resources as these plants require almost daily watering during the hot summer months.

Historically, the Potsdam sandstones have been renowned for their good quality water and, currently, one local company withdraws groundwater for bottling; two other commercial applications are under evaluation (Nastev et al. 2004a). In addition, Covey Hill is the sole region in Canada where Mountain Dusky salamanders are found. Their habitat, in the vicinity of natural springs, small creeks and seepage areas, is threatened by continued deforestation, and by agricultural and industrial activities (see URL, Environment Canada 2006). Despite the relative abundance of potable water in the region, the steady increase in groundwater use (Dagenais and Nastev 2005) combined with prolonged drought conditions evident over the last several years, have contributed to occasional shortages and potential disputes between various users who share the heavily exploited areas. Currently, the lack of a general understanding regarding the underlying hydrologic system and the availability of good quality groundwater precludes the formulation of suitable management plans by local water authorities.

The Quaternary sediments and the bedrock impose several distinct modes of hydrogeologic control that, when integrated, define the general hydrologic characteristics in the region. Coarse littoral sediments (reworked till), due to their relatively high porosity and hydraulic conductivity, are characterized with relatively low rates of surface runoff and high rates of infiltration and sub-surface runoff (Tremblay and Lamothe 2005; Croteau et al. 2005). The study area represents a major recharge zone for the regional aquifers found in the fractured rock units and, simultaneously, is an area that has a relatively high potential for surface contamination. The primary sandstone units have different structural characteristics as well and differ in the way they control the flow of groundwater (McCormack 1981; Lavoie 2005).

This study reviews the current state of knowledge regarding the groundwater resources of the Covey Hill area and reports on the results of a hydrogeological study recently undertaken to improve our conceptual understanding of the underlying hydrologic system (Nastev et al. 2004a).

Geology

Bedrock geology

The stratigraphic framework and structural geology of the study area is based primarily on fieldwork conducted by the Quebec Department of Natural Resources over a circa 20-year period (Clark 1966; Wiesnet and Clark 1966; Globensky 1987) and subsequent thematic studies concerned with the region's tectono-stratigraphic framework (Salad Hersi et al. 2002). The bedrock consists of Lower Paleozoic sedimentary rocks that overlie an uneven surface of crystalline rocks of Precambrian age. There are substantial differences among investigators over the precise definition of the lithology and spatial extent of the sedimentary units. The official bedrock map of the Quebec Department of Natural Resources (Globensky 1987) is referenced here for the purposes of this study (Fig. 2a). The bedrock structure, however, as described by Clark (1966) and by Wiesnet and Clark (1966), seems to better represent field observations and is used for the cross section presented in Fig. 2b (Lavoie 2005).

The oldest Paleozoic formation is the Covey Hill sandstone of the Potsdam Group. It is composed of interbeds of locally conglomeratic fine to commonly coarse-grained quartz (>50%) and feldspar (<50%), with some mudrock and pebbles. Locally, thin (≤5 m) fossiliferous and dolomitic sandstone unit was identified by Clark (1966) as Rivière aux Outards member at the top of this formation. Red shales are often found at the base of the Covey Hill formation. Compact beds are massive with a thickness of usually several tens of centimetres to a metre, but can also reach 2 m. In many places but mostly in lower beds, it can be conglomeratic with quartz pebbles as large as 2.5 cm and feldspar as large as 1.2 cm (Clark 1966). This rock has many varieties: white, gray to reddish-brown due to the presence of iron minerals in the cementing materials. These minerals influence the groundwater quality as well. The cementation in Covey Hill sandstones varies from loose to strong, and rocks can occasionally be very poorly consolidated and friable.

The upper part of the Potsdam Group is comprised of the Cairnside formation. It consists of crossbedded homogeneous light grey to creamy white quartz arenite (~98%) at the base and similar upper quartz arenite with subordinate interbedded dolomitic sandstone (Clark 1966; Globensky 1987). The grains are well-graded, rounded and well-cemented with siliceous cement or rarely with

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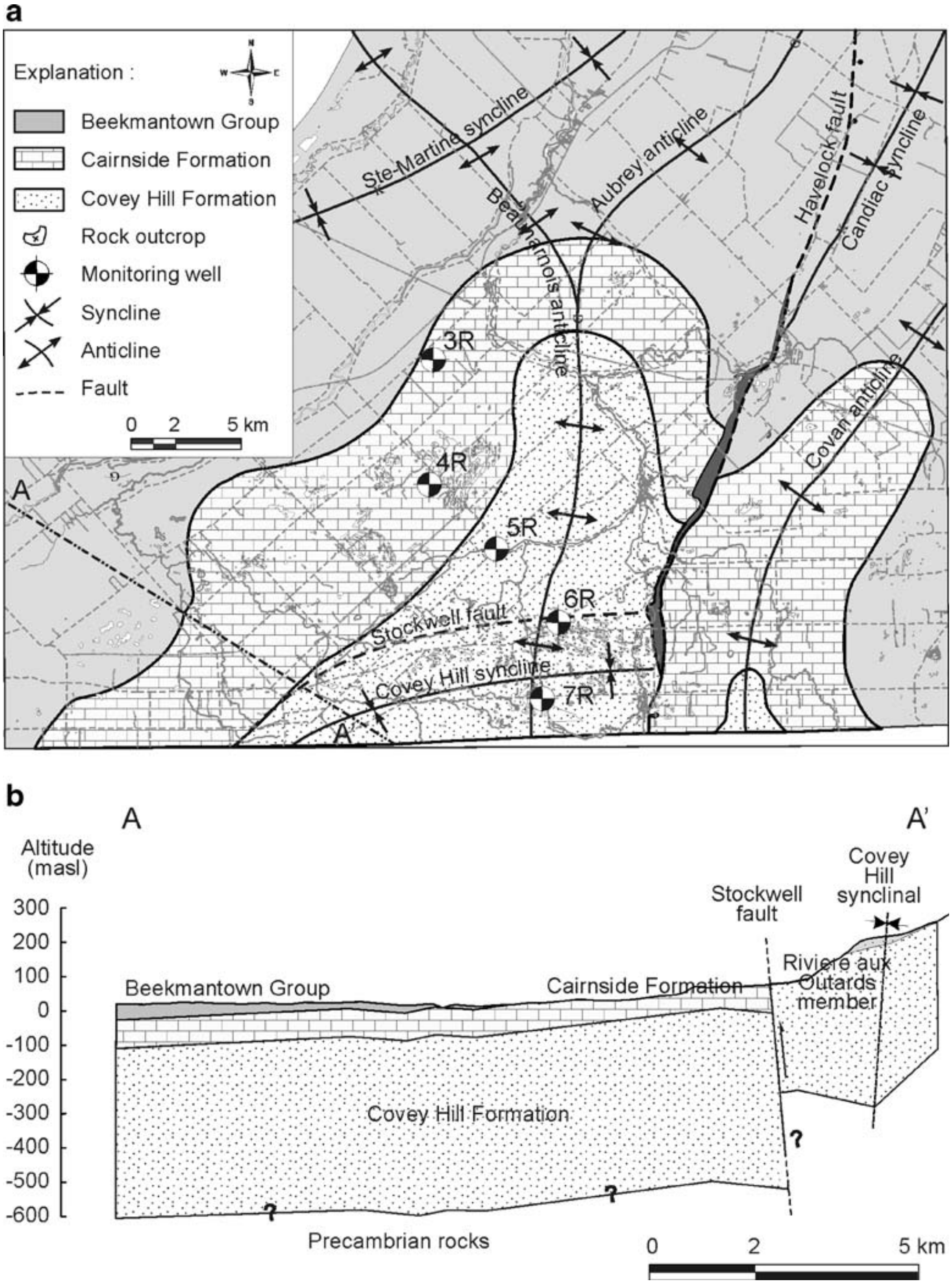
Fig. 2 **a** Bedrock map (modified from Globensky 1987, and Clark 1966), and location of monitoring wells; **b** Cross section (modified from Lavoie 2005)



dolomitic cement (in its upper part). Cairnside sandstone typically is relatively thin bedded, with most beds less than 15 cm thick and rarely reaching 60 cm. Thicker beds are usually more resistant and stand out as continuous escarpments. This is noticeable at sloping topography where harder beds form step-like elevation changes which give an undulating shape to the ground surface. Based on drilling experience, Cairnside sandstone is the hardest sedimentary rock in the region.

Bedrock folds and faults, mainly developed by E−W compression during the Appalachian orogenies, locally complicate aquifer geometry. As most of the tectonic elements trend northerly, regional compression was imposed in an E−W direction (Wiesnet and Clark 1966). On Covey Hill proper, sandstone beds are disposed along a synclinal axis plunging W−SW. Located a few kilometres to the north is the Stockwell fault, striking in an E–NE direction. This feature bounds Covey Hill on the north and is manifested as a reverse fault, thereby indicating significant compression (Lavoie 2005). The Stockwell fault accounts for the relatively abrupt-sloping terrain on the northwestern flanks of Covey Hill. Since the sandstone beds remain horizontal to sub-horizontal in this area, this fault represents a significant upward displacement of the

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southern block elevating the Covey Hill formation to its present outcroping level. To the east, Covey Hill is bounded by the Havelock fault which forms an important synclinal feature to the north but that gradually dies out to the south (Wiesnet and Clark 1966). The vertical displacement along the Havelock fault is estimated to be between 400 and 500 m (Clark 1966). Large blocks and angular fragments of Potsdam sandstones and brecciated carbonate rocks are aligned with this fault (Lavoie 2005). Two major anticlines border the Havelock fault to the east and to the west, plunging north and north-east. Several other low intensity folds are also observed. The relatively weak regional tectonics result in horizontal to sub-horizontal bedding planes with very low dips of 1–3° in general; along the hill slopes, dips can reach 4–5° (Clark 1966). The thickness from exposed field sections and cores for the Covey Hill ranges from 200 up to 500 m. The thickness of the Cairnside is more uniform reaching approximately 100 m.

Surficial sediments

Surficial sediments have been extensively studied recently by Tremblay and Lamothe (2005). Glacial till represents a regional unit as it covers the entire study area in a more or less continuous layer. It is in direct contact with the bedrock and underlies fine lacustrine and marine sediments found further northward (Fig. 3). The density and compaction of the till systematically increase with depth in such a way that drillers are often uncertain as to where bedrock is initially encountered at the base of a well. Glacial sediments are far from uniform and consist of coarse to bouldery materials completely surrounded by fine matrix. However, lenses of coarser sandy and gravely materials are often penetrated during drilling. These thin interbedded lenses are typically up to 1~2 m thick and may represent a potential low yield water-bearing unit sufficient for domestic water supply.

Due to its relative position in the vertical stratigraphy and its lateral extent, the hydrologic properties of till control most of the recharge in the study area. The arrest of the southward advance of the glaciers and the subsequent deglaciation processes were followed by the formation of the postglacial lakes and sea. The fresh glacial and marine waters reworked the upper part of the original glacial material and washed out a variable portion of fine particles. Such littoral sands and gravels are found around Covey Hill at altitudes ranging between 70 and 165 masl (Tremblay and Lamothe 2005), where their thickness can reach as much as 5–10 m. In general, they are in discontinuous contact with the bedrock. To the west, these coarse sediments are underlain by a compact till layer and, on the northeastern slopes of Covey Hill, they are often in direct contact with the bedrock. Between these two locations, a discontinuous till layer is found between the littoral sediments and bedrock.

Silty and clayey soils in the region were deposited in standing bodies of water during and after the glacial retreat. They are regularly found at altitudes of less than 60 m and in small depressions between the drumlin hills. These fine-grained materials represent a confining unit that, when present, hinders hydraulic communication between the aquifer units and the surface water network. The vertical flux through these sediments is thought to be minimal. Occasionally, the landscape contains closed depressions, a consequence of poor drainage through glacial tills. These depressions often remain filled with water following important precipitation events and/or rapid snowmelt, producing erosion and sedimentation of fine particles. Since glacial retreat, such conditions have

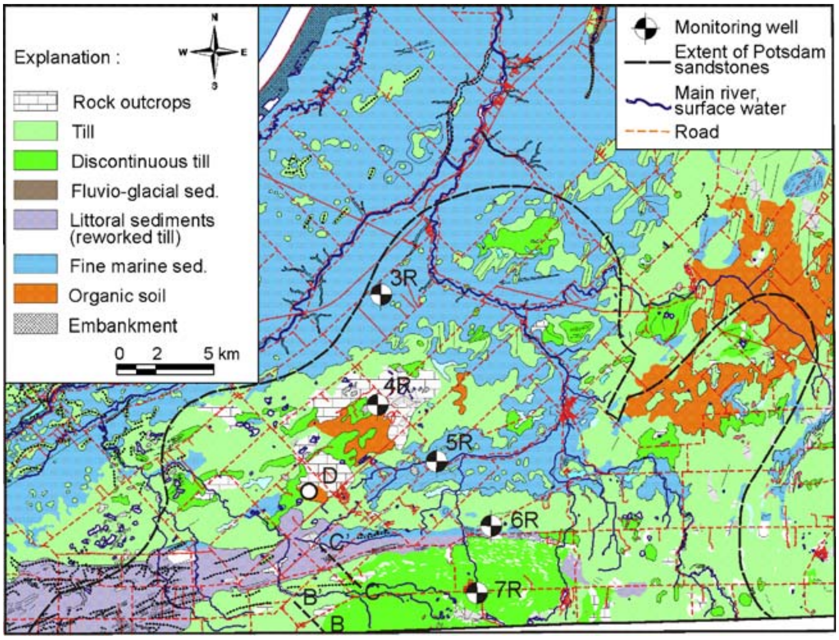

Fig. 3 Map of surficial sediments, along with locations of monitoring bedrock wells, pumping site, and cross sections (explained further in the text). *Black bold dashed lines* indicate the extent of Potsdam sandstones. The locations of the five monitoring bedrock wells (*3R*–*7R*) installed during this study are also shown. *B*–*B*′, *C*–*C*′ and *D* indicate locations of pumping tests discussed further in the text

resulted in the creation of bogs and wetlands, and in the accumulation of organic plant material surrounding and progressively spreading over the body of open water.

Hydrogeology

Groundwater levels

A regional potentiometric map (Fig. 4) was generated based on 150 field measurements of water levels in bedrock wells obtained during a regional survey performed in 2003, data collected from drillers' logs, and data for surface water elevations (Benoît et al. 2005). The potentiometric surface closely drapes the major topographic features: it has a dome shape originating at Covey Hill and discharges radially toward the Rocher plateau and the Chateauguay River further to the north, the aux Outardes River to the west, and the English River to the east. At topographic highs, depth to water occasionally attains several tens of metres and, close to the summit of Covey Hill, groundwater elevations reach approximately 250–300 masl. An important seepage zone was observed N–NE of Franklin near the Stockwell fault at an altitude of approximately 100–110 masl. This is a source area for the Noire River. Hydraulic gradients weaken near the Rocher plateau where the regional potentiometric levels stabilize at altitudes of 60–80 masl and flow becomes nearly horizontal. Further downgradient in the discharge zone, water levels are much closer to the ground surface and fluctuations are dampened.

On Covey Hill, bedrock water levels are strongly dependent upon the depth of individual wells. Due to the downward flow (recharge), wells intercepting deeper rock units (50~100 m) record deeper water levels, whereas water levels in shallower bedrock wells (<20 m) are closer to the ground surface. Thus, using the difference in the observed charges of two neighbouring wells as nominator in the hydraulic gradient and the vertical distance between the centers of the screened sections (open borehole) as denominator, strong hydraulic gradients have been estimated : i~0.5 at the monitoring well 7R (Fig. 3), and i~1 at the site of the pumping test No. 2 (Fig. 5b).

Besides the effects of topography and hydraulic gradient, groundwater level can be strongly influenced locally by the structure and distribution of bedding planes. Water levels in wells intercepting the same bedding plane remain relatively similar, with a slight slope downhill, even if wells are installed at different altitudes and several hundreds of metres apart (Fig. 5a and b). During drilling and well installation, a shallow water table is usually encountered at the contact between glacial sediments and bedrock. Cascading wells can also be observed in the region, where shallow water infiltrates the well at the base of casing or from the upper bedding plane partings and falls freely along the walls of the well. Depending on the input and output fluxes, a relatively stable but dynamic water level is reached in the open borehole. Occasionally, steep terrain and variable topography contribute to producing upward flow conditions, artesian pressures along bedding planes and flowing wells. Such is the site of the pumping test No. 3 (Fig. 5b).

Groundwater recharge

Recharge from precipitation infiltrating through Quaternary sediments and attaining bedrock aquifers was estimated by Croteau et al. (2005) and Croteau (2006). HELP software (Schroeder et al. 1994) has been used to obtain the spatial distribution of the water budget parameters. HELP simulates a comprehensive set of hydrologic processes on daily basis: surface runoff (SCS curve-number method); prediction of frozen soil conditions

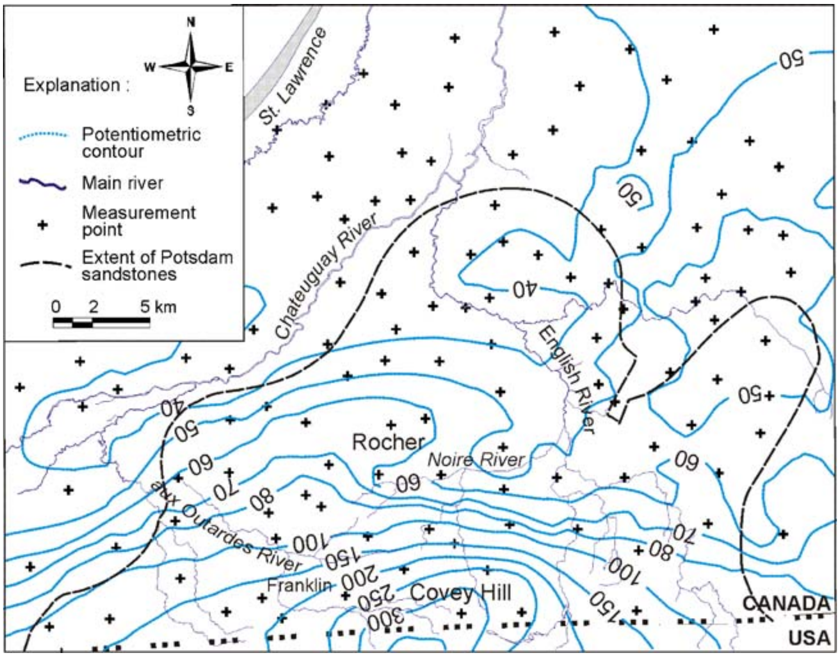

Fig. 4 Regional potentiometric surface

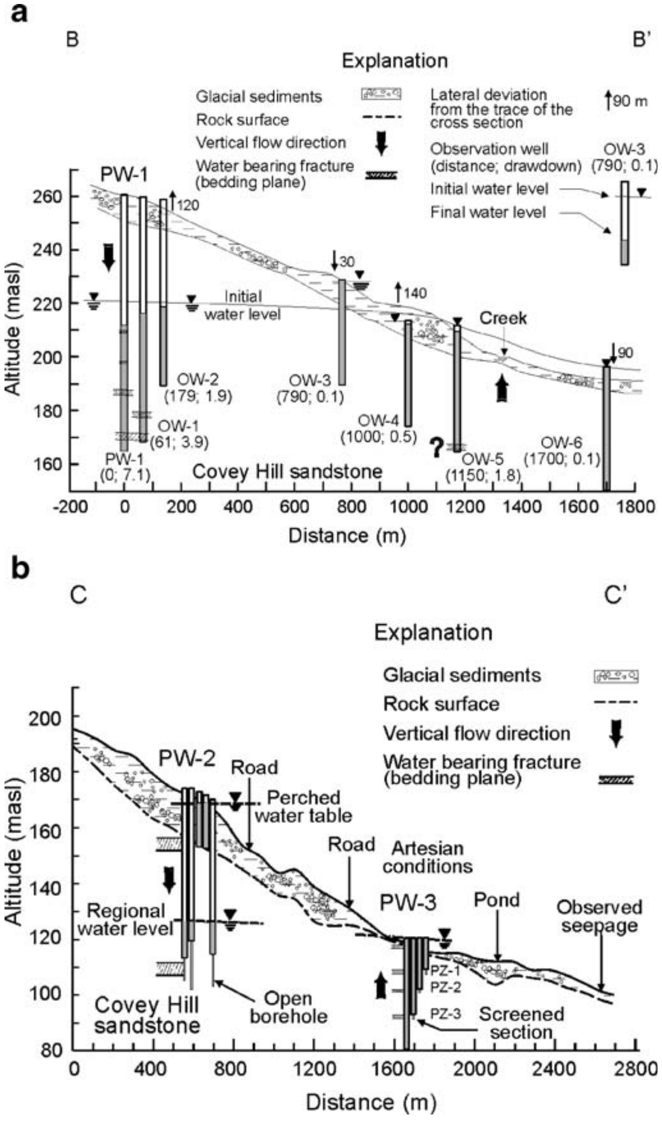

Fig. 5 Diagram of local piezometric levels. **a** Cross sections B–B', and **b** cross section C–C' (shown in Fig. 3). Wells identified as *PW* were used as pumping wells for aquifer tests discussed in text

based on antecedent air temperatures; snow accumulation and melt; rainfall interception by foliage; potential evapotranspiration using the energy-based Penman model (surface and water evaporation and plant transpiration); vegetative growth; gravity driven saturated and/or unsaturated vertical drainage; lateral saturated drainage. The hydrograph separation method provided independent estimates of the bulk water-budget parameters representative for areas upstream of the gauging stations. These were used to calibrate HELP simulations. For the considered period between 1964~2002, the measured average annual precipitation in the study area was 956 mm. The estimated bulk annual rates of the real evapotranspiration, surface runoff and infiltration over the study area were 546, 224 and 186 mm respectively. The calibrated recharge rate to bedrock aquifers was approximately 150 mm. Depending of the type of the unconsolidated sediments overlying the bedrock aquifers, the average recharge rates were: 21 mm for fine marine sediments, 112 mm for glacial sediments, 251 mm for coarse sand and gravel, and 191 mm in areas of shallow glacial sediments and/or rock outcrops (Croteau 2006).

Aquifer hydraulic properties

Existing multi-well pumping tests

Five large-scale, multi-well pumping tests were conducted in the study area by private companies to design groundwater supply systems. Three test sites were set in the Covey Hill formation: pumping test No. 1 (indicated by B–B' line in Fig. 3), and pumping tests No. 2 and No. 3, (indicated by C–C' line in Fig. 3), and the fourth site, where two pumping tests (No. 4 and No. 5) were conducted, is located in the Cairnside formation (indicated by D in Fig. 3). Figures 5a and b show the installation geometry for pumping tests No. 1 through No. 3. Aquifer hydraulic properties were obtained by interpreting the

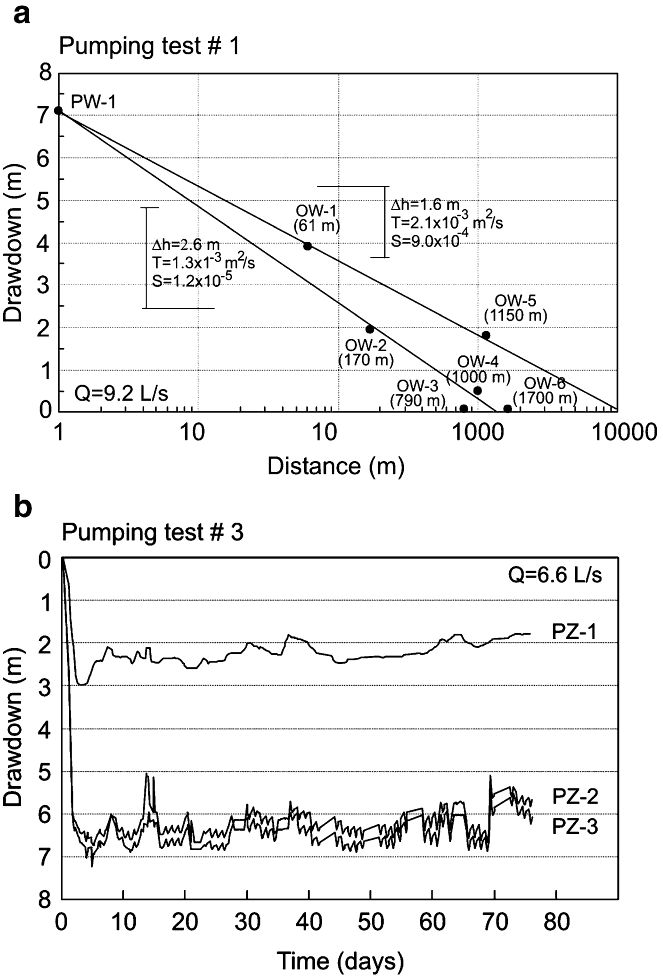

Fig. 6 Drawdown observed during pumping test No. 1 and No. 2 in Covey Hill sandstones. **a** Drawdown measured at the end of the 3-day pumping period of pumping test No. 1; distances to observation wells (*OW*) are given *in parentheses*. Δ*h* is drawdown for log-distance, *T* is transmissivity, *S* is storage coefficient, and *Q* is withdrawal rate. **b** Drawdown variation in three piezometers located 1.5 m from pumping well PW-3

recorded drawdown/recovery curves by using Theis and/or Cooper-Jacob straight line solutions for confined aquifers. Note that for these aquifer tests as well as for the single-well pumping tests discussed next, relatively small drawdown was observed. It occurred mainly in the well casing without observing any 'drying' of the intercepted water bearing bedding planes. Thus, in the applied interpretation methods, the assumption of equivalent porous medium at the test scale appears to be adequate. The obtained results of the multi-well pumping tests indicate transmissivity range of 5.8×10^{-4}~2.6×10^{-3} m/s^2 and storativity range of 5×10^{-5}~4×10^{-4}. What is more important, these tests provided useful information regarding the various interconnections that exist between the bedding planes and the aquifer anisotropy.

Pumping test No. 1. Observed drawdown produced by water extraction in pumping well PW-1 is given in Figs. 5a and 6a. As a result of the imposed constant withdrawal rate of 9.2 L/s, the drawdown in the vicinity of the pumping well PW-1 was ~7 m and the cone of depression decreased logarithmically with distance. The observed aquifer responses strongly suggest that pumping well PW-1 and the observation wells OW-2 and OW-4 on one hand, and OW-1 and OW-5 on the other, intercept same water-bearing bedding planes, which constitute distinct groundwater flow paths of a relatively large lateral extent, more or less isolated from the upper and lower geologic units. The Jacob straight line distance-drawdown method yields two estimates for the aquifer transmissivity and storativity (Fig. 6a). In the first case, the distance at which the pumping is affecting the water levels is approximately 1~1.5 km (OW-2, OW-4), whereas in the second case it may reach several kilometres (OW-1, OW-5). Drawdown is negligible in observation wells OW-3 and OW-6 which appear not to be hydraulically connected to PW-1.

Pumping test No. 2. The pumping well PW-2 and the two bedrock piezometers, distanced 10 and 32 m respectively, were screened over the same sub-horizontal water bearing bedding plane located at approximate depth of 65 m (Fig. 5b). Each bedrock piezometer was doubled with shallow piezometer screened at the bedrock/granular sediments interface to monitor the shallow water table. The applied extraction rate of 3.0 L/s over a period of 72 h generated a drawdown of 3.8 m in the pumped well, and 2.7 and 1.6 m in the bedrock piezometers. At the same time, the shallow piezometers did not show any measurable drawdown, indicating that the top of the bedrock and the granular sediments behave as a perched aquifer and at the test-scale the hydraulic contact with the deeper aquifer unit is insignificant.

Pumping test No. 3. Three major water-bearing bedding planes were intercepted during the drilling of the pumping well PW-3 (Fig. 5b). Three piezometers (PZ) were then installed at the same radial distance of 1.5 m from the pumping well and screened over each of the bedding planes. The hydraulic heads were measured using manometers dedicated to each well. Artesian head is observed at the site, approximately 2 m above ground surface in the deepest bedding plane (PZ-3), and decreasing linearly by 3~4 cm per bedding plane in the upward direction. The drawdown curves recorded by the piezometers show very similar variation, but the magnitudes differ. Figure 6b indicates a particular interconnectivity among bedding planes intercepted by PZ-2 and PZ-3, since these show similar drawdowns. The upper bedding plane intercepted by PZ-1 seems to have a weaker hydraulic contact with the other two. The diurnal (day/night) and weekly (week-end) fluctuations in water levels superimposed upon the typical time/drawdown records are due to the influence exerted by a pumping at a nearby commercial facility. The general decreasing trend of the drawdown by almost a metre over the considered period of 2.5 months is most probably due to the increased autumnal recharge.

Pumping test No. 4 and No. 5. The two aquifer tests undertaken in the Carnside formation (No. 4 and No. 5) consisted of two pumping wells and one observation well between them. The wells were aligned in a N–S direction with distances from the observation well to the pumping wells PW-4 and PW-5 of 350 and 450 m, respectively. The general direction of the groundwater flow is northward and depth to the initial water level is approximately 1.5 m. After 4 days of pumping, an extraction rate of 6.3 L/s in PW-4 produced drawdown of 21 m in the withdrawal well itself and 0.3 m in the observation well. Well PW-5 was pumped at a rate of 15.8 L/s during three days, and this resulted in a drawdown of 15.2 m in the pumped well and 0.5 m in the observation well. Thus, the estimated bedrock transmissivity is approximately 3.5 times greater in the vicinity of well PW-5 than it is near well PW-4, evidence of the heterogeneous nature of these fractured sedimentary rock aquifers.

Single-well pumping tests

Data extracted from the Quebec Ministry of Environment drillers' database provided valuable information about the regional hydraulic properties of the aquifers. The specific capacity of a well, defined as the ratio between the observed yield and the corresponding final drawdown, is usually obtained immediately after the completion of the drilling to determine the potential yield of the well. This data represents only a rough estimate for the aquifer transmissivity and a rigorous screening procedure was needed to eliminate incomplete and potentially erroneous data. The retained dataset consisted of 51 specific capacity data (41 in Cairnside and 10 in Covey Hill). The average well depth was 21 m (6~61 m); the open borehole length varied from 2 to 56 m; the average pumping rate was 1.7 L/s (0.2~19 L/s); the observed drawdown range was 0.3~29 m for an average of 5.3 m; and the test duration varied between 2 and 24 h. The hydraulic conductivity estimation for each measurement was obtained by the computerized technique presented by Bradbury and

Rothschild (1985) based on the Jacob's solution. The obtained range of the hydraulic conductivity was 5.1×10^{-6}~9.9×10^{-4} m^2/s.

During the course of this study, short duration single-well pumping tests were undertaken in four bedrock wells (3R, 4R, 5R, and 6R, Fig. 3). Digital pressure transducers were used to measure water levels during the tests. Pumping tests were interpreted with the Theis solution for confined aquifers, Neuman method with delayed gravity response, and with the Hantush's analytical solution for leaky confined aquifers. For all tests, data interpretation focused on the late drawdown in order to avoid the influence of the well-bore storage.

The same bedrock wells were hydraulically tested with slug tests, and with constant-head injection tests (see the following section). Water displacement curves for the slug tests were interpreted with the Bouwer and Rice method. The combined results for aquifer tests undertaken in the monitoring bedrock wells are given in Table 1.

Packer tests

The bedrock wells 3R through 7R (Fig. 3) were hydraulically profiled by means of a straddle-packer system with a test interval fixed at 3.75 m. Transmissivities from constant-head injection tests were computed using the Thiem equation (Freeze and Cherry 1979). The results show that most transmissivity values fall in the range of 10^{-8}–10^{-3} m^2/s (Fig. 7). Differences between adjacent vertical test intervals in many cases were greater than two orders of magnitude. This suggests that the measured variations in transmissivity are related to abrupt changes in the degree of aperture and/or connectivity between bedding planes and that the groundwater flow at the local scale is controlled by an interconnected network of selected fractures. In other words, the zones of high transmissivity ($>10^{-5}$ m^2/s) are likely dominated by fracture flow, whereas zones of lower transmissivity ($<10^{-7}$ m^2/s) are characterized by a more solid rock mass and the absence of pervasive fracturing. The contribution of the matrix porosity to the groundwater flow can thus been assumed as negligible.

Covey Hill sandstones were identified in wells 5R, 6R, and 7R. The transmissivity of the intact rock, representing the rock matrix interspersed possibly with some micro-cracks, lies in the range of 10^{-8}–10^{-6} m^2/s, with a gradual decrease in magnitude observed with depth. Typically, values on the order of 10^{-6} m^2/s appear in the upper part of the wells and of 10^{-7} m^2/s in the lower part. Cairnside sandstones were tested in wells 3R and 4R. Matrix transmissivity is roughly the same order of magnitude as that of Covey Hill sandstones (~10^{-7} m^2/s). However, bulk transmissivities integrated across the entire depth of the Cairnside wells are generally greater (~10^{-5} m^2/s) than those determined in the Covey Hill sandstones. More details regarding packer testing at this site are reported by Godin and Rouleau (2005).

Table 1 Hydraulic conductivity results in m^2/s obtained from various aquifer tests conducted in the bedrock wells 3R through 7R

Test type /Well	Pumping	Slug	Packer
3R	2.9E-6	7.0E-6	3.7E-6
4R	4.8E-6	3.6E-6	8.8E-6
5R	3.1E-6	8.1E-6	3.5E-6
6R	1.0E-6	–	1.4E-6
7R	–	–	5.7E-6
Mean	1.3E-6	5.9E-6	3.9E-6

Regional hydraulic conductivities

The hydraulic conductivity of bedrock aquifers was derived on the basis of the aquifer tests (multi-well and single-well pumping tests, slug tests, and packer tests) discussed earlier. The range, geometric averages, and spread in hydraulic conductivity are summarized in Fig. 8. Both sandstones display similar overall averages: 2×10^{-5} m^2/s for Covey Hill and 4×10^{-5} m^2/s for Cairnside. Thus, assuming equivalent effective porosities on a regional scale, average groundwater velocities associated with each formation will be over the same order of magnitude. The standard deviations of the log-hydraulic conductivity for the two rock formations are slightly different: 0.85 for Covey Hill compared to 0.7 for Cairnside. This difference can be attributed to the smaller data set but also to the sparser frequency of water-bearing fractures and to the more heterogeneous nature of the Covey Hill rocks.

Flowmeter tests

Ambient flow was measured in wells 3R through 7R using an electromagnetic borehole flowmeter (Young and Pearson 1995). This was done prior to disturbing the flow by pumping in order to investigate the natural flow path. Flow was determined to be downward in wells 6R and 7R, indicating a recharge zone, and upward in well 3R, indicating a discharge zone. No ambient flow could be detected in wells 4R and 5R within the resolution limitations of the tool, and these were considered to be static (horizontal flow). Similarly, initial pressures measured across permeable straddle-packer intervals confirmed that hydraulic conditions were underpressured in wells 6R and 7R (~7 m head below hydrostatic) and overpressured in well 3R (~0.2 m head above hydrostatic). Note, however, that the vertical flow measured with flowmeter tests indicates the existence of the vertical gradient at the well location. The flow itself may be a consequence of the vertical interconnection between the bedding planes allowed by the open borehole of the well.

After ambient flow had been measured, a pump was lowered into each well with the borehole flowmeter suspended below it and the vertical distribution of transmissivity was determined by the flowmeter/pumping technique (Morin et al. 1988; Molz et al. 1989). In this method, the pumping rate at the surface is maintained constant, drawdown is monitored, and vertical flow in the borehole is measured with respect to depth by raising and lowering the flowmeter. These tasks are performed

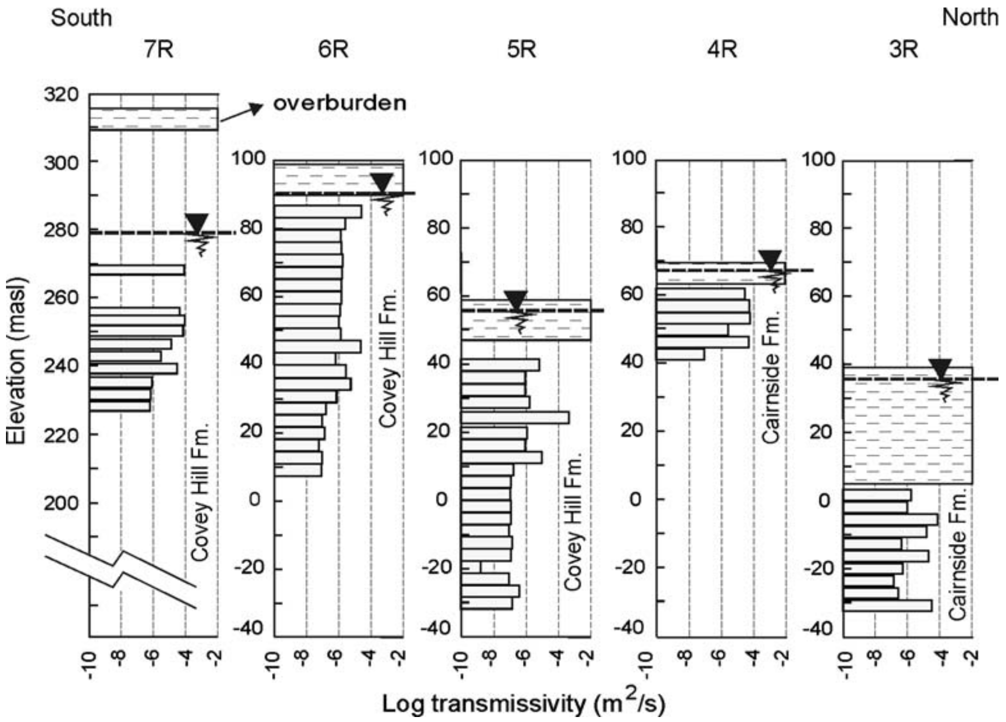

Fig. 7 Results of packer tests for the five rock wells

simultaneously and the transmissivity of individual producing zones is computed using the Cooper-Jacob equation once drawdown has reached a quasi-steady state. Because of inherent resolution limitations of the flowmeter, this method can measure transmissivities over roughly two to three orders of magnitude and detects only the most permeable zones intersecting a well (Paillet 1998).

Estimates of transmissivity are in reasonable agreement (within a factor of about 3) with results obtained from packer tests (Fig. 9). Discrepancies among the values can be attributed to scale effects, measurement resolution of field instrumentation, and well conditions and construction. The flowmeter/pumping method selectively identifies only the most permeable zones. The packer data are in reasonable agreement with these largest values and, moreover, they also quantify much lower transmissivities across numerous other zones. On the other hand, the flowmeter/pumping method is effective in boreholes with highly variable diameters and less-than-ideal installations. This method identified a highly permeable zone directly below casing at 34 m depth where the packer system could not be physically deployed (Fig. 9).

Acoustic televiewer images

Acoustic telewiever logs were recorded in all five R wells (Zemanek et al. 1970). Magnetically oriented, digital images of the borehole walls confirm that fractures intersecting the wells are predominantly horizontal to sub-horizontal (Fig. 10a). Most of the fractures in both sandstones dip gently to the north and are associated with bedding planes and partings. This is illustrated in Fig. 10b by a typical rosette (dip direction) and a lower-hemisphere, equal-area stereographic diagram constructed from contoured poles-to-planes data identified from the televiewer log obtained in well 6R.

Groundwater flow is predominantly controlled by fractures/bedding and permeable fractures are particularly sparse in the Covey Hill sandstones. On average, results of flowmeter tests indicate that only water-bearing fracture appears roughly every 80 m. The frequency with respect to depth of all fractures as determined from inspection of televiewer data in well 6R is approximately 5 per 5 m interval (Figs. 11a, 12). This finding supports Clark's (1966) description of this sandstone, composed of massive beds with a thickness that can reach 2 m. Sub-horizontal fractures are about twice as numerous in the Cairnside

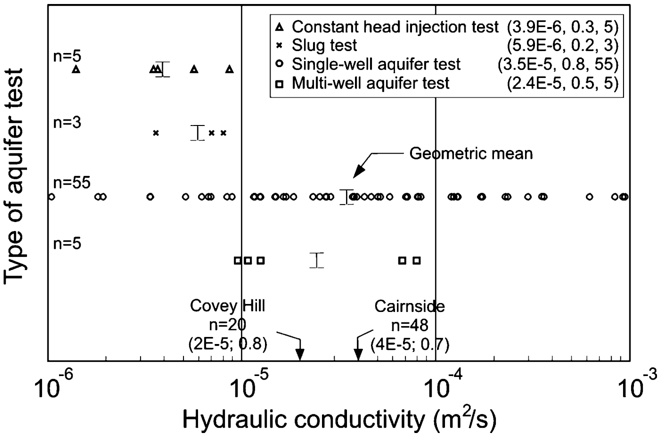

Fig. 8 Hydraulic conductivity results for sandstone aquifers obtained from various aquifer tests. Geometric means for each test type and overall mean values for each formation are given with *arrows*. *Values in parentheses* represent geometric mean and standard deviation of the logarithms; *n* number of data

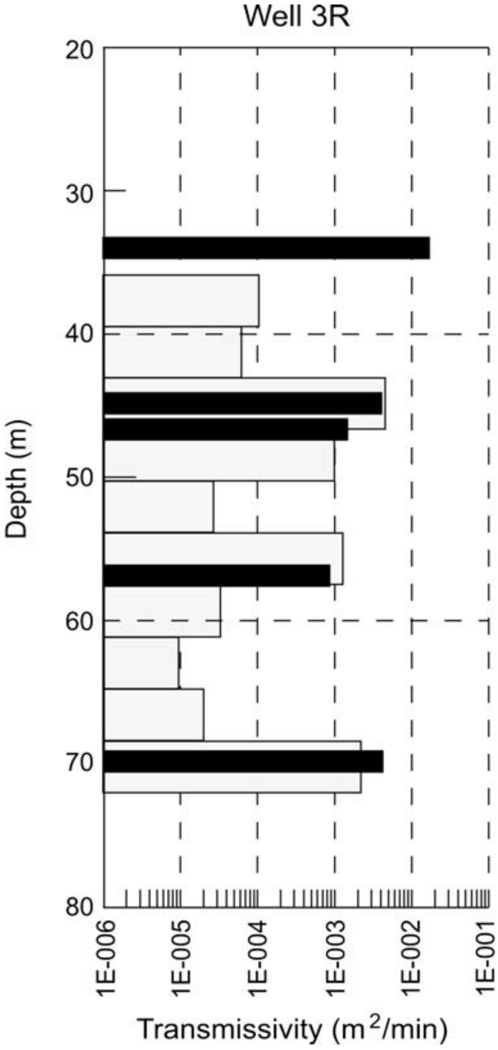

Fig. 9 Transmissivity values for *well 3R* determined from packer tests with 3.75-m straddle interval (*grey*) and computed from the flowmeter/pumping method (*black*)

sandstone, with a frequency of approximately 10 per 5 m interval (Fig. 11b). Moreover, the subset of fractures that are permeable, as identified from flowmeter/pumping tests conducted in well 3R, is significantly more numerous. In the Cairnside rocks, the frequency of water-bearing fractures is roughly 5 permeable fractures per 80-m depth interval, or about 5 times more than in the Covey Hill sandstone.

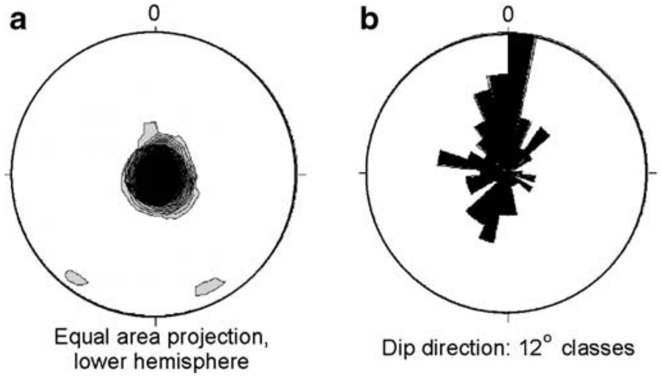

Fig. 10 Typical **a** stereographic diagram showing contoured poles-to-planes fracture orientations, and **b** rosette showing dip directions of planar features identified from televiewer images obtained in well 6R

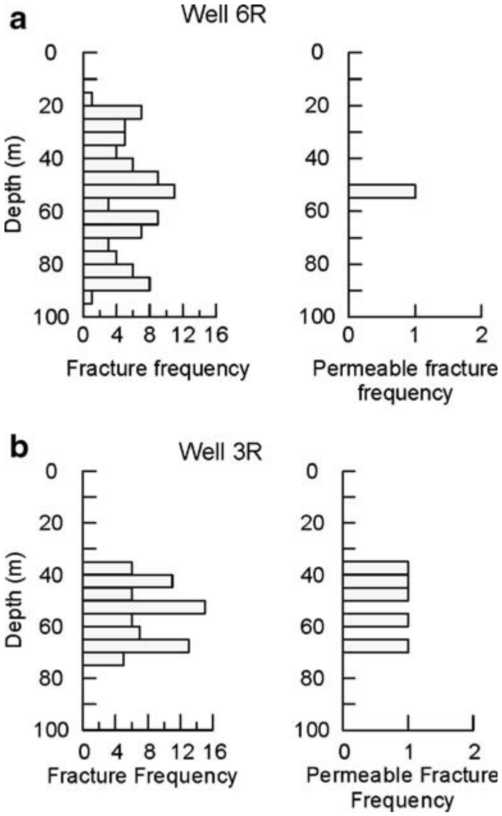

Fig. 11 Frequency of total fracture population (number of fractures per 5 m interval) determined from inspection of televiewer images and frequency of permeable fracture subset only obtained from flowmeter/pumping tests in **a** well 6R (Covey Hill sandstone) and **b** well 3R (Cairnside sandstone)

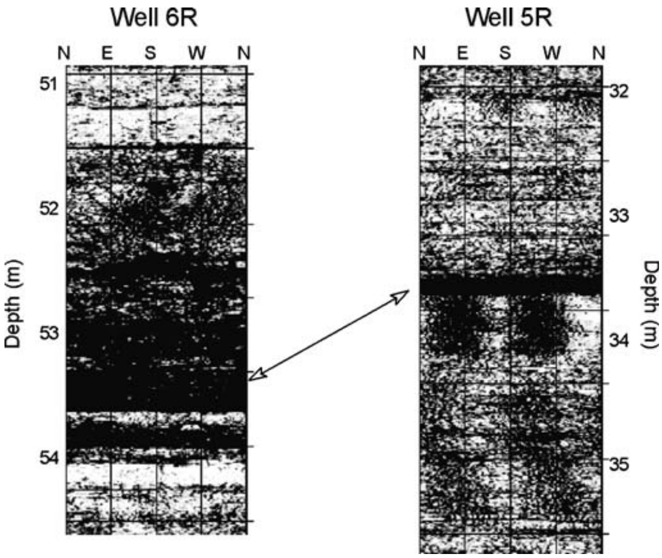

Fig. 12 Televiewer images of same fracture plane (*arrows*) appearing in two wells located 4.5 km apart. Depth offset between wells of 20 m was determined from curve matching of natural gamma logs

Table 2 Chemical data from selected domestic and monitoring wells (data source Blanchette 2006)

Well code	Rock formation	Well depth	Open borehole	Flow condition	Position on the flow path	EC - Electrical conductivity	TDS - Total dissolved solids	Hardness	Alkalinity	Ca	Mg	Na	K	Cl	SO_4	HCO_3	F	Fe	Mn	H_2S	NO_3	Sr	Br
		(m)	(m)			(µS/cm)	(mg/L)	(mg $CaCO_3$/L)		(mg/L)							(ug/L)						
CH-049	Covey Hill	25.9	11.5	SC	U	311	240	128	130	28.6	13.8	11.6	1.0	11	16.9	152.5	39.3	14.2	6.4	1.1	0.1	433.4	3.4
CH-062		36.6	34.4	WT	U	1,389	310	681	93	268.0	2.8	2.2	13.7	2.4	630.1	109.1	194.9	115.6	87.2	7.6	1.6	3476	3.3
R7		91.4	85.3	WT	U	61	378	18	9	4.7	1.5	1.2	2.0	1.6	9.8	10.6	175.7	9.0	5.0	15.4	3.7	27.6	3.5
CH-115		123.4	93.3	SC	U	607	355	246	110	84.8	8.2	7.7	3.3	12	176.6	131.7	154.6	11.6	15.6	8.6	0.0	1,657	30
CH-122		–	–	SC	U	250	178	113	110	29.9	9.3	2.5	0.6	0.6	12.4	131.7	39.3	1.9	0.3	3.2	1.1	125.6	2.3
CH-123		25.9	19.5	WT	U	96	503	32	29	7.9	3.1	1.4	1.7	2.2	6.7	35.1	19.2	3591	71.3	14.7	0.0	42.4	2.5
R6		91.4	85.0	WT	U	139	290	47	20	13.9	2.9	4.0	2.5	18	17.0	24.3	195.4	374.9	34.3	14.7	0.0	215.2	4.0
CH-011		39.6	34.4	WT	I	185	499	46	26	13.1	3.1	15.0	1.0	30	10.4	31.6	115.8	9.2	1.6	13.5	0.7	89.6	4.7
CH-050		30.5	26.3	WT	I	239	313	89	71	25.3	6.3	11.9	1.2	23	14.6	85.9	78.2	16.8	0.8	11.8	3.9	146.4	3.2
CH-101		38.7	32.7	WT	I	345	342	140	86	44.5	6.9	4.6	2.4	4	66.4	103.3	116.5	52.0	51.9	4.9	0.1	540.8	16.0
CH-109		51.8	43.8	SC	I	1,062	366	407	220	122.4	24.6	34.8	7.7	78	173.8	260.1	38.9	713.9	19.9	6.3	0.0	2,731	76.0
CH-134		24.1	16.6	WT	I	897	1,148	281	210	76.8	21.8	60.9	4.8	130	34.5	250.0	233.0	109.5	48.9	6.6	0.0	912.6	11.0
R5		91.4	77.2	C	D	1,616	379	430	170	151.0	12.8	138.4	19.8	100	423.4	200.3	212.4	565.2	38.7	5.1	0.0	6,680	150
CH-105		15.8	8.2	SC	D	600	567	242	160	77.3	12.0	7.9	3.2	27	92.1	190.6	117.1	557.9	48.4	4.9	0.5	1,556	13.0
CH-108		53.3	31.8	C	D	1,065	761	154	190	34.1	16.7	149.5	13.3	160	79.9	226.9	151.5	165.9	13.5	3.4	0.0	927.3	200
CH-131		16.5	7.4	C	D	1,117	348	442	330	115.6	37.3	35.8	9.1	75	132.6	389.9	154.5	1604	52.7	9.0	0.0	3,666	40
CH-049		25.9	11.5	SC	U	311	628	128	130	28.6	13.8	11.6	1.0	11	16.9	152.5	94.8	14.2	6.4	1.1	0.1	433.4	3.4
CH-121	Carnside	16.5	13.8	SC	I	346	452	139	130	40.8	8.9	7.4	0.8	12	35.4	156.6	57.6	58.8	21.7	9.1	0.0	83.7	5.8
CH-006		13.7	3.2	SC	I	405	582	184	170	51.2	13.7	6.5	2.4	5	31.8	203.1	407.1	293.4	53.0	6.1	0.2	542.2	4.9
R4		30.5	24.1	WT	I	471	539	215	210	68.2	10.9	6.5	4.8	16	15.2	251.4	308.0	825.9	132.9	11.6	0.0	413.8	6.2
CH-046		30.5	1.0	SC	I	493	227	203	200	45.7	21.5	18.0	4.7	8.8	42.9	236.2	136.6	410.0	46.9	2.1	0.0	433.3	12
CH-052		38.1	10.8	WT	I	246	1,267	116	92	32.2	8.7	4.0	0.9	8.6	10.8	111.0	97.7	0.4	0.0	9.6	7.1	117.3	5.7
CH-080		22.9	18.2	SC	I	617	31	287	300	73.7	25.1	11.5	12.6	10	41.0	357.8	53.0	0.5	1.5	8.1	4.7	121.7	6.8
CH-087		12.2	2.0	SC	I	667	419	286	210	79.3	21.5	14.2	1.0	62	53.5	248.7	333.4	349.7	63.8	3.7	0.0	291.1	6.6
CH-088		10.7	2.0	SC	I	414	183	188	150	56.0	11.7	3.9	1.9	3.8	47.2	177.6	78.3	0.0	0.1	2.1	1.2	207.1	11.0
CH-099		60.0	53.5	WT	I	424	54	173	130	48.0	12.9	8.4	3.5	5.6	69.6	155.7	52.1	101.8	89.5	5.2	0.0	817.4	12.0
CH-104		30.5	23.6	WT	I	460	105	207	180	54.2	17.4	3.3	1.8	10	30.7	215.4	90.1	1.0	0.3	5.8	19.9	200.3	4.4
CH-132		22.9	21.2	WT	I	554	171	182	160	61.4	6.9	34.0	1.3	63	5.6	191.2	78.8	3459	354.2	10.9	0.0	77.0	13
R3		73.2	40.3	C	D	1,981	84	176	240	39.9	18.5	386.6	7.5	330	309.2	283.6	112.6	255.6	13.2	2.1	0.0	1,687	430
CH-034		57.6	41.2	C	D	573	229	189	240	38.0	22.7	42.9	4.2	31	19.1	285.9	157.6	162.8	41.4	3.3	0.2	688.8	32
CH-035		29.0	3.1	SC	D	775	769	376	150	137.2	8.2	15.4	3.3	1.7	259.2	176.6	191.9	383.2	82.1	4.4	0.2	2,062	13
CH-072		16.8	1.5	C	D	1,018	592	376	300	89.8	36.8	47.8	4.6	95	111.9	354.2	96.2	2295	206.2	6.5	0.0	903.3	11
CH-073		30.5	14.0	SC	D	484	996	191	220	41.0	21.4	25.9	3.6	15	43.1	261.7	485.4	288.7	119.8	3.3	0.0	563.4	14
CH-079		15.8	15.9	SC	D	780	431	356	280	85.2	34.8	16.8	3.8	55	71.8	330.7	214.8	744.8	61.1	4.9	0.0	304.3	12
CH-081		14.3	10.5	SC	D	568	558	270	260	66.8	25.0	4.9	1.2	6.7	45.4	307.1	447.7	347.1	71.7	3.0	0.0	280.4	4.5
CH-096		56.4	47.9	WT	D	1,078	852	189	170	43.0	19.8	129.4	16.2	150	131.1	202.8	264.8	286.9	17.7	4.0	0.0	1,262	280
CH-128		61.0	28.0	C	D	974	240	217	280	44.7	25.6	109.5	5.6	81	77.4	333.0	39.3	361.4	45.5	3.7	0.0	1,012	110
min		10.7	1.0	–	–	61.0	30.5	17.9	8.6	4.7	1.5	1.2	0.6	0.6	5.6	10.6	19.2	0.0	0.0	1.1	0.0	27.6	2.3
Avg.		40.0	28.1	–	–	647.4	448.5	222.6	167.7	63.7	15.4	38.5	4.8	45.7	93.0	199.3	161.0	515	53.3	6.7	1.3	980.6	43.3
max		123.4	93.3	–	–	1,981	1,267	681	330	268	37.3	387	19.8	330	630	390	485.4	3591	354	15.4	19.9	6,681	430.0

WT water table; *SC* semi-confined; *C* confined; *U* upstream; *I* intermediate; *D* downstream

Curve matching of natural gamma logs obtained in wells 5R and 6R (not shown here) indicates a relatively low elevation offset of approximately 20 m between these two wells located about 4.5 km apart, with well 5R being downslope of 6R. Consequently, a distinctive feature or zone identified at a certain elevation in 6R reappears in 5R at an elevation that is 20 m shallower. This is an important observation because the predominant transmissive zone identified in 6R (at 53 m depth) displays this same 20-m elevation offset as it aligns itself with the major permeable zone seen in 5R (at 33 m depth). In other words, the one major zone that controls permeability in 6R seems to be the same one that controls permeability 4.5 km away in well 5R. Televiewer images of this dominant hydrologic feature are presented in Fig. 12 as it appears in both wells. Packer tests indicate that the fracture in well 6R has a transmissivity of 10^{-5} m^2/s and an even higher transmissivity of 10^{-3} m^2/s in well 5R.

Groundwater chemistry

To define the natural quality of the groundwater, water samples have been collected from 32 domestic wells and from the five monitoring bedrock wells. Seventeen wells derive their water from the Covey Hill formation and the other 20 from the Cairnside formation. Collected samples were analysed in situ for pH, temperature, Redox potential and electrical conductivity, and in laboratory for major, minor and trace inorganic elements. Table 2 presents a synthesis of select analytical results and descriptive statistics. Characteristics of the sampled wells, respective flow conditions (water table, semi-confined, confined), and position of the wells on the general flow path direction: (upstream-recharge area, intermediate, and downstream-discharge area) are also presented.

No marked difference exists in groundwater chemical composition in both sandstone formations. The major elements: Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2-} and HCO_3^-, have highest concentrations: 630 mg/L for SO_4^{2-}, more than 300 mg/L Na^+, Cl^-, and HCO_3^-, and 268 mg/L for Ca^{2+}. The low TDS range of 30–1,267 mg/L is characteristic for relatively fresh groundwater indicating both sandstone formations have low chemical reactivity limiting the interactions with groundwater. The electrical conductivity reflects closely the variation in TDS content with high correlation coefficient of $r=0.96$. The major elements account for more than 90% of the total dissolved solids (TDS). Few minor elements: F^-, Fe^{2+}, Mn^{2+}, and Sr^{2+} show concentrations close to 1 mg/L. Usually considered as trace element, Br^- shows occasionally relatively high concentration. Marked correlations are observed between Ca^{2+} and SO_4^{2-} and between Mg^{2+} and SO_4^{2-} concentrations with $r=0.84$ and $r=0.92$ respectively. Groundwater derive calcium and magnesium most probably from leaching of carbonate minerals: dolomite (Mg^{2+}, HCO_3^-) and gypsum (Ca^{2+}, SO_4^{2-}) commonly present in the unconsolidated sediments, particularly glacial till, and occasionally in thin layers within the upper sandstone formations (Globensky 1987; Tremblay and Lamothe 2005). The noticeable increase in TDS, electrical conductivity and Na–Cl concentrations in wells sited at the end of the flow path (indicated as downstream wells) may be explained from both dissolution of halite (NaCl) also present in unconsolidated sediments and in bedrock (Globensky 1987; Tremblay and Lamothe 2005), and/or because of mixing with older more mineralized Champlain Sea waters left in place some 9,500 years ago (Blanchette 2006). Major problem with potable water, however, is of aesthetic nature and comes from increased Fe and Mn chemical content. Iron and manganese, ubiquitous in groundwater over the study area, are found in minerals contained in cementing materials and show a significant correlation of $r=0.72$.

The analytical results for the monitoring wells R3 through R7 were used to identify the evolution of the groundwater composition along the flow path. Wells R7 and R6 are located in the upstream part in a recharge area; R3 and R5 are sited at the end of the flow path in discharge areas; and R4 is representative of water-table conditions approximately in the mid of the flow path. Figure 13 shows the enrichment of the ionic composition with distance along the flow path. The R7 and R6 wells have consistently low concentrations of dissolved chemical constituents as the aquifer is regularly replenished with fresh infiltration water. Highest concentrations are observed in wells R5 and R3, particularly for sodium which follows a similar pattern as Cl along the flow path, and for Ca and SO_4. Figure 13 confirms the fact that the slowly seeping groundwater on its path from the recharge area to the discharge to surface waters is exposed to increase in ionic composition (Freeze and Cherry 1979).

Conceptual model of regional groundwater flow

A simplified hydrostratigraphic section of the region under study is shown in Fig. 14. Potsdam sandstones form the primary aquifer unit. Overlying this regional aquifer are unsorted glacial sediments (till) that constitute an aquitard

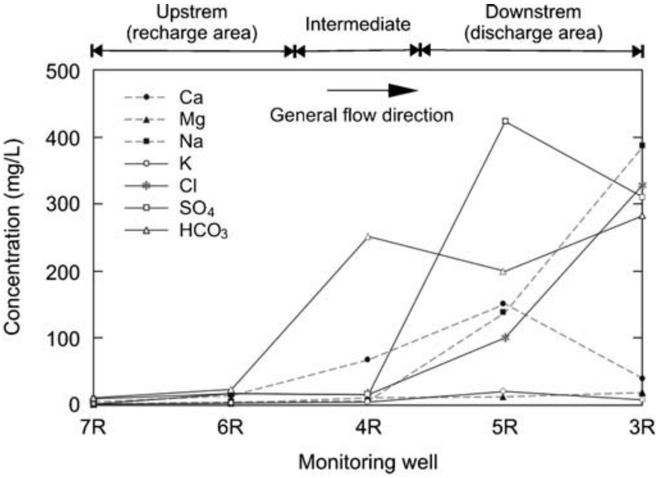

Fig. 13 Regional profile of major ion concentration on the groundwater flow path along the 7R–3R cross section

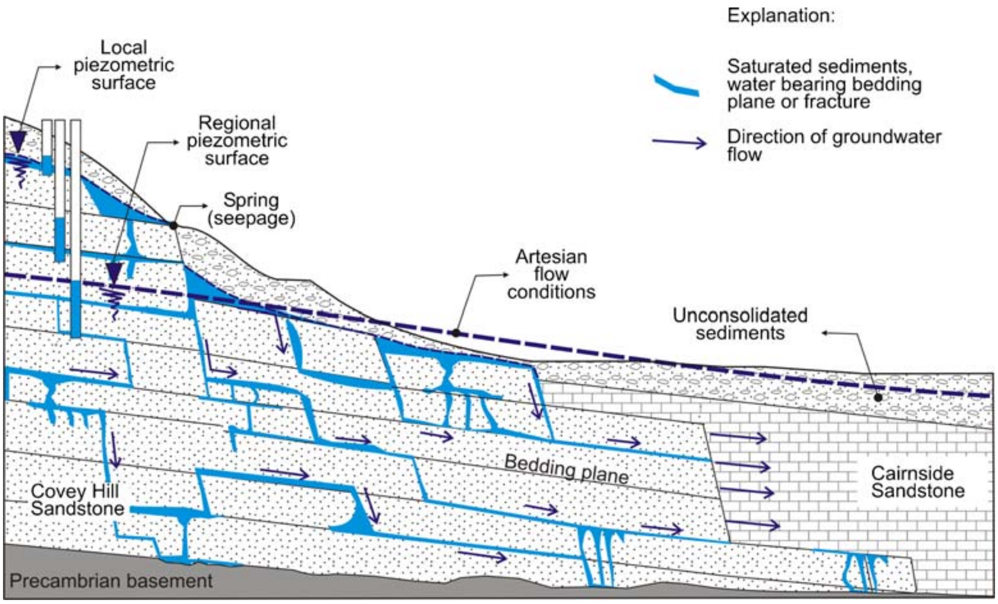

Fig. 14 Conceptual model of regional groundwater flow through Potsdam sandstones. Groundwater flow through both sandstones is restricted to select bedding planes and vertical fractures and joints. Water bearing fractures are much sparser in the Covey Hill sandstones where roughly 1 permeable sub-horizontal fracture is encountered every few dozens of metres depth with lateral continuity that can reach several hundreds of metres to kilometres, whereas in the Cairnside rocks, the water-bearing bedding plane partings are about 5 times more numerous

layer. Due to the high content of fine-grained materials, this unit generally yields small amounts of water and groundwater flow is mainly in the vertical direction. The reworked upper part of the original glacial material, lying in discontinuous contact with the bedrock, represents a preferential recharge zone. Because this unit permits the lateral flow of groundwater, it can also be considered as an interface aquifer unit discontinuously overlying the regional aquifer.

Before reaching the dominant aquifer units, percolating groundwater accumulates just above the bedrock pavements and forms a perched water table, where it is then conveyed laterally in the direction of the hydraulic gradient. This shallow water does not seem to be in direct hydraulic contact with the deeper groundwater. However, it does eventually migrate further downward once it encounters a vertical joint that connects it to deeper bedding planes. At lower altitudes, marine and lacustrine clay and silt overlie the glacial deposits. These fine sediments represent a confining unit that inhibits significant interaction between surface water and groundwater.

Both sandstones are highly interbedded. Groundwater flow occurs primarily through a network of fractures consisting of sub-horizontal bedding plane partings. Fractures are interspersed within an essentially impermeable sandstone matrix and flow through the primary pore space is considered to be negligible. The degree of interconnection between bedding planes via sub-vertical joints is highly variable. Fractures appear to be sparser in Covey Hill sandstones, which may therefore be considered to be a discontinuous aquifer. In Cairnside rocks, a higher frequency of water-bearing bedding plane partings and joints promotes a more uniform and dispersed flow.

Piezometric data recorded in these aquifers reveal several additional hydrologic characteristics. The potentiometric pressure appears to be a function of the intercepted host bedding plane rather than the altitude of the ground surface. Depending upon the distribution and frequency of sub-vertical joints, sites several hundreds of metres apart on steep terrain may have very similar heads if there is no interconnection with other adjacent (upper, lower) bedding planes. Alternatively, two neighbouring wells that intercept different sub-horizontal fractures may display sizeable differences in hydraulic heads. At recharge zones, deeper wells display deeper water levels; cascading and flowing wells are also common in these areas.

Conclusions and discussion

The Potsdam sandstones represent a unique source of water for the population of Covey Hill. The rocks consist of two formations: the basal Covey Hill and the upper Cairnside. The condition of the groundwater flow (water table, semi-confined, confined) and the recharge to regional aquifers is controlled by the type of overlying granular sediments. Highest recharge rates are estimated for reworked glacial sediments ~250 mm. Fine marine sediments, which represent the regional confining unit, have lowest recharge rates of ~20 mm. Groundwater quality is dominated by the position on the flow path. Water sampled in recharge areas shows lowest ionic composition which gradually increases on the path toward the discharge zones. Both rock units have similar bulk hydrologic properties, with measured hydraulic conductivities ranging from 2×10^{-5} to 4×10^{-5} m/s. However, their individual fracture patterns significantly influence the spatial distribution of groundwater flow. These sandstones are characterized by an orthogonal fracture network consisting of sub-horizontal bedding planes combined with a series of sub-vertical joints that are enclosed in an essentially impermeable sandstone matrix. For both formations, distinct permeable zones display significant transmissivities that are orders of magnitude greater than that of the competent, unfractured rock. In Covey Hill fractures are relatively sparse, with only about one permeable sub-horizontal fracture encountered every few dozens of metres depth. Field tests demonstrate that sub-horizontal bedding plane partings in this unit can be laterally continuous for several hundreds of metres to kilometres. Water-bearing bedding plane partings are about 5 times more numerous in Cairnside and, consequently, groundwater flow through these rocks is considerably more dispersed; the more numerous permeable zones are scattered throughout the formation. The probability of intersecting vertical fractures with vertically drilled wells is low, and high-angle fractures were rarely observed in the televiewer logs. Nevertheless, based upon the visual investigation of quarry walls, vertical fractures were quite common. However, the probability of intersecting vertical fractures with vertically drilled wells is low. Consequently, high-angle fractures were rarely observed in the televiewer logs and those that were recognized did not appear to be associated with permeable bedding planes. This type of fracture distribution enhances aquifer anisotropy (horizontal to vertical) produced by layered sedimentary rocks and promotes dominant flow paths that are aligned with dip of bedding.

These findings potentially have important implications for developing wellhead protection strategies for the region. Different flow regimes are associated with the two different formations and, consequently, the local geology imposes structural controls on the local hydrology. The flow regime defined by Covey Hill sandstones is controlled by only a few distinct fractures or bedding planes. These are sub-horizontal, separated vertically by thick, massive units, and are laterally continuous. Hydraulic communication in these rocks appears to be very good horizontally but very poor vertically, and each of these water-bearing bedding planes may be considered as a separate, two-dimensional aquifer unit. This implies that groundwater users hundreds of metres to kilometres apart who exploit the same permeable zone may be vulnerable to each other's production activities. The second flow regime occurs in Cairnside sandstones, where permeable fractures/bedding planes are again sub-horizontal, but also more frequent and vertically more interconnected. Planar, sub-horizontal flow is still dominant but horizontal-vertical anisotropy is less substantial. As a result, groundwater flow is more dispersed three dimensionally.

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