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Characterization of a Regional Aquifer System in the Maritimes Basin, Eastern Canada

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Abstract A regional hydrogeological study was carried out in the Maritimes provinces, in one of the main aquifer systems in Canada. The study area covers a land surface of 10,500 km^2, of which 9,400 km^2 is over Carboniferous and younger rocks. The sedimentary fractured bedrock is composed of a sequence of discontinuous strata of highly variable hydraulic properties, and is overlain by a thin layer of glacial till (mostly 4 to 8 m). Depending on areas, 46 to 100% of the population relies on groundwater for water supply. Almost all residential wells are shallow (28 m on average) open holes that are cased only through the surficial sediments. This paper describes a regional hydrogeological investigation based on targeted fieldwork, the integration of a wide variety of existing multisource datasets and groundwater flow numerical modelling. The aim of this paper is to present the current state of understanding of the aquifer system in a representative area of the Maritimes Basin, along with the methodology used to characterize and analyze its distinct behaviour at the regional, local and point scales. This regional hydrogeological system contains confined and unconfined zones, and its aquifer lenticular strata extend only a few kilometers. Preferential groundwater recharge occurs where sandy tills are present. The estimated mean annual recharge rate to the bedrock aquifers ranges between 130 and 165 mm/year. Several geological formations of this Basin provide good aquifers, with hydraulic conductivity in the range of 5×10^{-6} to 10^{-4} m/s. Based on numerical flow modelling, faults were interpreted to play a key role in the regional flow. Pumping test results revealed that the aquifers can locally be very heterogeneous and anisotropic, but behave similarly to porous media. Work performed at the local scale indicated that most water-producing fractures generally have a sub-horizontal dip along a north-east (45°) strike.

Keywords Groundwater · Regional hydrogeology · Maritimes Basin · Fractured porous media · Groundwater flow numerical modelling

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1 Introduction

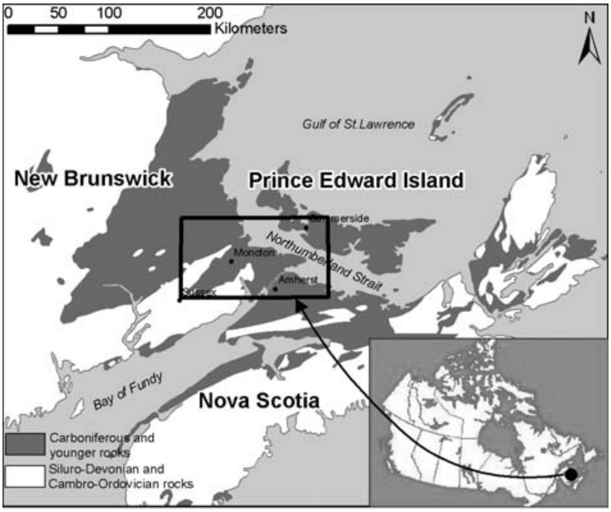
Canada is currently developing a national-scale inventory of its groundwater resources. The assessment of the groundwater resources, at regional and national scales, is crucial for their effective management. Indeed, increasing demands and costs to secure clean water and its decreasing availability in some areas have important social and economic consequences (Rivera et al. 2003). This work is part of several studies carried out to characterize main aquifer systems and to address regional groundwater issues in Canada (Rivard et al. 2007, 2008; Grasby et al. 2005; Côté et al. 2006; Sharpe et al. 2002; Kennedy and Woodbury 2003;Nastev et al. 2006; Fagnan et al. 1999). Although these regions are not highly exploited (as other aquifer systems in the world such as those presented in El Rahman 2001 and Robins et al. 1999), their study represents nonetheless a first step in the process of protection and management of their groundwater resources.

The study area included portions of three provinces of eastern Canada: New Brunswick (NB), Nova Scotia (NS) and Prince Edward Island (PEI; Fig. 1). In these Maritimes provinces, 46 to 100% of the population relies on groundwater, mainly from fractured sedimentary rock aquifers, for its water supply. Groundwater is exploited both by municipal wells and by shallow (28 m deep on average) private residential wells that are 15 cm (6 in.) open boreholes that are cased only over the surficial sediments.

The objective was to carry out a regional assessment of groundwater resources in the Maritimes Basin, a large basin made up of several subbasins and complex sequences of intertonguing lithofacies, and to better understand the hydrodynamics in order to support groundwater management. Only one regional hydrogeological study had been previously done within this study area to delineate and characterize the aquifers on a regional scale (Carr 1964, for the Moncton sub-basin only, i.e. 1100 km^2), but many local investigations were conducted (for the list of previous studies see Rivard et al. 2008).

This study was based on a common methodology for regional hydrogeology characterization, i.e. mostly using existing data, as new fieldwork could not cover the entire study area in detail. It involved the synthesis of a large number of available non-uniformly distributed data of variable reliability, well targeted complementary fieldwork and the development of a groundwater flow numerical model. Nitrate contamination related to agricultural activities is

Fig. 1 Location of the study area



the main groundwater contamination concern in some parts of the study area. However, there are no other major contamination problems. Therefore, our study mainly focussed on the hydraulics of the aquifer system. Geochemistry, only representing a small part of this project, is not presented in this paper (for details, see Rivard et al. 2005a, 2008; and for a specific project on the nitrogen cycle in PEI, see Paradis et al. 2006; Savard et al. 2007).

2 Description of the Study Area and Geological Contexts

2.1 Physiography and Climate

The Maritimes Basin (MB) is located in the eastern portion of the Appalachian physiographic region, which extends from Newfoundland (Canada) to Alabama (USA). The study area, outlined on Fig. 1, covers an area of 14,100 km^2, of which 9,400 km^2 enclose Carboniferous and younger sedimentary rocks. The remainder consists either in the basement complex (Pre-Carboniferous rocks, 1000 km^2) or water bodies (3,700 km^2). The topography of the Basin is relatively flat (see Fig. 2). The altitude may reach 300 m in the Pre-Carboniferous rocks (Caledonian Mountains, NB).

Due to the low relief of the Basin, the major influence on climate is the distance to the sea. Daily-average air temperature varies in the summer between 17 and 24°C; and during the winter between −12 to −4°C. Precipitation varies from 900 to 1,500 mm/year, with an overall average of 1100 mm/year. Mean annual evapotranspiration varies between 345 and 440 mm/year (estimated using Coutagne 1954 and Turc 1954 methods, see Section 3.4).

2.2 Bedrock Geology and Structural Settings

The MB is a composite post-Acadian successor basin consisting of a series of sedimentary subbasins, which unconformably overlie a complex collage of pre-Carboniferous terranes

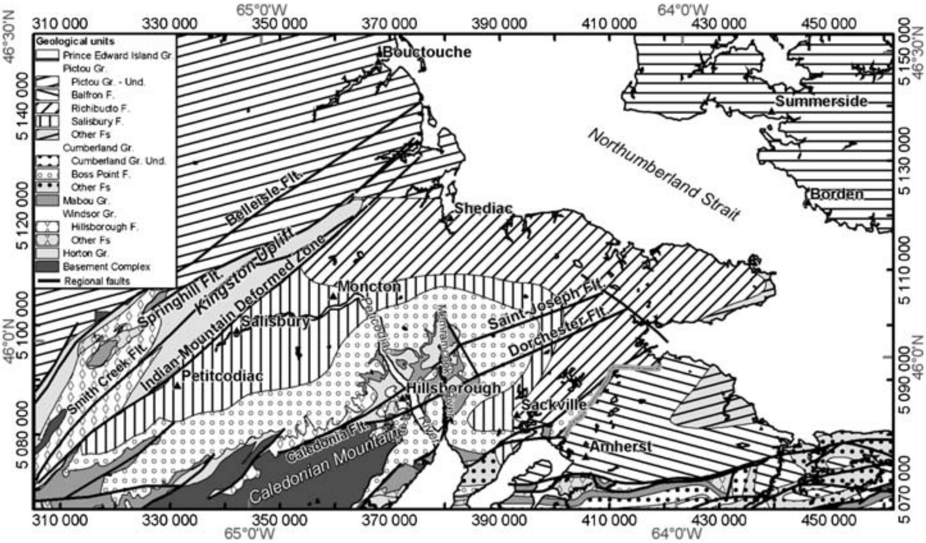


Fig. 2 Simplified geological map of the study area (compiled from 1:50,000 NB maps and 1:250,000 Lynch et al. 1998 maps, see Rivard et al. 2005b for the complete colour map)

(see Van de Poll et al. 1995, for a synthesis). Subbasins are oriented in a general northeast to east trend and are separated by basement uplifts (e.g., Caledonian and Kingston Uplifts) along large regional faults. A relatively thin cover of unconsolidated Quaternary glacial deposits overlies almost uniformly the entire Basin.

The overall lithostratigraphic subdivision is composed, from base to top (Van de Poll et al. 1995), of the following main groups: the Horton, Windsor, Riversdale-Mabou, Cumberland, Pictou, and Prince Edward Island. Table 1 summarizes the lithological units and their aquifer potential. A geological map of the study area was developed using 1:50,000 NB maps (95-22F; G; H; J; 95-8; 95-9; 97-7; 97-9; 99-23 and 99-26) and 1:250,000 Lynch et al. (1998) maps, and updated based on the latest information provided by the provincial authorities. Figure 2 presents a simplified version showing formations of most interest for hydrogeology, mainly because of their aquifer potential or significant extent in the area. Complete versions of the geological map and Table 3 are presented in Rivard et al. (2005a, 2008).

The sedimentologic setting of the majority of units of the MB is essentially of continental origin (St. Peter 1993; Van de Poll et al. 1995), except for a marine episode during the Windsor Group deposition. The strata represent several alluvial-lacustrine or alluvial-marine cycles in the early basin fill (Horton, Windsor, Mabou groups), which are covered by multiple stacked cycles of meandering fluviatile, inter-channel, and paludal deposits (Cumberland and Pictou groups; St. Peter 1993). According to St. Peter (1993), the angular unconformity between Cumberland and Pictou strata implies structural inversions of the basin fill causing uplift, tilting and erosion of parts of the stratigraphic packages. The Early Permian PEI Group strata are gradational above the Pictou Group.

Internal stratigraphy of the various formations belonging to each group is complex and often laterally discontinuous, as the result of different sedimentation rates, syn-sedimentary faulting and reworking. The MB is composed of a thick sequence of recurring bedrock lithologies (mainly composed of sandstone, conglomerate, siltstone, and mudstone). Their variable hydraulic properties imply that some bedrock units act as aquifers whereas others behave more like aquitards. Lenticular bodies of sandstone in the Lower Pictou Group, for example, are thought to generally extend less than 3 km in width and have highly variable lengths (Hacquebard and Barss 1970; St. Peter, personal communication). The assessment of the lateral extent and thickness of individual rock types, and their correlation across subbasins, is thus a nearly impossible task at the regional scale.

2.3 Surficial Geology Settings

Sandy and gravely unconsolidated sediments, known to be excellent aquifers, are restricted to very limited locations within the study area, such as stream valleys. Surficial deposits of the MB are mainly composed of till and glacio-fluvial deposits (Vaughan and Somers 1980; Rampton et al. 1984; MacDougall et al. 1988). Wells in glacial tills can barely provide enough water to supply a family dwelling. However, this layer plays a major role in the Basin, as most of the recharge supplying bedrock aquifers infiltrates through the till. Very few data were available on hydraulic properties of the till.

The till layer thickness usually varies between 0 to 20 m, with average values of 8, 4 and 8 m for NB, PEI and NS, respectively. The matrix of this deposit varies from sandy to clayey, generally reflecting the composition of the underlying bedrock, the sandy till being found over sandstone and the clayey till over shale (Carr 1964; Boisvert 2004). Most of the unconsolidated sediments were deposited during the late Wisconsinan glacial episode.

Table 1 Lithological units and aquifer potential in the MB[a]

Period	Group	Formation	Dominant Lithology	Aquifer potential
Permian	PEI	All	Red sandstone, conglomerate, wacke and minor mudstone	Good
Carboniferous	Pictou	Undivided	Typically sandstone and mudstone	Usually good
		Balfron	Arkosic sandstone and mud-clast conglomerate; siltstone and mudstone; calcareous sandstone concretion abundant	Variable
		Richibucto	Sandstone, conglomerate, siltstone; minor thin coal seams	Usually good
	Cumberland	Salisbury	Mudstone, siltstone and fine-grained sandstone; quartzose sandstone and pebbly sandstone, mud-clast and polymictic conglomerate	Poor
		Undivided	Sandstone, mudstone, and minor conglomerate and coal	Variable
		Boss Point	Sandstone and conglomerate, siltstone, minor mudstone, locally with carbonate calcareous nodules and/or calcrete	Variable
	Riversdale-Mabou	All	Sandstone, polymictic conglomerate; siltstone and mudstone	Poor
	Windsor	Mainly Hillsborough	Polymictic conglomerate and lithic sandstone; minor mudstone, limestone, and minor breccia	Variable to poor
	Horton	All	Polymictic conglomerate; sandstone; siltstone, mudstone and shale	Poor[b]
Pre-Carboniferous	Basement complex		Undivided, foliated mafic to felsic volcanic and intrusive rocks; metasedimentary rocks and undeformed intrusive rocks	Aquitards

[a] Not to be perceived as a lithostratigraphic column.

[b] Poor aquifers with poor water quality

3 Methodology

A regional hydrogeological study generally includes the following steps: (1) selection of the study area, (2) data compilation, (3) fieldwork, (4) data analysis and interpretation and (5) map production (Michaud et al. 2004). Numerical groundwater flow modelling was also added as a sixth step for this study in order to make a more quantitative assessment of the regional groundwater resources.

3.1 Selection of the Study Area

The MB was selected for this study because it represents one of the key aquifer systems in Canada, and also considering the important role of the groundwater resource for water supply in this part of the country. However, because of the large area covered by this Basin (46,000 km^2), a smaller representative area was retained for the project. Still, the region under study covers 10,500 km^2 and parts of three Maritime provinces, representing a standard 1:250,000 map sheet.

3.2 Data Compilation

A thorough review of available relevant reports and studies, provincial databases, thematic maps and scientific papers was done in order to develop a preliminary understanding of the hydrogeological setting. Targeted relevant information primarily consisted of borehole logs, meteorological data, water well data (depth, flow rate, static water level, etc.), water chemistry data, and pumping test results. These data were first validated using mainly geographical locations, negative or aberrant values, and consistency between reported measurements for a well, e.g. the water depth must be smaller than the well depth. The data were then compiled into a large hydrogeological database, which ensured optimal data manipulation and integrity, and their availability for all project stakeholders via internet.

Hydraulic conductivities (K) were obtained by dividing the transmissivities T (values generally provided in databases and reports) by the open section of the well, since $T=K \cdot b$, assuming that the flow is dominantly horizontal close to the well. The open section (b) was estimated by subtracting the casing length from the well depth, as most wells are open boreholes in the bedrock and cased only over surficial sediments. When the casing length was unknown, an average value based on surficial deposit thickness data from provincial databases was used. This allowed the estimation of representative hydraulic conductivity values for the bedrock aquifers as a whole (rather than for specific fractures). Table 2 summarizes the information obtained within the study area. Almost no quantitative hydrogeological data were available for surficial deposits, as the great majority of wells are completed in fractured rocks.

3.3 Fieldwork

Fieldwork was carried out during two summers (2001 and 2002) to gather additional data on stratigraphy, hydraulic properties, fracturing and groundwater characteristics in specific areas to fill the main information gaps. Fieldwork carried out and number of results in both the fractured rocks and the surficial deposits are summarized in Table 3.

Groundwater level surveys were conducted to determine water level depths and map hydraulic heads in order to delineate regional groundwater flow. Five vented pressure

Table 2 Summary of compiled existing data

Data	Number
Description of wells in provincial databases and reports, including: location, depth, yield, etc. (many fields missing)	188,700 wells (e.g. static water levels: 22,800 data)
Borehole logs for surficial geology	2997
Pumping tests (>4 h; T, S)	50 for T, 24 for S
Water sample analysis	1900 samples
Meteorological data	21 weather stations
Stream hydrographs (in NB and PEI)	16 gauging stations
Grain size analysis for the till	75

transducers with data loggers were installed in bedrock wells to record their annual water level fluctuations and obtain well hydrographs.

Six boreholes were drilled within the sedimentary bedrock (depths 62.5 to 91.5 m), and seven boreholes within the surficial deposits (depths from 12 to 29 m). In addition to short and long-term pumping tests, constant head injection packer tests were also performed in six wells in order to evaluate the hydraulic properties of distinct bedrock lithologies. Zones of interest for packer testing were predetermined using geophysical logging. Geophysical logs were obtained in 10 wells scattered throughout the region to obtain information on stratigraphy, water bearing fracture features, along with their individual flow rate. Geophysical logging operations included the use of caliper, natural gamma, electrical resistivity, acoustic televiewer and flowmeter under ambient as well as pumping conditions (Morin et al. 2002; Rivard et al. 2005b, 2008). For the characterization of surficial deposits, slug and pumping tests were performed in sand units, and several permeameter and infiltrometer tests were conducted in various till units (Boisvert 2004).

Finally, twenty-three rock samples from various formations were collected to evaluate their matrix porosities using thin-sections and soil samples were collected for grain-size analyses.

Table 3 Summary of fieldwork carried out in the summers of 2001 and 2002

Category	Activity	Number of data	
		Fractured rocks	Surficial deposits
Survey	Measurements of water levels in wells	433	29
Monitoring	Installation of pressure gages and data loggers in wells	5	–
Drilling	Rotary hammer and diamond drilling	6	
	Standard and hollow stem auger drilling	–	7
Hydraulic testing	Pumping tests and slug tests	10	7
	Permeameter and infiltrometer tests	–	26
	Packer tests	40 in 6 wells	–
Geophysics	Borehole geophysics	10 wells	–
Analyses	Water	17	5
	Soil (grain size)	–	80
	Plant macrofossiles	–	21
	Rock (thin sections)	23	–

loc.=locations

3.4 Data Analysis and Interpretation

3.4.1 Data from Fieldwork

Pump test results for pumping wells typically showed a behaviour following a Theis type curve. However, observation wells were either unavailable or did not respond "normally" at 8 out of the 10 bedrock well sites. Therefore, they could not provide quantitative information. One of the wells showed a drawdown behavior similar to the Gringarten and Ramey (1974, in Kruseman and de Ridder 2000) type curves, and was thus assumed to be located in the same vertical fracture as the pumping well. Slug test results were interpreted with the Bouwer and Rice (1976) or the Butler and Garnett (2000) methods depending on the type of response obtained. For packer tests, the hydraulic conductivity (*K*) of each tested interval was obtained using the Thiem equation, thus assuming steady-state flow conditions. Since the investigated intervals were only the most transmissive ones, the *K* value for each well was calculated using an average matrix value of 5×10^{-8} m/s in non-tested intervals (see Rivard et al. 2008). This average value was obtained from various intervals, when the targeted (permeable) fractures were missed. The results of permeameter and infiltrometer tests were interpreted with the Elrick et al. (1989) solution and Darcy's law (Boisvert 2004). From trends in the orientation, distribution, and frequency of the structural features shown by borehole geophysics, a conceptual understanding of the groundwater system was developed.

3.4.2 Existing Data—Groundwater Recharge and Water Balance

Existing data were used to calculate recharge rates, and to verify previous results as in the case of pumping tests. Scattered information on recharge rates for various small areas was available from technical reports. Since recharge estimation methods have varying reliability (Scanlon et al. 2002), three different approaches were used to evaluate the aquifer recharge (*W*): stream hydrograph separation, water balance and numerical modelling. Figure 3 presents the location of gauging and weather stations. Some of the stations used fall outside the area shown, but were however kept as they provided boundary values for data interpolation.

For hydrograph separation, two approaches were selected: graphical (HYSEP by Sloto and Crouse 1996) and digital filters (Chapman 1991; Furey and Gupta 2001). Earliest records of the available 16 gauging stations date back to 1961. All three methods were compared (Rivard et al. 2008); since two of the methods generally over-estimate base flow during recession curves (especially HYSEP), only the Chapman method was retained for future comparison.

The annual water balance was then calculated using this simplified equation (all terms in mm):

$$Recharge = P - R - ET - \Delta\, SWS \tag{1}$$

where *P* is the precipitation (mm), *R* is the runoff, *ET* is the evapotranspiration, and *SWS* is the soil water storage (whose variations tend toward zero over the long term). The evapotranspiration was estimated using the Thornthwaite (Chow et al. 1988), Turc (1954) and Coutagne (1954) methods (Stigter et al. 1998; Cruz and Silva 2001; Mahlknecht et al. 2004; Ben Kabbour et al. 2005). The Thornthwaite method is commonly used to estimate potential evapotranspiration (ET), whereas the last two are simple empirical equations that helped bracket the range of actual ET in the study area. All three methods could be applied using readily available data over the study area. The recharge was calculated for each year

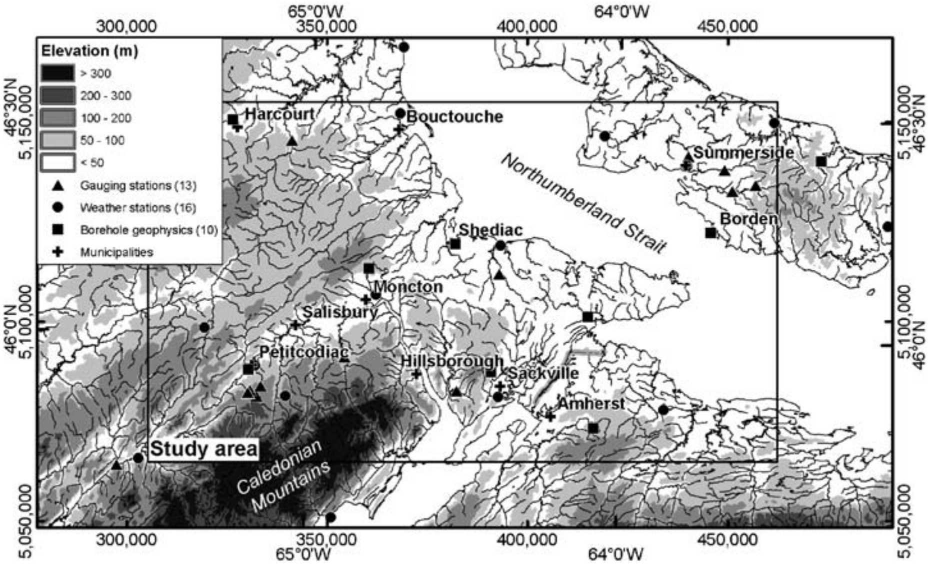


Fig. 3 Topography of the study area, along with the location of the weather stations and gauging stations that were used for the calculation of recharge rates, and location of wells used for borehole geophysics

where mean annual precipitation and temperature were available (between 3 and 95 years) at the 21 stations. Runoff was calculated using the CN method developed by the US Soil Conservation Service (Steenhuis et al. 1995) and soil water storage (*SWS*) was obtained by multiplying the root depth, derived from the vegetation map, by the water storage capacity coefficients taken from Nyvall (2002). Estimations were spatially distributed using GIS tools over a grid with 500 m×500 m cells.

The water balance method provides a potential recharge without considering hydrogeological conditions. Since a significant proportion of the study area exhibits discharge or artesian conditions (where recharge to bedrock does not occur), the recharge rates obtained were corrected by eliminating such areas. Water balance recharge estimates were thus corrected by multiplying them by an average proportion of area where recharge is possible (see Section 4.7).

3.5 Map Production

Regional mapping of hydraulic properties and hydraulic heads was carried out. Data for hydraulic conductivity (*K*) discretely plotted on a map showed a lot of spatial variability. Furthermore, there was no obvious spatial correlation in a variogram of the available *K* values. These were taken as evidences of the system's strong heterogeneity, resulting from variability in fracturing and stratification. For display purposes, the hydraulic properties from wells located within an arbitrary 3 km radius were aggregated using a geometric mean.

Hydraulic heads were evaluated based on water level measurements, by subtracting water levels (depths) from ground surface elevations (and, when available, the length of the casing above the ground was included in the estimation). A map of hydraulic heads for the bedrock flow system was produced through kriging using an exponential variogram with a correlation length of 21 km. A considerable amount of information on groundwater depths was available, but a high level of uncertainty was attached to the data, mostly because static water levels were often measured immediately after the well construction. Moreover, fluctuations within a year or a decade can certainly be large. For this reason, only the most recent data (after 1998) from each provincial database were retained, giving more weight to the water level survey. This also avoided dealing with long-term fluctuation patterns or trends. All bedrock wells were used without discrimination regarding their depths, since this information is not always available and most wells are open from right under the surficial deposits to the bottom of the well. In all, 433 data points from fieldwork and about 700 values from provincial databases were used to generate this map. Water levels thus represent a broad range of seasonal conditions, both in dry and wet seasons. To obtain a more realistic map of hydraulic heads when performing the interpolation, manual control points were added, especially in low relief areas close to streams and along the coast where few measurements were available.

3.6 Numerical Modelling

Due to the large area covered by this study and the inherent heterogeneity of the MB, only conceptual and simplified 2D and 3D numerical flow models were developed. Numerical models were developed in 2D with SEEP/W (GeoSlope International 1997) and in 3D with FEFlow (WASY 1998), two finite element numerical simulators, using steady state conditions to obtain a quantitative representation of the hydrogeological system dynamics. Even if the MB is a fractured porous media, it was assumed that fractures and faults are sufficiently connected to provide a relatively homogenous flow system at the regional scale that can be mapped onto an equivalent porous media. Furthermore, the majority of pumping wells in the provincial database behave as if they were located in a porous media, following Theis type curves (see below).

4 Hydrogeological Context

4.1 Bedrock Stratigraphy and Fracturing

As mentioned, the fractured rocks of the MB are highly stratified and lenticular in nature, consisting mainly of sequences of sandstone, shale, siltstone, and conglomerate that appear in varying proportions in each geological formation. Individual beds range in thickness from few centimetres to several meters, and their extent is variable. Fractures have been noted in all rock types. However, they are predominantly encountered in sandstone layers, and along lithological contacts and bedding-plane partings. A moderate to high number of small vertical fractures likely intersects the latter.

The identification of fractures and their orientation using a borehole televiewer, and the measurement of individual flow rate with a flow meter during borehole geophysics work, as well as the observation of an anisotropic response from several observation wells during pump tests clearly revealed the spatially consistent pattern of fracture orientations dipping to the southeast and striking approximately N45°E, south from the Kingston Uplift. This structural correlation among wells is in good agreement with the orientation of local faults and the regional stress regime (Morin et al. 2002). Borehole geophysics indicated that the vast majority of the geological features, whether discrete fractures or bedding plane partings, are subhorizontal; very few steeply dipping features are identified in these logs, even when considering the sampling bias inherent in locating subvertical fractures from vertical wells (Terzaghi 1965). Only about 5% of all planar features have dips greater than

50°. Data acquired suggest that the bedrock north of the Kingston Uplift has been subjected to different tectonic forces, as fractures exhibit no clear trend in orientation and no correlation with other sites (Morin et al. 2002). According to drillers, provincial hydrogeologists and some reports (Francis and Gale 1988), fractures in every strata decrease in both number and aperture with depth and, as a result, the permeability of bedrock aquifers should generally decrease with depth. Average well depth in the study area is 28 m.

4.2 Hydrostratigraphic Units of Interest for Exploitation

Four bedrock formations were identified as major hydrostratigraphic units to be prioritized within this region, based on their productivity and proximity to main urban centres. These formations, from the youngest to the oldest, are: those of the PEI Group, Richibucto, Boss Point and Hillsborough. However, the aquifer potential of these units is often variable. In general, the higher the percentage of sandstone present within (or close to) a borehole is, the higher the transmissivity will be (Carr 1964). Wide ranges in hydraulic properties are however mostly due to the presence or absence of fractures. Nevertheless, good and "variable" aquifer units cover a large part of the study area.

In particular, formations included in the PEI Group have a high percentage of (red bed) sandstones, providing very good aquifers with hydraulic conductivities (K) ranging between 4.3×10^{-6} and 2.5×10^{-3} m/s. Variable proportions of siltstone, breccia and conglomerate are also present. The Richibucto Formation (Pictou Group) is composed mainly of grey, multistoried sandstone interstratified with red-mudrock dominated sequences (Johnson 1995). This formation has a good aquifer potential, K varies from 1.4×10^{-6} to 1.9×10^{-4} m/s. The Boss Point Formation (Cumberland Group) comprises mostly sandstone and conglomerate with subordinate lithic and feldspathic sandstones and mudstones, and minor coaly shale, coal and limestone (St. Peter 1993). The Boss Point Formation varies from a good to a poor aquifer ($1.1\times10^{-6}<K<3.8\times10^{-5}$ m/s). Lastly, the Hillsborough Formation (Windsor Group), whose exposure is restricted to small areas, is mainly comprised of red conglomerate, grit and sandstone with minor mudstone (St. Peter 1993). Its aquifer potential is highly variable ($1.6\times10^{-8}<K<1.2\times10^{-5}$ m/s). The range of hydraulic conductivities quoted corresponds to minimum and maximum values taken from the database (see Section 2 for the calculation of K).

4.3 Regional Bedrock Hydraulic Properties

Considering the very large extent of the region under study, relatively few pumping test data were available. Moreover, pumping tests rarely had been carried out using observation wells other than the pumping well. Consequently, very few aquifer storage coefficients (S, corresponding to the overall elastic storage plus specific yield) could be estimated and their reliability is questionable. Using all results from pumping tests that lasted more than 4 h, a total of 60 K and 26 S values were available to characterize the fractured aquifers within or nearby the study area. Only six values of horizontal to vertical hydraulic conductivity ratio K_H/K_V were available from packer tests; they ranged between 4 and 2,700, with a geometric mean of 105.

Figure 4a shows the spatial distribution of K data classified into three ranges. K values could not be interpolated, since values mostly depend on the local geologic formations and consequently, the gradual transition between data would not be realistic (K values showed no spatial correlation). Data points are mostly concentrated along the coastline and river valleys, where the density of population is higher. As expected, K data exhibit large variations between hydrostratigraphic units and even within each individual unit (see Fig. 4b). These internal variations attest to the strong heterogeneity of each formation and reflect the strong influence of fracturing. Average K values of most formations usually range between 5×10^{-6} and 10^{-4} m/s. The Richibucto and the Boss Point formations, and especially all formations of the PEI Group, usually exhibit the largest average K values, typical of high-capacity formations. However, other formations can locally provide a groundwater flow rate sufficient to supply small communities.

Since most pumping tests were not performed over long periods, estimated storage coefficients were considered to be relatively inaccurate. Nevertheless, values found within the MB generally range between 10^{-4}–10^{-3}, but values as low as 7×10^{-6} and as high as 0.4 were reported. This, in conjunction with drilling logs, monitoring well hydrographs and knowledge of hydraulic conductivities of the till, indicate that the hydrogeologic system is partly confined, as both confined and unconfined conditions can be encountered. Variations of hydrogeological conditions may be explained by the variability in thickness and composition of the surficial deposits, as well as by the fracturing condition of overlying fine-grained layers (siltstone, claystone or shale).

Total porosity of each rock type can vary widely within a geological formation, mainly due to the presence of calcite or other cements within the pores. Compiled and estimated total porosities of the formations showed values ranging between 0 and 20%, with averages ranging between 5 and 10%. Earlier work had shown that the matrix porosity of the PEI Group Formations decreases significantly with depth, from 20% at the surface to 12% 1 km deep on average (Chi et al. 2003). These relatively high porosity values could lead one to expect that the MB flow system would hydraulically react like a double porosity medium. However, well tests do not exhibit such a double porosity behaviour but rather show drawdown curves representative of equivalent porous media. This is interpreted to be caused by the presence of a very well developed fracture network having itself enough storage to act as an equivalent porous medium. Six well hydrographs located in PEI in areas under unconfined conditions allowed an estimation of specific yields (S_y; or drainage porosities). S_y values in the range of 2 to 7% were found, showing a significant storage capacity that is coherent with total porosity estimates.

4.4 Surficial Deposit Hydraulic Properties

The study of surficial deposits revealed the presence of three types of tills based on hydraulic properties (Boisvert 2004). The first type, associated with the Salisbury Formation, is characterized by a silty matrix and an average K of 6.5×10^{-9} m/s (geometric mean of 11 infiltration tests). The second type, generally sandy, is associated with the Boss Point Formation and has an average K value of 1.3×10^{-6} m/s (five tests). Finally, the third type of till corresponds to the deposits overlying the Richibucto Formation; the till layer presents about 40 cm of sandy till with a K value of 1.4×10^{-6} m/s (five tests), overlying a silty–sandy till unit having a K value of 5.3×10^{-8} m/s (five tests). In general, tills were poorly compacted and, in some places, contained freeze/thaw or drought fissures, favouring infiltration.

An attempt to find granular aquifers in both the Petitcodiac and Memramcook river valleys was carried out. Sandy units were identified, but they contained brackish water (Boisvert 2004).

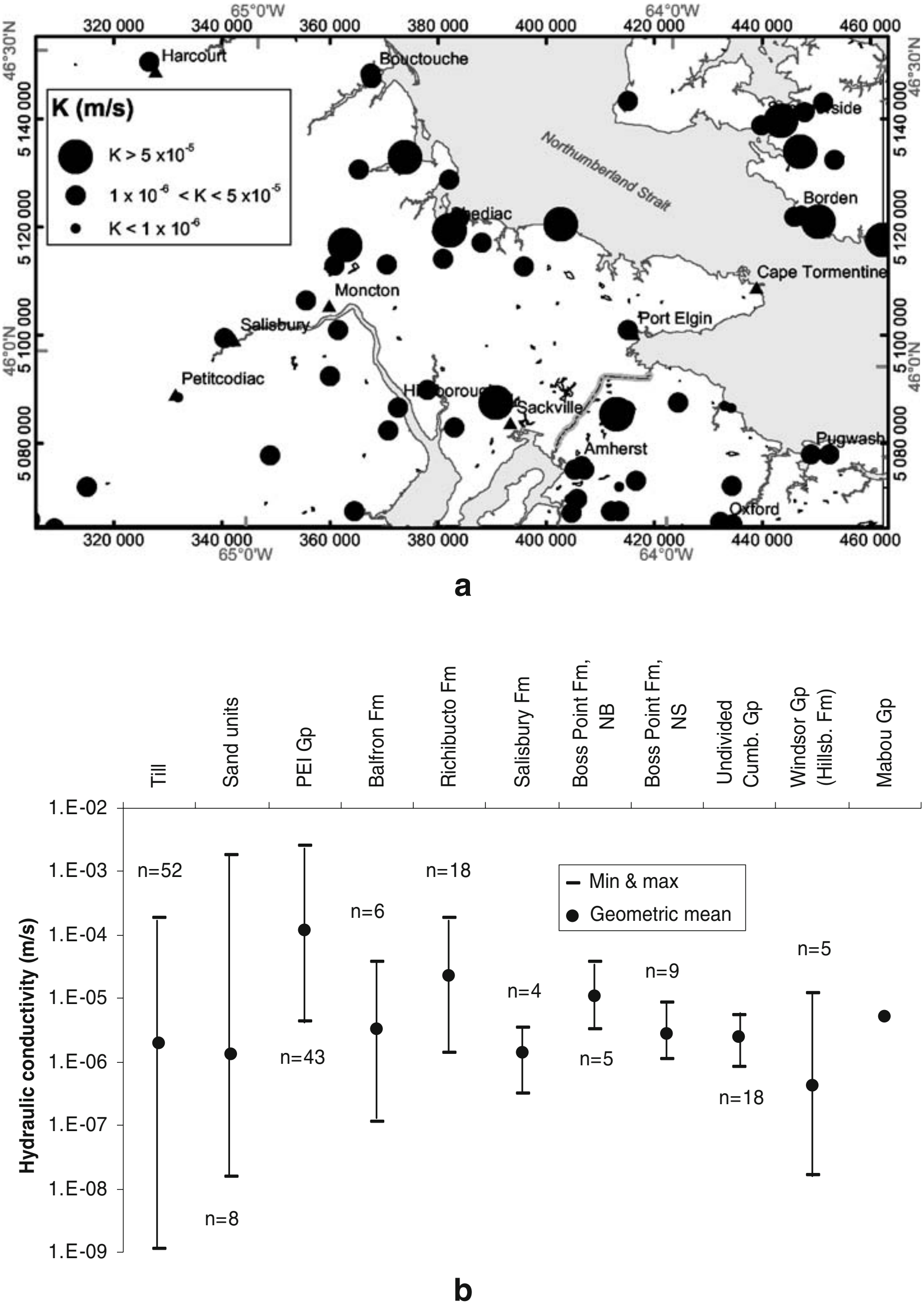


Fig. 4 **a** Spatial distribution of hydraulic conductivities and **b** Minimum, maximum and mean *K* values (m/s) for each hydrostratigraphic unit with the number (*n*) of data available

4.5 Hydraulic Behaviour of Bedrock Aquifers Under Pumping

The large number of sub-horizontal fractures striking in a north-eastern direction seems to impart a quasi horizontal 2D flow, with a preferential component along strike. Indeed during pumping, observation wells located close to a N45°E direction from the pumping well reacted very strongly. As this orientation drifted further from N45°E direction, the observation well drawdown decreased. These features result in local anisotropy and strong heterogeneity (and thus channelling). Nevertheless, as mentioned, pumping tests showed a porous medium behaviour, as they followed a Theis curve.

40% of pumping tests performed during this project did not show evidence of boundaries during the test period. However, the remainder (60%) revealed that after a certain time (ranging from 3 h to 24 h), less transmissive boundaries were encountered, as indicated by the typical increase in drawdown. To make sure that this behaviour of the drawdown curve was due to an impermeable boundary, the theoretical Theis curve was subtracted from the second part of the measured curve. The residual drawdown also followed the Theis curve, thus confirming that it was caused by an imaginary well related to the presence of a negative boundary. This is in complete agreement with the structure of the sedimentary bedrock, which is composed of lenticular strata of variable permeabilities and extents. Actually, some drawdown curves showed the influence of more than one impermeable boundary, as would be expected if wells were close to one end of the lenticular permeable strata.

In summary, the MB is a fractured porous media, having a total porosity ranging mostly from 5 to 10%, but usually follows porous media Theis type curves when pump tests are conducted. The lenticular nature of the different rock types and the great influence of lithology on fracturing have a large impact on the flow system behaviour at the local scale. Pump tests confirmed the MB limited permeable facies extents, and indicated a fracture-driven anisotropy. However, at the regional scale (scale of the study area), it was not known if factures were sufficiently connected to impart a behaviour typical of an equivalent porous media. Modelling was used to test this assumption (see section 5.3).

4.6 Hydraulic Heads and Groundwater Flow

Water levels, from fieldwork and existing data, varied from artesian flowing conditions to depths in excess of 50 m, with a median depth of 6.7 m. The groundwater level generally follows the topography. Artesian conditions may seem unlikely in this relatively flat area. However, they could be explained by the fact that fractures are gently dipping towards the Northumberland Strait and that overlying fine-grained beds or accumulations of fine-grained sediments (in areas close to streams or the ocean) act to confine aquifers. Due to the absence of confinement, few artesian wells are expected on PEI, and none were identified during field surveys.

The map of hydraulic heads of the study area is presented in Fig. 5. Groundwater generally flows towards the ocean, but watersheds of large rivers such as the Petitcodiac River have a significant influence on groundwater flow. The highest hydraulic heads are located in topographic highs, for instance on the Caledonian Mountains and, to a lesser extent, on the Kingston uplift, and in the centre of PEI island. These major hydraulic domes do not necessarily correspond to major recharge zones, as their *K* is sometimes very low. Preferential aquifer recharge areas are rather associated to sandy till covers and bedrock outcrops. The horizontal hydraulic gradient is usually smaller than 0.01. This regional map of hydraulic heads thus provides a portrayal of the upper part of the bedrock aquifer system, sometimes under confined and sometimes under unconfined conditions. Even if conditions

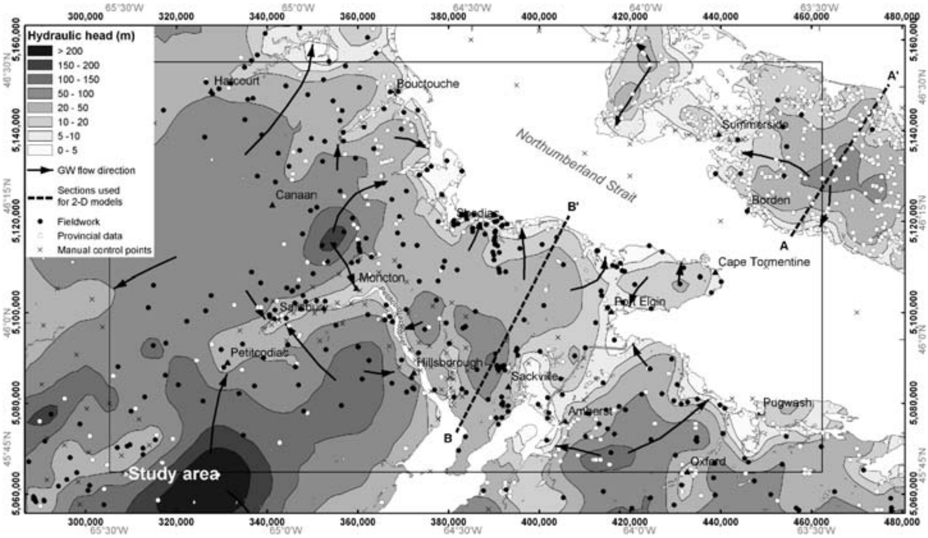


Fig. 5 Map of hydraulic heads of the bedrock aquifers obtained from water level measurements. Arrows indicate general groundwater flow directions

are changing within this flow system, connected permeable zones ensure the hydraulic continuity regionally.

4.7 Water Balance

Groundwater recharge estimates based on river hydrograph separation vary widely, from 90 to 435 mm/year (see Table 4). However, watersheds for which data were available were located only over the most permeable formations (Richibucto/Und. Pictou, Boss Point and PEI Group). Recharge estimated using the water balance method provided values varying between 35 and 310 mm/year, with a minimum, mean and maximum weighted average over the study area of 115, 185 and 250 mm/year depending on values attributed to each parameter during the process (see Table 5). Values of 120 to 405 mm/year were obtained for the most permeable formations (considering minimum and maximum values), with means ranging between 190 and 310 mm/year, in agreement with the river hydrograph separation method. These recharge estimates correspond to the total amount of water that infiltrates into the till cover. However, a significant portion of the recharge is likely to reach streams by subsurface flow before infiltrating into the bedrock aquifer system. The reaching of streams by subsurface flow is facilitated by a well developed hydrographic network.

An investigation of contexts in which recharge to bedrock is unlikely was made, that included: 1) where upward flow is indicated by the vertical hydraulic gradients (estimated to be 29% over the whole territory), 2) zones where the map of hydraulic heads is significantly above the ground surface (accounting for the precision of interpolated water levels and DEM, being 26%, 18% and 11% for a 2, 5 and 10 m precision respectively), and 3) visited sites where shallow water levels (<1 m), artesian wells or springs were observed (12%). Based on these indications, it was estimated that between 11 and 30% of the territory is probably under artesian conditions or represent discharge areas (except for PEI where a minimum of 5%, based on provincial authority information, was used). Therefore,

Table 4 Annual recharge rates estimated based on hydrograph separations (Chapman method)

Gauged river	X UTM[a]	Y UTM[a]	Watershed Area (km^2)	Period covered	Recharge (mm/year)
Kennebecassis River, NB	297490	5064219	1100	1961–1999	359
Coal Branch River, NB	341364	5145409	166	1964–1997	345
Kinnear River, NB	393052	5111957	32.1	1985–1993	348
Petitcodiac River, NB	331779	5090071	391	1961–1997	317
Turtle Creek, NB	354403	5091108	129	1962–1997	436
Palmers Creek, NB	382344	5082633	34.2	1966–1985	432
Hayward Brook, NB	332489	5081346	4.3	1995–1997	270
Hayward Brook, NB	330782	5082816	1.37	1995–1997	246
Hayward Brook, NB	330420	5082081	6.5	1995–1997	324
Hayward Brook, NB	330208	5082276	2.34	1995–1997	282
Hayward Brook, NB	333488	5083821	15.2	1995–1997	92
				Mean:	314
Plat River, PEI	440280	5141374	4.5	1970–1982	173
Wilmot River, PEI	449281	5137937	45.4	1972–1997	318
North Brook, PEI	451308	5132786	12.9	1971–1987	310
Emerald Brook, PEI	457066	5134132	5.6	1974–1992	262
Dunk River, PEI	451199	5132665	114	1961–1997	354
				Mean:	283

[a] *X* and *Y* are given in Nad 83, zone 20, coordinates

an average of 130 to 165 mm/year is considered most likely representative of the groundwater recharge for the study area (see Rivard et al. 2008 for more details).

Based on a study of groundwater usage carried out for NB (77% of the study area; Johnson 2002) and assuming that NB is representative of the entire study area, groundwater withdrawal was evaluated to be on the order of 137,000 m^3/day, which is equivalent to 6 mm/year, once applied over the whole territory. Values estimated for the water balance and groundwater use in the study area are summarized in Fig. 6. The annual recharge corresponds to 13.5% of the annual total precipitation, while 48% goes to runoff and 38% to evapotranspiration. The total groundwater withdrawal represents only 0.5% of the total precipitation or 4% of the recharge. In comparison with other parts of the country and worldwide, the MB seems privileged in regard to the annual aquifer recharge. However,

Table 5 Water balance recharge estimates for the various geological units

Formation or Group	Area (km^2)	Percent total area	Potential recharge (mm/year)		
			min	mean	max
PEI Group	1560.3	13.5%	224	300	387
Undiv. Pictou and Cumberland Gp, Richibucto and Balfron Fm,	5923.0	51.3%	122	192	245
Boss Point Fm	1272.9	11.0%	198	310	403
Salisbury Fm	884.4	7.7%	0	40	118
Horton, Mabou, Windsor Gp	1460.1	12.6%	0	51	120
Basement Complex	443.4	3.8%	0	33	106
Weighted average:			115	184	251

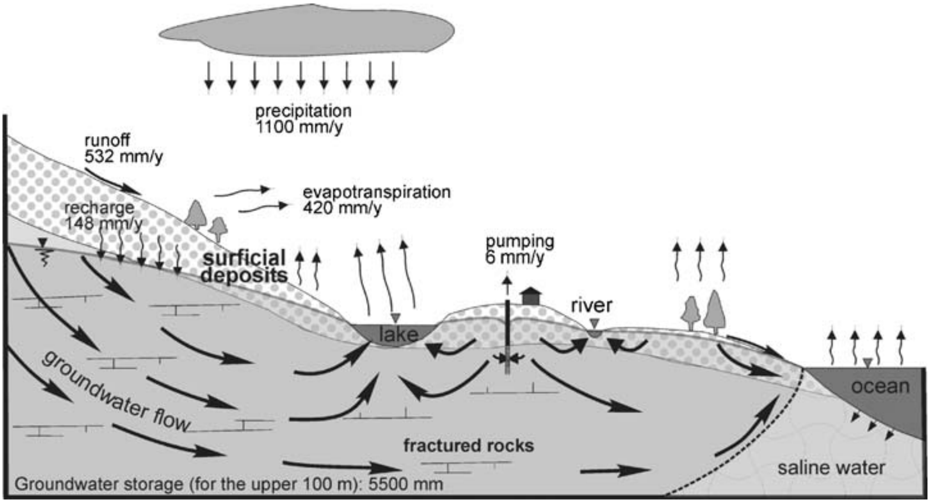


Fig. 6 Schematic cross section summarizing the estimated annual water balance. Precipitation, runoff, and evapotranspiration were obtained using 21 meteorological stations with 3 to 30 years of data. Calculations of water balance terms are described in Sections 3.4 and 4.7. Pumping uses the equivalent of 6 mm/year of the total recharge (148 mm/year), so the effective recharge is 142 mm/year

these recharge values are only global estimates representative at the regional scale. For exploitation purposes, local studies need to be conducted.

5 Numerical Groundwater Flow Models

5.1 General Description of the Numerical Models

Numerical models were used in this project mainly to confirm the general flow directions and groundwater recharge rates and hydraulic conductivities. Due to the MB lenticular nature of permeable bodies and strong heterogeneity, the geology had to be simplified to build the 2D and 3D models. Models were thus developed using only the dominant formation for a given region, and a horizontally stratified media with homogenous properties for each layer (since hydraulic conductivities decrease with depth). The first layer of each hydrostratigraphic unit was assigned a hydraulic conductivity (*K*) value based on the geometric mean of pumping test results. Formations or groups for which none or very few values were available were assigned *K* values according to judgement, based on their dominant stratigraphic composition. The subsequent layers were assigned *K* values according to reported porosities as a function of depth available for PEI (Chi et al. 2003) and empirical relationships between porosity and permeability (Blatt et al. 1980). This homogeneity assumption for each layer is supported by other studies (Brown 1971; Carr 1969) where evidence of hydraulic continuity throughout the layered aquifer–aquitard system was found. Considering the similarities in rock properties throughout the MB, this conclusion can likely be extended to the whole study area.

Probable recharge rates (*W*) were also assigned to each formation or group, based on results from the prior study on recharge (see Table 5). The till layer was assigned property values obtained from fieldwork and, where not available, based on their presumed composition since the latter is related to the underlying bedrock formation.

5.2 2D Models

Vertical 2D section models, comprising only the bedrock, were first developed to test some hypotheses. Two sections, one in the central part of PEI (A–A′ cross-section shown in Fig. 5) and the other in NB located between the Bay of Fundy and the Northumberland Strait (B–B′ cross-section), were modelled. Knowing the approximate hydraulic head distribution across the sections from measurements, a sensitivity analysis was performed, using plausible recharge rates and K data based on previously found values. Four different values of K were used over the model to vertically characterize the island, with $K_x=10^{-4}$ m/s at the surface to 10^{-6} m/s deeper than 300 m, with a conservative anisotropy ratio of 1/10 ($K_z=K_x/10$), based on packer test results and reported information.

Even if most of the flow occurs within the most permeable part of the section (<200 m, and especially in the upper 100 m), the PEI model has shown that not considering the deep part of the flow section would result in an unrealistic rise of the water table. For the PEI section, a combination of W=250, 300 and 350 mm/year for recharge with K_x=1.2, 1, and 0.7×10^{-4} m/s in the upper portion respectively gave a realistic water table elevation.

The NB section suggested that regional faults had a major impact on the system's hydraulic behaviour. Simulations showed that it was impossible to obtain the observed water table profile using previously estimated K and W values. The major faults, perpendicular to the section, could not be represented in the 2D model. Provincial authorities confirmed that these faults tend to be brittle structures, which seem to act as conduits.

5.3 3D Model

5.3.1 3D Model Description

The 3D numerical model covers a total area of 27,300 km^2. This time, the till layer was included, but with a constant thickness (4 m in PEI and 8 m for NB and NS). Twelve layers were used for the model, and approximately 3000 linear (three-node) triangular elements of similar area discretized each layer for PEI and 7,000 in the case of NB and NS. Similarly to the 2D models, a horizontally stratified media was used. Table 6 provides the initial and calibrated hydraulic conductivity (K) and recharge (W) values used in the model for the upper part of the bedrock unit. For the till layer, K values obtained from fieldwork (see Section 4.4) were used.

Dirichlet boundary conditions (constant head) were assigned almost everywhere on the boundaries, since the modelled area was chosen larger than the one specifically under study so as to be able to include natural boundaries such as major rivers. The only exception is at the eastern part of Nova Scotia, where a no-flow boundary (along a streamline) was used based on the map of hydraulic heads. The Petitcodiac River (NB) was also included in the model as a Dirichlet boundary condition since it represents a major discharge zone.

5.3.2 Results of the 3D Model

Simulations for PEI confirmed that the aquifer underlying the island is very permeable and that recharge is abundant. An overall recharge of 300 to 350 mm/year can be applied over the territory to retrieve a hydraulic head distribution similar to the map of hydraulic heads (Fig. 5) when using a hydraulic conductivity of 10^{-4} m/s, in agreement with previously found values.

Table 6 Combination of possible values of hydraulic conductivity and recharge rate for the (dominant) formations of the calibrated numerical model

Group	Stratigraphic unit	K initial[a] (m/s)	K model (m/s)	W initial[b] (mm/year)	W model (mm/year)
PEI	Undifferentiated	1.2×10^{-4}	10^{-4}	285	300 or 350
Pictou	Richibucto/Undivided	2.2×10^{-5}	3×10^{-5}	134–169	100
	Balfron	3.3×10^{-5}	3×10^{-5}	134–169	100–150
	Salisbury	1.4×10^{-6}	10^{-6}	28–35	20
Cumberland	Boss Point NB	1.1×10^{-5}	3×10^{-5}	217–273	150
	NS	2.8×10^{-6}	3×10^{-6}	–[c]	100
	General (undivided)	4.9×10^{-6}	5×10^{-6}	–[c]	50
Mabou	Hopewell	5.1×10^{-6}	5×10^{-6}	36–45	20
Windsor	Hillsborough	4.1×10^{-7}	5×10^{-7}	36	20
Horton	Weldon	–	10^{-7}	36	20
Basement Complex	Pre-Carboniferous	–	10^{-9}	23–29	negligible, <1

[a] Mean values calculated using pumping test results.

[b] Mean values taken from Table 5 minus 11–30%.

[c] Recharge rates obtained from existing data were calculated only within the study area.

Initial runs for NB and NS using probable *K* and *W* values showed unrealistic potentiometric values, hydraulic heads being too high in comparison with the water level measurements. Therefore, based on the 2D modelling, major faults shown on the geological map (Fig. 2) were added to the model. Since FEFlow cannot explicitly represent faults, they were integrated in the model using narrow segments of very high hydraulic conductivity in the bedrock layer ($K_{\text{fault}}=1$ m/s, an arbitrary value used only to see the impact of a much larger *K*). This modification greatly improved the results. Too high simulated hydraulic heads were likely due to the fact that water could not be evacuated freely with the original (equivalent porous media) model that did not account for the potential effect of major faults. It thus provided a plausible mechanism for reproducing observed hydraulic heads in the model that was preferred to the alternative mechanism of increasing K regionally at values much higher than hydraulic measurements.

Over large areas such as geological formations or groups, some *K* and *W* values had to be modified compared to mean values previously found (see Table 6). However, numbers used in the model were always within plausible values, recharge rates being included in the range of values (minimum and maximum) previously estimated (see Table 5) and *K* values taken from the formation log *K* distributions (Fig. 4b). A summary of the mean recharge rates obtained with the three methods is presented in Table 7. Ranges of *W* provided by all methods for most permeable regions are of the same order of magnitude; they represent 10 to 30% of total precipitation. Weighted average for the modelled region gives 135 mm/year, a value lying within the range obtained with the corrected water balance method (130–165 mm/year).

The simulated map of hydraulic heads is presented in Fig. 7. The potentiometric isocontours are of course simplified in comparison with the map drawn from water level measurements (Fig. 5), but hydraulic heads are well reproduced with this simplified numerical model. The mean absolute error (measured minus simulated) is 4 m, indicating a slight underestimation of heads by the model (Fig. 8). That error is within the range of the digital elevation model accuracy (≈5 m). There is not much bias in the simulated heads, as shown by the closeness of the linear regression line to the perfect fit line. The root mean square error is relatively large, at 33 m, and exceeds the model calibration target, which was

Table 7 Recharge rate summary

Method	Mean recharge rates (mm/year)	
	Most permeable formations	Regional value
Stream hydrograph separation	92–436	–
Corrected water balance	138–241	130–165
Modelling	100–350	135

set at 25 m (about 10% of the range in hydraulic heads in the study area). Even though there is considerable spread in simulated versus observed heads, the model calibration generally supports the conditions used. The model is thus coherent with the combination of estimated hydraulic conductivity and recharge. The model also confirms the potentially important role of faults in the regional flow system. The spread of hydraulic heads about the perfect fit may also reflect the heterogeneity of the flow system: potentially large local variations in hydraulic conductivity could lead to significant departures of measured head compared to predictions from a model using uniform hydraulic properties. The water balance from this steady-state condition model shows that 100% of the recharge comes from infiltration through the overlying surficial deposit layer. All boundaries, representing streams or the ocean, consequently act as discharge areas.

6 Discussion–Presentation of the Hydrogeological Conceptual Model

The present understanding regarding the hydrostratigraphic units, regional and local groundwater flow systems, hydraulic behaviour under pumping, and water balance of the study area are summarized in Tables 8 and 9, as well as Fig. 9. Three scales were used to

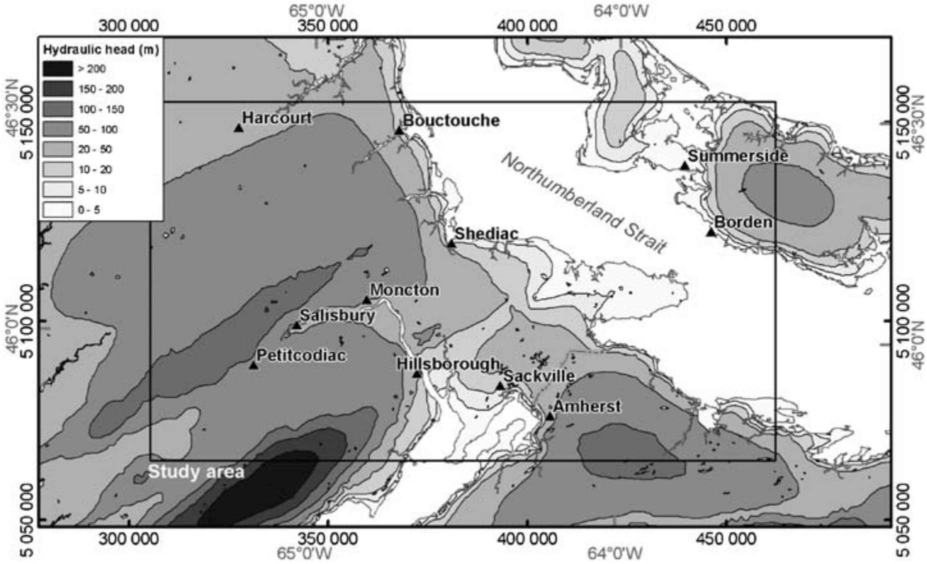


Fig. 7 Simulated map of hydraulic heads obtained with the simplified 3D model. Comparison can be made with the map of measured heads (Fig. 5)

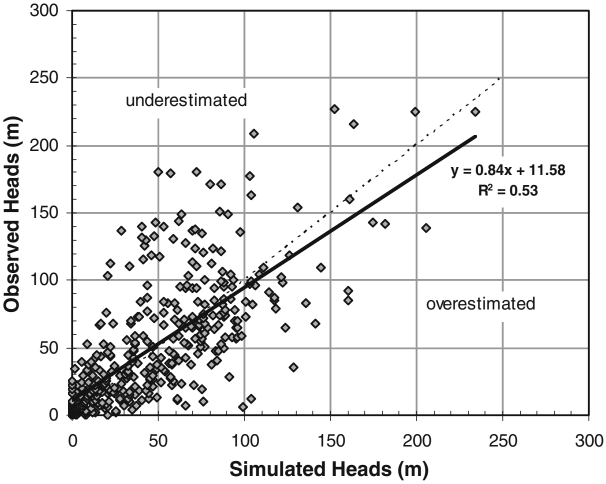


Fig. 8 Observed versus simulated heads. The dashed line is the theoretical perfect fit presented for reference. The full line is the linear regression whose equation and R^2 are indicated on the graph. Labels indicate if simulated heads "overestimate" or "underestimate" observations

schematically describe the characteristics and conditions of the MB hydrogeological system: regional, local and point scales.

The regional scale conceptual model, encompassing the entire study area, cannot take into account the individual lenticular bodies of sedimentary rocks, which form a discontinuous and layered aquifer-aquitard sequence within geological formations, as they have small extents and variable thicknesses. Regionally, each geological formation must therefore be considered as a single hydrostratigraphic unit over the entire model thickness, though with stratified layers, as hydraulic conductivity decreases with depth. Above the bedrock aquifer, the upper part of the conceptual model is composed of unconsolidated glacial till. The till layer composition is directly related to the underlying bedrock formation (the till matrix varies from silty to sandy). Due to a lack of information and uncertainty about the till thickness in many areas, a constant till thickness layer is assumed at this scale. Recharge mainly occurs through the till cover and, preferentially, through sandy tills, but a portion of this water probably never reaches the bedrock and reaches streams by subsurface flow. A large portion of the study area is likely under confined conditions. The system is thus said to be partly confined, as both confined and unconfined conditions can be found, depending on the till layer composition and fracturing of overlying beds. Regional faults are presumed to have an important influence on groundwater flow. Groundwater levels generally follow the surface topography.

The local scale corresponds to the area being influenced by a pumping test, which is on the order of a few km^2. At this scale, the layering and fracturing of the heterogeneous bedrock aquifers can strongly influence the hydraulic behaviour. The sketch in Fig. 9 depicts a hypothetical sequence of the common sedimentary rock types encountered in the region. The proportion of each rock unit varies from one geological formation to another; unit thickness is also highly variable within each formation. Pumping tests revealed that aquifers can locally be very heterogeneous and anisotropic due to these discontinuities and fracturing, but behave as equivalent porous media, likely because fractures are well interconnected. In addition, they confirmed the limited extent of the aquifers by showing impermeable boundaries in many cases. Locally, the till layer is characterized by a variable thickness (ranging from 0 to 20 m).

Finally, the third scale presents the aquifer material heterogeneity with plausible fracture patterns and matrix characteristics of the fractured bedrock aquifers. Mean matrix porosities range between 5–10%. Strata are generally subparallel to the surface with bedding planes dipping gently towards the Northumberland Strait. The thick sedimentary rock sequence is

Table 8 Main characteristics of the surficial deposits and bedrock within the study area

Unit	Role and characteristics
Till layer	Role: provide aquifer recharge Characteristics: Preferential groundwater (GW) recharge occurs through sandy till units The nature of tills depends on the underlying bedrock formation Permeable (sandy): PEI Gp and Boss Point Fm: $K=1.3\times10^{-6}$ m/s Low permeability (silty): Salisbury Fm, $K=6.5\times10^{-9}$ m/s Moderately permeable: others: $K_{\text{first 40 cm}}=1.4\times10^{-6}$ m/s; $K_{>40\text{ cm}}=6.5\times10^{-9}$ m/s Thickness ranges from 0 to 20 m, but is generally <10 m (75th percentile)
Carboniferous rocks	Role: provide good quality groundwater (aquifers) Characteristics: Fractured porous media; Main aquifer units: PEI Gp, Richibucto Fm, Balfron Fm, Undivided Pictou Gp, Boss Point and Hillsborough Fm Main aquitard units: Salisbury Fm, Horton and Mabou Gp Lithologies: sandstone, siltstone, shale and conglomerate. Mean percentage of each rock unit varies from one geological formation to another Lenticular and discontinuous beds. Partly confined, as unconfined and confined conditions are present Some intergranular porosity is present (5–10% on average) Fractures are mostly horizontal and related to bedding planes and lithological changes Vertical fractures are not as common but link horizontal fractures Fracturing better developed in conglomerates and sandstones Fractures show a very strong N45°E preferential orientation Hydraulic properties (closely related to the presence or absence of fractures): mean K for aquifer units varying from 5×10^{-6} and 1×10^{-4} m/s mean S between 10^{-4} and 10^{-3} (for all types of conditions) For PEI, mean S_y values between 2 and 7% Well typical specific capacity ≈0.01 l/s/m (domestic) Aquifer vulnerability: Low where low-K till is present (e.g. Salisbury Fm) High where high-K till is present (especially PEI Gp and Boss Point Fm). Good groundwater quality of $CaHCO_3$ type for the upper 100 m. Problems of nitrates in PEI.

highly fractured, showing a large number of discontinuities along the bedding planes with some major and likely a moderate to high number of small vertical fractures intersecting the bedding planes. Fractures are also more numerous in sandstone and conglomerate units. Most fractures seem to have a N45°E strike, in agreement with regional structures (e.g. Caledonian and Kingston Uplifts). These features seem to infer a quasi horizontal 2D flow, with a preferential component along strike.

7 Conclusion

This project represents a first regional inventory of the groundwater resources in the Maritimes Basin (Eastern Canada) at the 1:250,000 map sheet scale. It provided, amongst other things, a hydrogeological database, a water balance, a map of hydraulic heads indicating flow directions, as well as conceptual and numerical models for this vast region.

Table 9 Characteristics of each conceptual model scale

Regional scale (characterization of the entire study area, 14,000 km^2)

GW Recharge:
- Mainly occurs through till (supposed of constant thickness, due to a lack of information and uncertainty)
- Preferential GW recharge zones where till is sandy
- GW recharge rates vary from 22 to 271 mm/year with a weighted average of 130 to 165 mm/year over the study area when using 11 to 30% of areas with upward GW flow where recharge cannot occur (discharge areas)

General GW flow patterns:
- Lenticular discontinuous beds cannot be considered individually at regional scale. Therefore, each formation is taken as one hydrostratigraphic unit over the model depth using average pumping test results
- Gravity-driven system with flow from topographic highs towards the sea or major streams
- GW depth is on average 6.7 m, but varies from 50 m deep to artesian
- Major streams affect regional GW flow, thus mostly connected to aquifers but may be independent of aquifers locally, i.e. water elevations different in wells and streams
- K decreases with depth (connected fractures sparser or not as open), main GW flow occurs in the upper 100 m
- Major faults seem to act as preferential GW flow zones. Such “drains” are required in the GW flow numerical models to allow the drainage of estimated recharge volumes

Local scale (hydraulic behaviour as observed during pumping tests, ≈1 km^2)
- Aquifer conditions depend on nature and thickness of overlying till, partly confined in NB and NS, unconfined in PEI
- Frequent and well connected sub-horizontal fractures impart a quasi 2D flow
- Behaviour as equivalent porous media (EPM) under pumping (follow Theis type curves)
- Lenticular and discontinuous beds; leads to frequent negative hydraulic boundaries for wells under pumping
- Very anisotropic, observation well response very dependant on orientation of main fractures (wells may not respond away from the preferential N45°E orientation)
- Individual rock strata thickness is highly variable within each formation

Point scale (scale of borehole, ≈1 m^2)
- Fractured porous media
- For fracture pattern characteristics, see Table 8
- Low K matrix. Sandstone matrix without fracturing on the order of 10^{-7} to 10^{-8} m/s
- Typical matrix porosity (5–10%) for sedimentary rocks allowing significant water storage

The hydrogeological synthesis and the work performed underscored the great complexity of this hydrogeological system.

The MB, a fractured porous medium, was found to react similarly to an anisotropic porous medium when pumped, due to the presence of a well developed fracture network, having a main strike north-east. Fractures of this large flow system were initially thought to be sufficiently connected to provide an equivalent porous media at the regional scale, but modelling showed that major faults had an important role in the groundwater flow. Indeed, faults had to be added to the groundwater flow model to capture the system response.

Good to variable aquifer units are present in most of the study area. High hydraulic conductivities (K) on the order of 5×10^{-6} to 10^{-4} m/s can be found in many areas. The mean overall recharge rate (W) of the study area was estimated to be on the order of 130 to 165 mm/year. The results of this study did not show groundwater over-exploitation, as groundwater use was estimated to be on the order of 5% or less of the recharge. Based on the

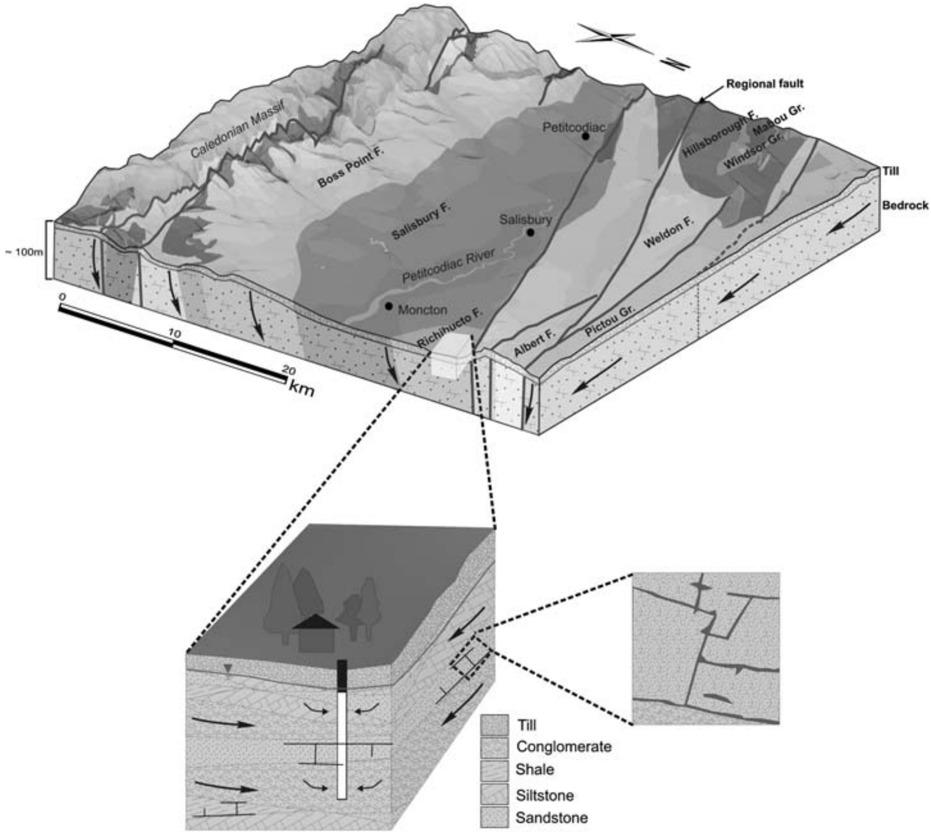


Fig. 9 Schematic conceptual model showing regional, local and point scales. Arrows indicate general GW flow

till layer composition and recharge rates, the territory investigated was either assigned a low, moderate or high level of vulnerability. Only the PEI Group and Boss Point formations were classified as highly vulnerable to surface contamination due to their sandy matrix cover.

This synthesis and characterization project allowed a regional understanding of the hydrodynamics within the MB and, therefore, should help the prediction of its behaviour at a given scale, and, as a result, contribute to the development of long-term groundwater resource management. However, it also shed light on several issues for the MB and in general, including (1) the system's anisotropy, (2) the continuity/discontinuity of the aquifers, (3) the specific role and extent of the faults on the regional flow, and (4) the data uncertainty and their impacts on the results. These topics are quite complex and exceeded the scope of this regional study, as each would deserve a dedicated project.

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References

Ben Kabbour B, Zouhri L, Mania J (2005) Overexploitation and continuous drought effects on groundwater yield and marine intrusion: considerations arising from the modelling of Mamora coastal aquifer, Morocco. Hydrological Processes 19:3765–3782

Blatt H, Middleton G, Murray R (1980) Origin of sedimentary rocks, 2nd edn. Prentice-Hall Inc., Englewood Cliffs, New Jersey, p 782

Boisvert V (2004) Hydrogéologie des formations quaternaires et influence sur la recharge de la région de Moncton, Nouveau-Brunswick. Master thesis, Université du Québec, INRS-Eau, Terre et Environnement, p 96

Bouwer H, Rice RC (1976) A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. Water Resources Research 12(3):423–428

Brown DD (1971) Hydrogeology of Taylor Island New Brunswick. Ph.D Thesis, University of Western Ontario, London, Ontario, p 160

Butler JJ Jr, Garnett EJ (2000) Simple procedures for analysis of slug tests in formations of high hydraulic conductivity using spreadsheet and scientific graphics software. Kansas Geological Survey Open-File Report. 2000–40, p 23

Carr PA (1964) Geology and hydrogeology of the Moncton map-area. New Brunswick, Canada. Ph.D. Thesis, University of Illinois, p 104

Carr PA (1969) Salt-water intrusion in Prince Edward Island. Canadian Journal of earth Sciences 6(63):63–74

Chapman TG (1991) Comment on “Evaluation of automated techniques for base flow and recession analyses” by R.J. Nathan and T.A. McMahon. Water Resources Research 27(7):1783–1784

Chi G, Giles PS, Williamson MA, Lavoie D, Bertrand R (2003) Diagenetic history and porosity evolution of Upper Carboniferous sandstones from the Spring Valley #1 Well, Maritimes Basin, Canada—Implications for reservoir development. Journal of Geochemical Exploration 80(2):171–191

Chow VT, Maidment DR, Mays LW (1988) Applied hydrology. McGraw-Hill International Editions Civil Engineers Series, Singapore, p 572

Côté M-J, Lachance Y, Lamontagne C, Nastev M, Plamondon R, Roy N (2006) Atlas du basin versant de la rivière Châteauguay. Collaboration étroite avec la Commission géologique du Canada et l’Institut national de la recherche scientifique—Eau, Terre et Environnement. Québec: ministère du Développement durable, de l’Environnement et des Parcs, p 64

Coutagne A (1954) Quelques considérations sur le pouvoir évaporant de l’atmosphère, le déficit d’écoulement effectif et le déficit d’écoulement maximum. La Houille Blanche, pp 360–374

Cruz JV, Silva MO (2001) Hydrogeologic framework of Pico Island, Azores, Portugal. Hydrogeology Journal 9(2):177–189

El Rahman HA (2001) Evaluation of groundwater resources in lower cretaceous aquifer system in Sinai. Water Resources Management 15(3):187–202

Elrick DE, Reynolds WD, Tan KA (1989) Hydraulic conductivity measurements in the unsaturated zone using improved well analyses. Ground Water Monitoring Review 9:184–193

Fagnan N, Bourque É, Michaud Y, Lefebvre R, Boisvert É, Parent M, Martel R (1999) Hydrogéologie des complexes deltaïques sur la marge nord de la Mer de Champlain. Hydrogeologie, BRGM, Numéro spécial sur l'hydrogéologie au Québec, no 4, pp 9–22

Francis RM, Gale JE (1988) Permeability distribution in a fractured sedimentary aquifer system. IAH Proceedings, Canadian National Chapter, Atlantic region, Halifax, Nova Scotia, May 1988, pp 72–79

Furey PR, Gupta VK (2001) A physically based filter for separating base flow from streamflow time series. Water Resources Research 37(1):2709–2722

GeoSlope International (1997) SEEP/W version 4—Geo-Slope User’s guide. Geo-SlopeÒ: http://www.geo-slope.com/products/seepw.asp

Grasby SE, Chen Z, Hamblin AP, Sweet A (2005) Regional groundwater study of the Paskapoo Formation, SW Alberta. in: Proceedings of the 58th Canadian Geotechnical and 6th Joint CGS-IAH Groundwater Specialty Conferences. Saskatoon, September 18–21

Hacquebard PA, Barss MS (1970) Palaeogeography and facies aspects of the Minto coal seam, New Brunswick, Canada. International Congress on Carboniferous Stratigraphy and Geology 3:861–872

Johnson M (2002) Withdrawal water use in New Brunswick. Department of Environment and Local Government, Sciences and Reporting Branch, New Brunswick, p 73

Johnson SC (1995) A preliminary report on the stratigraphy of Late Namurian to Stephanian fluviatile strata in southeastern New Brunswick. Current Research 1995-E, Geological Survey of Canada, pp 13–320

Kennedy PL, Woodbury A (2003) Regional Scale Flow and Transport Model of Carbonate and Sandstone Aquifers in Southern Manitoba. Proceeding of the 56th annual Canadian Geotechnical Conference and 4th Joint IAH-CNC and CGS Groundwater Specialty Conference, Winnipeg, Manitoba, Canada, September 29–October 1 2003

Kruseman GP, de Ridder NA (2000) Analysis and evaluation of pumping test data, 2nd edn. International Institute for Land Reclamation and Improvement, The Netherlands, p 377

Lynch G, Giles PS, Deblonde C, Barr SM, Piper DJW, St. Peter C, Hetu RJ, Johnson SC, Pe-Piper G, St. Jean R, Murphy JB, Chandler FW, Boehner RC (1998) Magdalen Basin NATMAP Onshore Geological Database. Geological Survey of Canada, Open File 3564, CD-ROM

MacDougall JI, Veer C, Wilson F (1988) Soils of Prince Edward Island. Research Branch, Agriculture Canada, no 83–54, p 210

Mahlknecht J, Schneider JF, Merkel BJ, Navarro de León I, Bernasconi M (2004) Groundwater recharge in a sedimentary basin in semi-arid Mexico. Hydrogeology Journal 12(5):511–530

Michaud Y, Lefebvre R, McCormack R (2004) Guide méthodologique pour la cartographie hydrogéologique régionale des aquifères granulaires de surface. Report submitted to the Ministère de l'Environnement du Québec

Morin R, Thériault T, Therrien R, Michaud Y (2002) Generalized hydrogeologic properties of the Maritimes Carboniferous Basin from downhole measurements in selected wells, Eastern Canada. In: Ground and Water: Theory to practice. Proceedings of the 55th Canadian Geotechnical and 3rd joint IAH-CNC and CGS Groundwater Specialty Conferences, Niagara Falls, Ontario, October 20–23, 2002, pp 247–254

Nastev M, Lefebvre R, Rivera A, Martel R (2006) Quantitative assessment of regional rock aquifers, South-Western Quebec, Canada. Water Resources Management 20(1):1–18

Nyvall J (2002) Soil water storage capacity and available soil moisture. Water Conservation Factsheet no 619000-1, Ministry of Agriculture, Food and Fisheries, British Columbia, Canada, p 4

Paradis D, Ballard JM, Savard MM, Lefebvre R, Jiang Y, Somers G, Liao S, Rivard C (2006) Impact of agricultural activities on nitrates in ground and surface water in the Wilmot watershed, PEI, Canada. 7th Joint CGS/IAH-CNC Groundwater Specialty Conference, October 1–4, 2006, p 8

Rampton VN, Gauthier RC, Thibault J, Seaman AA (1984) Quaternary geology of new Brunswick. Geological Survey of Canada, Memoir 416:77

Rivera A, Crowe A, Kohut A, Rudolph D, Baker C, Pupek D, Shaheen N, Lewis M, Parks K (2003) Canadian Framework for Collaboration on Groundwater (CFCG). Government of Canada, p 60. Issued on the Internet at: http://www.cgq-qgc.ca/cgsi <http://cgq-qgc.ca/cgsi>

Rivard C, Deblonde C, Michaud Y, Boisvert V, Carrier C, Castonguay S, Lefebvre R (2005a) Hydrogeological Atlas of the South-Central Area of the Maritimes Carboniferous Basin. Geological Survey of Canada, Open File no 4884, p 54, 1 CD-ROM

Rivard C, Michaud Y, Boisvert V, Calvert T, Morin RH, Deblonde C, Lefebvre R, Pupek DA (2005b) Hydrogeological data from the South-Central Area of the Maritimes Carboniferous Basin (MGWI project), Geological Survey of Canada, Open file 4942, p 143, 1 CD-ROM

Rivard C, Deblonde C, Boivin R, Bolduc A, Paradis D, Paradis SJ, Liao S, Gauthier M-J, Blackmore A, Trépanier S, Fernandes R, Castonguay S, Drage J, and Michaud Y (2007) Canadian groundwater inventory: Hydrogeological atlas of the Annapolis Valley, Nova Scotia, GSC Open File 5541, p 128

Rivard C, Michaud Y, Deblonde C, Boisvert V, Carrier C, Morin RH, Calvert T, Conohan D, Castonguay S, Vigneault H, Parent M, Lefebvre R, Rivera A (2008) Canadian Groundwater Inventory: Regional Hydrogeological Characterization of the South-Central Area of the Maritimes Basin. GSC bulletin no 589, p 128 (in press)

Robins NS, Jones HK, Ellis J (1999) An aquifer management case study-the chalk of the English South Dows. Water Resources Management 13(3):205–218

Savard MM, Paradis D, Somers G, Liao S, van Bochove E (2007) Winter nitrification contributes to excess NO_3^- in groundwater of an agricultural region: A Dual Isotope Study. Water Resources Research, 43, W06422, p 10

Scanlon BR, Healy RW, Cook PG (2002) Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeology Journal 10:18–39

Sharpe DR, Hinton MJ, Russell HAJ, Desbarats AJ (2002) The Need for Basin Analysis in Regional Hydrogeological Studies: Oak Ridges Moraine, Southern Ontario. Geoscience Canada 29(1):3–20

Sloto RA, Crouse MY (1996) HYSEP: a computer program for streamflow hydrograph separation and analysis. U. S. Geological Survey, Water Resources Investigations, Report 96–4040, p 46

St. Peter C (1993) Maritimes Basin evolution: key geologic and seismic evidence from the Moncton Subbasin of New Brunswick. Atlantic Geology 29:233–270

Steenhuis TS, Winchell M, Rossing J, Jzollweg JA, Walter MF (1995) SCS Runoff Equation Revisited for Variable-Source Runoff Areas. Journal of Irrigation and Drainage Engineering 121(3):234–238

Stigter TY, van Ooijen SPJ, Post VEA, Appelo CAJ, Carvalho Dill AMM (1998) A hydrogeological and hydrochemical explanation of the groundwater composition under irrigated land in a Mediterranean environment, Algarve, Portugal. Journal of Hydrology 208(3–4):262–279

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

Turc L (1954) Le bilan d'eau des sols: relations entre les précipitations, l'évapotranspiration et l'écoulement. Annales agronomiques (Série A):491–595

Van de Poll HW, Gibling MR, Hyde RS (1995) Upper paleozoic rocks. In: Williams H (ed.) Chapter 5 of geology of the appalachian-caledonian orogen in Canada and Greenland. Geological Survey of Canada, Geology of Canada 6:449–566

Vaughan JG, Somers GH (1980) Regional water resources. Nova Scotia Department of the Environment, Cumberland County, Nova Scotia, p 81

WASY – Institute of Water Resources Planning and System Research Ltd (1998) FEFLOW – Reference Manual, Berlin. WASY FEFLOWÒ: http://www.wasy.de/english/produkte/feflow/index.html