HYDROGEOLOGICAL OVERVIEW OF THE TRANSBOUNDARY AQUIFERS IN THE CHÂTEAUGUAY RIVER BASIN, CANADA-UNITED STATES

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ABSTRACT
The Châteauguay River Watershed is located south of Montreal and extends on both sides of the Canada - USA border. The Châteauguay River flows out from the Upper Châteauguay Lake in the New York State and flows into Lac St-Louis on the south shore of the St. Lawrence River. Approximately 65% of the 100,000 habitants in the region rely on groundwater as the only source of water supply. The regional aquifers consist mainly of Lower Paleozoic sedimentary fractured rocks; sandstone, dolostone and limestone. Indications of important rock depressions are found below the modern rivers. Glacial and fine marine sediments cover regional aquifers. Regional recharge occurs at higher altitudes where rock crops out. The groundwater flow occurs from south to north and follows closely the direction of the surface waters flow.

RÉSUMÉ
Le basin versant de la rivière Châteauguay est situé au sud de Montréal et s'étend des deux côtés de la frontière canado-américaine. La rivière Châteauguay prend ses sources du Lac Châteauguay, État de New York, et se jette dans le Lac Saint-Louis sur la rive sud du fleuve Saint-Laurent. Approximativement 65% d'une population de 100,000 habitants dépend sur l'eau souterraine comme source d'alimentation en eau potable. Les aquifères régionaux se retrouvent dans les roches sédimentaires paléozoïques : grès, dolomies et calcaires. Des indications d'importantes dépressions rocheuses ont été retrouvées sous les rivières Châteauguay et aux Anglais. Les roches sédimentaires sont recouvertes par des dépôts glaciaires et marins. La recharge régionale s'effectue dans les hauts topographiques où l'écoulement se fait dans des conditions de nappe libre. La direction de l'écoulement de l'eau souterraine est du sud vers le nord et suit de près l'écoulement des eaux de surface.

1. INTRODUCTION

The Châteauguay River Watershed is located in south-western Quebec, south-west of Montreal. It extends on the both sides of the U.S. (New York State) Canada border. In Canada, it is a relatively densely populated region with approximately 100,000 habitants exerting important stress on the water resources in the region. Approximately 65% of the population rely on groundwater as the only source of water supply. Private wells are used mainly in the rural regions and it is estimated that approximately 20,000 wells tap their water from the regional aquifers. The industrial activity in the region resulted in one of the most important contamination cases in Canada in the early 70s when the DNAPL contamination in the Lagunes de Mercier forced the authorities of the Ville de Mercier and Sainte Martine to abandon the exploitation of the municipal wells. In rural regions located mainly to the north, the increased use of fertilizers and pesticides, and manure spreading potentially contribute to the alteration of the groundwater quality. The peat soils (terres-noires) of Sherington and Huntington are intensively used for truck farming. At higher altitudes in the Franklin region, the apple industry accounts for approximately 1/3 of the total production in Quebec. Currently, one bottling company withdraws groundwater for commercial purposes, but other industrial applications are under evaluation by the Quebec Ministry of Environment. Finally, the Covey Hill, located on the Canada USA border, is the unique location in Canada where Mountain Dusky salamanders are found. Their habitat, predominantly close to natural springs and seepage areas, is threatened by the industrial and agricultural activities and is of highest concern for the environmentalists of the both sides of the border (Environment Canada URLa).

The regional aquifers consist mainly of Lower Paleozoic sedimentary fractured rocks: sandstone, dolostone and limestone (McCormack 1981, Globensky 1987, Salad-Hersi et al. 2002, Salad-Hersi et al. 2003). These aquifers have been known for a long time to contain large water quantities, and many wells in the region were reported as flowing wells with abundant yields (McCormack 1981). Simard and Des Rosiers (1980) put these aquifers in the category of high permeability aquifers in Quebec with an average well yield of 360 m^3/d. The estimated mean transmissivity was $1{,}1x10^{-3}$ (m^2/s) for an average well depth of 30,5 m, resulting in average hydraulic conductivity of $3{,}6x10^{-5}$ (m/s). Regional aquifers are occasionally overlain by permeable fluvio-glacial sediments, which increase the overall transmissivity. Despite the relative abundance of groundwater resources, the steadily increase in groundwater use, in addition to the contamination cases and the prolonged drought conditions in the last several years, contribute to occasional shortages and potential disputes between various users in the heavily exploited areas. The local groundwater authorities are unprepared to face such problems as the lack of general understanding of the groundwater resource and of knowledge for the available groundwater quantity and quality precludes the formulation of suitable management plans. This was the main reason for the Geological Survey of Canada and for the Quebec Ministry of Environment (MENVQ) to initiate in 2003 a joint large-scale hydrogeological assessment of the Châteauguay River Watershed. This project is aligned with the Quebec Water Policy (MENVQ 2003) and with the Framework for collaboration on groundwater (Rivera et al. 2003), which aim to an inventory of major aquifers in Quebec and in Canada and to ensure sustainable management and protection of the groundwater resource. The main objectives of the Canadian investigation project are to define: 1) major aquifer units and their hydraulic properties, 2) groundwater dynamic parameters (recharge, flow rates, natural discharge, use) and groundwater buget for the study area, 3) groundwater quality 4) aquifer vulnerability to surface contamination and, 5) sustainability of the groundwater resource. In 2004, a proposal has been submitted for a hydrogeological study in the U.S. part of the Châteauguay River watershed (Reynolds and Williams 2004). The major objective of the proposed U.S. Geological Survey study is to extend the Canadian investigation of the Châteauguay River aquifers into the United States.

This paper presents a hydrogeological overview of the watershed, a summary of available data and some preliminary results based on the 2003 summer field campaign, the drilling works of the winter 2004, and on the beginning of 2004 summer field campaign. The discussion is concentrated on the geological data and hydrogeological descriptions of the main aquifer and aquitard units in the watershed.

2. STUDY AREA

The watershed of the Châteauguay River is located in south-western Quebec, south-west of Montreal. It extends on both sides of the USA (New York State) - Canada (Québec) border (Figure 1). Of the total surface of 2490 km^2, in Canada it encompasses approximately 1450 km^2, or 57%. This is one of the densely populated regions in Canada with some 100,000 habitants (Statistics Canada, 2001). Approximately two thirds (65%) of the population rely on groundwater as the only source of water. In the U.S., the watershed covers the eastern part of the Franklin County and the western part of the Clinton County. The aquifer system supplies largely rural population of small villages and farms.

The watershed encompasses two distinct physiographic regions: the St. Lawrence Lowlands, mainly in Canada, and the Adirondack Mountains in the New York State (Fig. 1). The Châteauguay River flows out from the Upper Châteauguay Lake in the New York State and flows into the Lac Saint-Louis on the south shore of the St. Lawrence River. The main tributaries are the rivières à la Truite and aux Anglais. The altitude of the land surface ranges from 22 masl along the St. Lawrence River to 1160 masl at the summit of the Lyon Mountain, at the southern edge of the watershed. With 340 masl altitude, the Covey Hill dominates the Canadian part of the watershed (Fig. 1). During the Wisconsinian Period, glaciers covered the entire region. Following the formation of the Champlain Sea, fine sediments of important thickness were laid down. Thus, besides the lithological and structural control exerted by the bedrock, the current relief is a product of the glacial movement and of the subsequent sedimentation under marine and fluvial conditions. Steep hillsides and narrow valleys are characteristic for the upper part of the watershed. In the lower part, valleys open to relatively gently sloping lowlands and flat terraces. The higher altitudes in the study area are typically dominated by rock outcrops or rock covered by a thin till layer. At lower altitudes (≤ 60 masl), thick marine deposits cover bedrock valleys filled first with stratified glacial deposits of variable thickness (Tremblay et al. 2004).

The regional aquifers consist of Lower Paleozoic sedimentary fractured rocks: sandstone, dolostone and limestone, occasionally overlain by coarse glacio-fluvial sediments. The sedimentary units overlie the crystalline rocks of Precambrian age. Fine marine sediments confine regional aquifers at altitudes below 60 masl. in most of the study area. At higher altitudes, regional aquifer units crop out or are in semi-confined conditions covered by shallow glacial deposits. Most of the regional recharge occurs in these high latitude areas. In the upper part of the watershed, groundwater flows mainly in unconsolidated glacial and fluvial deposits. Groundwater flow in the study area follows closely the surface water flow and occurs mainly in a south to north direction with the St. Lawrence River as the major regional discharge zone.

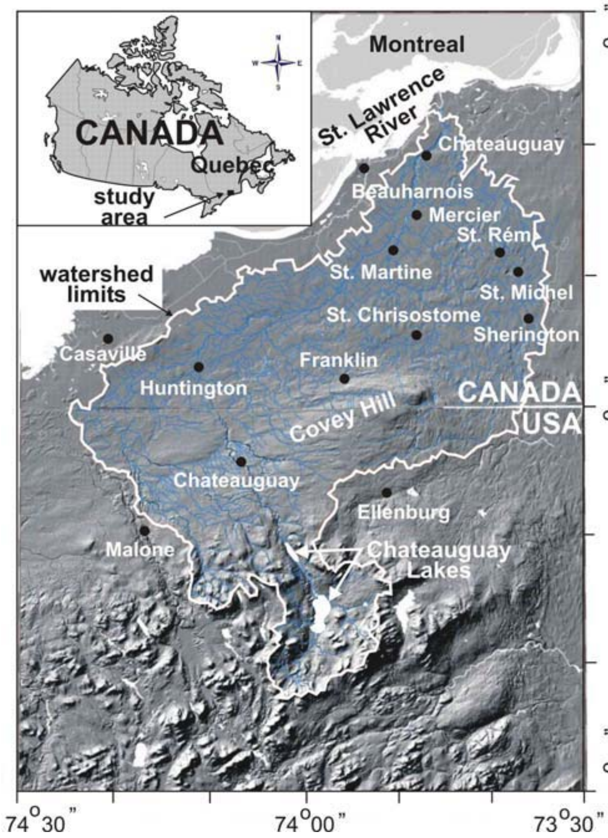

Figure 1. Study area with the DEM as background

The study area belongs to the Great Lakes and St. Lawrence climate region. It is characterized by a temperate climate with cold wet winters and hot wet summers (Environment Canada). Monthly air temperatures are lowest in January with a mean of -11.4 °C and peak in July with a mean of +20.9 °C. Ground frost develops generally by late November and lasts until mid-March when the spring snowmelt begins. The total annual precipitation varies between 930 and 1130 mm, with some 20% in the form of snowfall. The monthly precipitation is relatively uniform, with highest averages recorded in September, 101 mm, and lowest in February, 63 mm. This relatively abundant precipitation results in a positive water budget for the region.

Precipitation fluctuates both spatially and temporally. Spatial differences in mean annual precipitation are primarily controlled by the topographic effect. Mean annual precipitation averages 1200 at the Upper Châteauguay Lake (elevation 500 m), 1048 mm at Franklin (elevation 170 m), and 1000 at Beauharnois (elevation 30 m). Precipitation is weakly seasonal. Most precipitation occurs primarily as rain between April and October. Snowstorms, taking place mostly in January and February, are responsible for approximately 10% of the total precipitation. Annual potential evapotranspiration averages 450 mm based on the Thornthwaite method and varies spatially with the mean annual temperature, from north to south.

3. METHODOLOGY

The Châteauguay River Basin groundwater assessment project is currently in its second year. The techniques applied are rather conventional, first in order to comply with the project's budget and, second in order to meet the project objectives in the scheduled time length of three years.

The adopted methodology is shown in Figure 2. The first year of the project served primarily for the collection of existing data. The most important suppliers of existing data were the Quebec Ministry of Environment (drillers' logs, various hydrogeological reports), the Quebec Ministry of Natural Resources (geological and quaternary maps, exploration and drilling reports, geophysical transects, and satellite images), the Quebec Ministry of Agriculture Fishing and Alimentation (soil-pedologic maps). Climate and hydrologic data were provided by Environment Canada. Other collected data consisted of private companies reports, municipal and research studies.

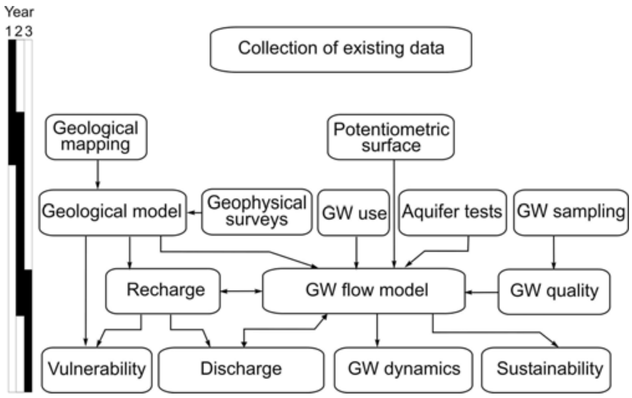

Figure 2. Applied methodology and time schedule of the 3 year groundwater assessment project

The multidisciplinary field studies include geological mapping of Quaternary deposits (Tremblay et al. 2004), stratigraphic and lithological mapping (Salad Hersi et al., 2002, 2003), borehole geophysics, hydraulic testing (slug tests, pumping tests, packer tests), and geochemical sampling. Potentiometric surface measurements and well drilling were carried out in summer 2003 and winter 2004. Bulk of the field work is scheduled for summer 2004.

4. PRELIMINARY FINDINGS

4.1 Geology

The bedrock geology consists of generally flat lying sedimentary strata of the Lower Paleozoic (Globensky 1987, Salad-Hersi et al. 2002, 2003). The Lower Paleozoic sedimentary strata are underlain by Grenvillian metamorphic rocks of Precambrian age, which form the Adirondack Mountains to the south. In the following text, crystalline rocks refer to both metamorphic and intrusive rocks.

Sandstone : The lower part of the sedimentary strata consists of Cambrian rocks with the siliciclastic-dominated units of the Potsdam Group. This sandstone-dominated unit is divided into two formations, the Covey Hill at the base and Cairnside at the top. The Covey Hill Formation is formed by feldspathic mostly reddish coarse sandstone. This facies is poorly sorted and poorly cemented, with a basal conglomerate layer. Its thickness exceeds 500 m. Diagenetic alteration within the uppermost part of the Covey Hill Formation has locally degraded the sandstone into a loose, oxidized and highly permeable breccia. The Cairnside formation is a homogeneous quartz-rich sandstone that contains up to 98% of well-sorted, rounded and well cemented quartz grains. The maximal thickness of the Cairnside Formation reaches 250 m (Globensky 1987).

Dolostone : The Potsdam Sandstone is overlain by the Lower to Middle Ordovician carbonate-dominated Beekmantown Group, a succession of mostly dolostone, limestone, and subordinate siltstone and shale with a total thickness of up to 460 m (Bernstein 1992, Salad-Hersi et al. 2002). In the study area, the Beekmantown Group is divided into two extensive formations, the Theresa at the base and the overlying Beauharnois. The Theresa Formation consists of interbedded quartz arenite, dolomitic sandstone and dolostone. The Beauharnois Formation is subdivided into two members, the Ogdensburg in the lower part, and the Huntington in the upper part, both of which contain dolostone with bioclastic and oolitic interbeds in various portions (Salad-Hersi et al. 2003).

Limestone : The uppermost sedimentary rock units are the limestones of the Chazy and Trenton groups and the siliciclastics of the Lorraine Group. The Chazy Group is represented by the Laval Formation. It is made up of sandstone at the base with shale and more or less dolomitic limestone in the upper portion. Its maximal thickness in the region can reach 100 m. The Trenton Group is divided in the St. Michel Member (Montréal Formation) at the base and the Tétrauville Formation at the top. With a maximal thickness of 250 m, it is composed of shaly limestone, with an upward increase in shale interbeds (Globensky 1987). The Lorraine Group is presented with the Nicolet Formation. It is a relatively thin unit (30 m) dominated by silty shale and fine sandstone.

It can be observed in Figure 3 that discrepancies in mapping of the bedrock units exist between Canadian and U.S. interpretations. Thus, a mixed dolomite and sandstone unit was identified in the U.S. It corresponds to the Cairnside and Theresa Formations on the Canadian side.

Using mainly the drillers' logs, it was possible to interpret the surface to sub-surface bedrock topography and interpolate the bedrock surface in the region. Figure 4 shows important rock depressions located more or less on the same axes as the modern day Châteauguay and Aux Anglais Rivers. These depressions represent former tertiary fluvial valleys are thought to have been eroded by the advancing ice sheets and/or by meltwater erosion. If filled with permeable sediments, they could provide storage and preferential direction for the regional groundwater flow.

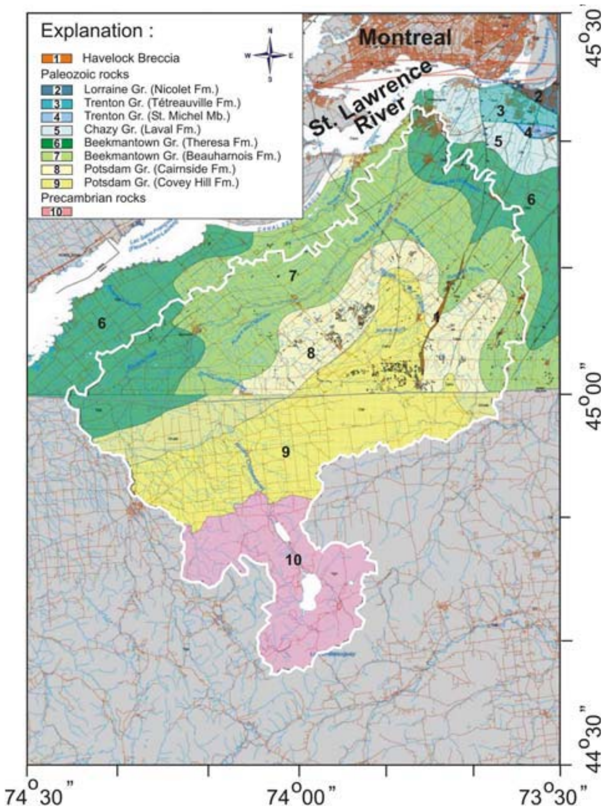

Figure 3. Regional map of bedrock geology (after Fisher et al. 1970, and Globensky 1987)

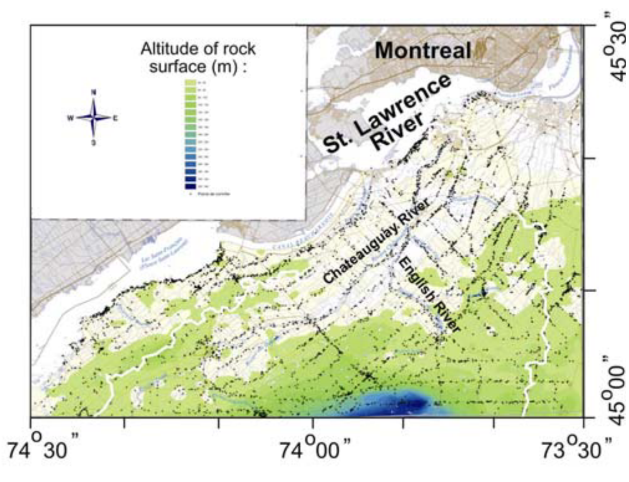

Figure 4. Bedrock topography. Black dots indicate the location of the drillers' logs used for the interpolation

4.2 Quaternary geology

Unconsolidated sediments overlay the bedrock units. Their thickness is variable and can reach as much as 45 m along the rock depression below the Châteauguay River. The most complete description of the Quaternary sediments has been obtained during the excavation of the Beauharnois naval channel and regional field campaigns in the U.S. portion of the St. Lawrence valley (MaClintock et Stewart, 1965).

The sediments at the base of the Quaternary sequence are glacial deposits (till). They extend in continuous layers over tens of kilometres and form a regional unit. The thickness of these sediments is several meters to several tens of meters and the grain size distribution is very variable. The fine matrix consists of a high portion of silt and clay size particles originating from the underlying sedimentary rocks (carbonates and shales) with a minor contribution from the crystalline rocks of the Precambrian basement. Occasionally, coarse deposits of sand and gravel and in some places even bouldery gravels are found at the base of the glacial till. These sediments were laid down when the sub-glacial meltwater partially or completely eroded the earlier glacial sequence. Generally, there are of two types of till: the Malone Till at the base, and the Fort-Corvington Till. They are separated by glacio-lacustrine sediments, e.g. Lake Châteauguay sediments which occur as varves and fluvio-glacial sediments at certain locations in the Mercier, St-Rémi and St-Michel sectors. Most of the times, the till is almost invariably observed immediately above the rock sequence. It is inferred from the well data and from the Beauharnois channel excavations that no sediments older than the Lower Till exist in the area. It seems that the glacial erosion of the earlier sediments was intense and complete during the last Wisconsian glaciations. The lack of transverse valleys crosswise to the main ice movement of the south and south-west directions confirm this hypothesis. Large fields of drumlins (till ridges) are present and are aligned in these directions. More westward, in the Huntington-Casaville sector, the drumlins were remoulded by later ice movements in a south-east direction (Delage 1997).

During the ice melt, a fluvio-glacial sequence has been occasionally deposited above till sediments. The Mercier, Athelstan and Beaver-Crossing ridges are eskers partly buried under marine slits and clays. Because of the subglacial fluvio-glacial erosion in channel valleys, the eskers in the study area are usually in direct contact with the underlying sedimentary rocks. Significant littoral-reworked rock-derived till and fluvio-glacial sediments are found in the vicinity of the Covey-Hill and at altitudes between 70 and 170 masl (Figure 5, unit CH).

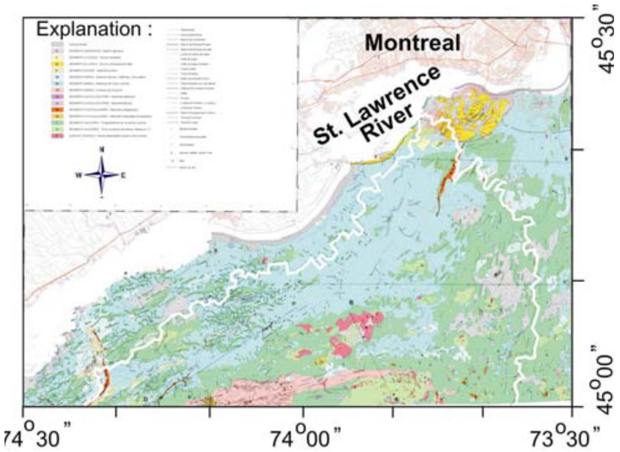

Figure 5. Surficial deposits (after Tremblay et al. 2004)

Champlain Sea and freshwater lakes inundated areas at lower altitudes after the ice melt and retreat between 10,000 and 11,000 BC. The Champlain Sea silts and clays are ubiquitous at altitudes below 50 masl. They constitute most of the land surface and are the most important confining unit in the region (Figure 5). The marine retreat allowed the formation of occasional littoral and fluvial sandy cover attaining several meters at some localities, primarily near fluvio-glacial and reworked till ridges. In some places, Lampsilis Lake Sediments are presents. These sediments are the remnants of the transition from the Champlain Sea to the modern surface waters drainage network. A Holocene terrace at 40 masl altitude is located along the St-Lawrence River between Beauharnois and La Prairie. It corresponds to the late evolution of the proto St. Lawrence River. Only few thick accumulations of alluvial sediments are present in the area. This is primarily because of the lack of available sandy materials (except near eskers) but also because of the flat topography of the silty and clayey plains. Thus, the current streams transport mainly fine particles which are readily transferred in the St-Lawrence Gulf as suspended load.

The Sherington and Huntington areas are particularly rich in Holocene organic matter soils. These peat soils are remnants of eutrophic lakes located mainly in depressions in rocks and/or in drumlins fields (Figures 1 and 5).

4.3 Potentiometric surface

Potentiometric data has been measured and compiled for the rock units in the study area. Groundwater levels were measured during the regional survey in summer 2003. 150 measuring points were selected in private wells intercepting the upper portion of the rock sequence, usually 10 to 30 m of open borehole length. They cover the study area, give an evenly distributed data set, and intercept regional aquifers in both confined and water table conditions. A high precision GPS (sub-meter precision) was used to position the wells. At the same time, physical properties of groundwater were measured:

temperature, pH, conductivity, dissolved oxygen and Redox potential.

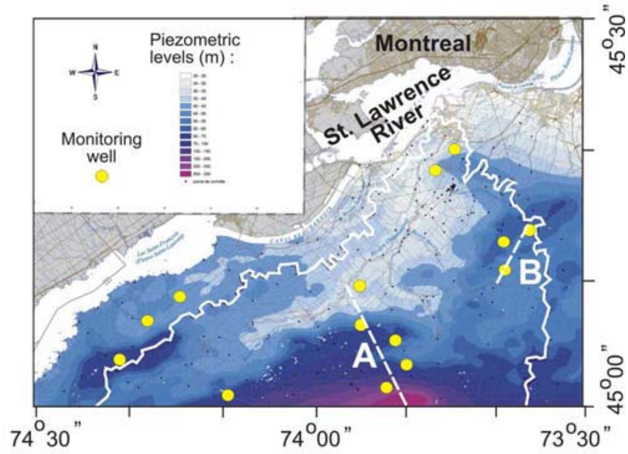

Figure 6. Regional potentiometric map. The yellow circles represent the locations of monitoring wells. The two major transects of groundwater flow are indicated with A and B.

Figure 6 shows the obtained potentiometric surface map created by generating contour lines from points with equal elevations. In addition to the measurement points, data from the drillers' logs were also used to define the piezometry in regions of higher hydraulic gradients and water divides. Both sets of points were separately krigged. The resulting potentiometric surface indicates that the regional groundwater flow is primarily from south to north. Locally, the groundwater flow follows the same general direction of the major streams and their tributaries. At the same time, the equipotentials replicate closely the terrain topography, being in general a few meters below the land surface. The boundaries of the flow domain coincide with hydrogeological features and topographic divides. Along the shore of the St. Lawrence River, the regional piezometry intercepts surface water elevations. Groundwater elevations attain approximately ~300 masl in the recharge areas at Covey Hill extending across the Canada-U.S. border.

In winter 2004, 13 rock wells and 7 piezometers were installed at 14 sites. This network has been established to monitor the long-term fluctuations of groundwater levels. The distribution of the monitoring wells is shown on Figure 6. Five of the sites have been chosen to coincide with the major south-north axe (Covey Hill – Châteauguay River) of the groundwater flow in the central part of the study area, transect A. Tree other wells form the other transect (B) located in the subwatershed of the Norton Creek, tributary of the aux Anglais River. The open borehole length of rock wells attains 100 m, whereas the piezometers screen over 1,5 m length the unconsolidated sediments right above the rock sequence. Automatic data loggers have been installed in each of these wells. Other water levels are also measured manually on a weekly to monthly basis.

In the beginning of June 2004, the USGS carried out geophysical logging of the rock wells. Caliper logs (vertical profiles of well diameter) were obtained for all rock wells preceding the constant head injection tests. A complete geophysical logs: conductivity, resistivity, temperature, sonic, acoustic tele-viewer and flow meter, were obtained in the 5 rock wells of the transect A. The rest of the rock wells will be logged in summer 2005.

4.4 Conceptual model for the regional groundwater flow

Following the data collected in the first year of the project and the preliminary results, it was possible to build a simplified conceptual model of the regional ground water flow (Figure 7).

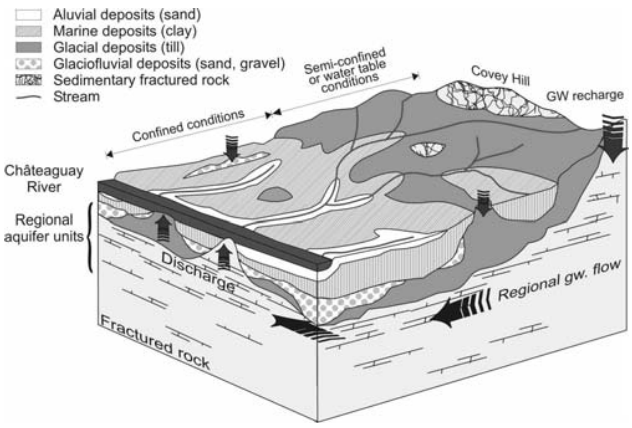

Figure 7. Conceptual model for the regional groundwater flow

On top of the regional aquifer system, the Quaternary aquitard consists of unsorted tills, which due to the high content of fine-grained materials yields small amounts of water. Locally, intermediate water bearing lenses with coarser matrix deposits can be present within the till layer, but the observed yields are only sufficient for domestic water supply. In most of the study area and at lower altitudes, low permeability clay-rich sediments overlie tills. In the first 3-5 m from the ground surface, clays can be weathered permitting limited infiltration. At higher altitudes, generally above 50 masl, clayey sediments become irregular, much thinner or absent. Here, the regional aquifers are semi-confined with shallow till sheets. The water table conditions prevail at rock outcrops close to the U.S. border. These areas are considered as 'recharge areas'. After reaching the regional aquifer, the vertically percolating infiltration water moves horizontally towards the longitudinal axis of the rock depressions, which usually coincides with the flow direction of the current streams. Discharge to streams occurs only through occasional windows in the confining layer filled with coarser matrix sediments, or in sections where fine sediments were completely flushed away.

5. CONCLUSIONS

The Quebec Ministry of Environment and the Geological Survey of Canada are jointly carrying out a hydrogeological assessment project in the Châteauguay River watershed. In the Canadian part of the watershed, the regional aquifers consist of Lower Paleozoic sedimentary rocks. They are confined by glacial and fine marine deposits. At higher altitudes, unconsolidated sediments become thinner and rock crops out. These are the major recharge zones in the watershed. The regional groundwater flow is from south to north. It follows the major directions of the surface water flow.

Most of the field work planned for the summer 2004 consists of: systematic hydraulic testing of newly drilled rock wells with slug, pumping and constant head injection tests; representative groundwater samples collected in some 120 private wells; approximately 30 groundwater samples collected at various depths (multi-level samples) as indicated by results from geophysical logs and packer tests; and field surveys and verifications of the Quaternary and bedrock geology. The regional recharge will be estimated based on the water budget computations for regular grid elements (250x250 m) considering climate, geological, soil and land-use data. The regional recharge will be calibrated against the base-flow rate obtained by separation of river hydrographs at 13 gauging stations on the Canadian side and 6 on the U.S. side of the watershed. As very few water counters are used to measure pumping rates in the region, the estimation of the groundwater use will be carried out by screening important industrial and agricultural users and by systematic interviews with the households in the region. Collected data (geology, hydrogeology, recharge estimates, groundwater use, etc.) will be compiled in a numerical model of the regional groundwater flow. It will be calibrated against the regional potentiometric surface and base-flow rates at gauging stations. The calibrated numerical model will be used for simulation of ground water flow scenarios under future stress and climate conditions. At the same time, a parallel study will be carried out considering the sociological aspects of the groundwater use in the Franklin region (Covey Hill). This municipality is known to be area where groundwater resources are heavily exploited and area where disputes occurred in the past among various groundwater users.

Finally, very little is known about the hydrogeology of the aquifer system in the U.S. part of the Châteauguay River basin. A proposal for extending the hydrogeological study to the entire basin has thus been submitted (Reynolds and Williams 2004). The joint effort for hydrogeological assessment of the Châteauguay River basin between the Geological Survey of Canada and the U.S. Geological Survey will deepen the collaboration between both institutions.

6. ACKNOWLEDGEMENTS

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