Hydrochemical characterisation of groundwater to understand the flow dynamics of the Saint-Mathieu/Berry Esker, Abitibi, Québec

Daniel Blanchette[1], Vincent Cloutier[1], René Lefebvre[2] and Ian Clark[3]
[1] Groupe de recherche sur l'eau souterraine, Département des sciences appliquées – Université du Québec en Abitibi-Témiscamingue, Campus d'Amos, Amos, Québec, Canada
[2] Centre Eau Terre Environnement – Institut national de la recherche scientifique (INRS-ETE), Québec, Québec, Canada
[3] Department of Earth Sciences – University of Ottawa, Ottawa, Ontario, Canada

ABSTRACT

In Abitibi-Témiscamingue, eskers having an exposed crest and edges confined by the Barlow-Ojibway Lake clay provide high quality groundwater resources. However, these aquifers are vulnerable to degradation by surface activities. It is thus necessary to develop a characterization approach providing the information needed by decision makers for sustainable groundwater management. This paper describes the initial hydrochemical characterization of the Saint-Mathieu/Berry esker near Amos, Québec. It is shown that the chemical composition of precipitations and groundwater can be used as tracers to efficiently understand the groundwater flow dynamics associated with esker aquifer systems.

RÉSUMÉ

En Abitibi-Témiscamingue, les eskers avec une crête libre et des flancs confinés par les argiles Barlow-Ojibway fournissent d'excellentes ressources en eau souterraine. Toutefois, ces aquifères sont vulnérables à la dégradation reliée aux activités de surface. Il est donc nécessaire de développer une approche de caractérisation qui fournisse aux gestionnaires les informations requises pour la gestion durable de ces ressources. Cet article décrit la caractérisation hydrochimique initiale de l'esker Saint-Mathieu/Berry près d'Amos au Québec. Il est montré que la composition chimique des précipitations et des eaux souterraines peut être utilisée en tant que traceur pour efficacement comprendre la dynamique de l'écoulement dans les systèmes aquifères des eskers.

1 INTRODUCTION

The last glaciation and ice retreat, which ended around 8 ka in Abitibi, Québec, left several glaciofluvial granular deposits as eskers, which consist of sand and gravel. Many eskers in Abitibi are partly or totally covered by clay deposited in glacial Lake Barlow-Ojibway. Some of these eskers are aquifers that are supplying excellent quality groundwater to several municipalities and to a water bottling company. Despite this good aquifer potential, development of economic activities, such as gravel and sand pits and logging, could negatively impact these aquifers. Conflicts are thus emerging about human activities surrounding aquifers in the perspective of the sustainability and protection of these groundwater resources. Decision makers thus need reliable information to make sound decisions regarding economical activities, while also considering the sustainable development of groundwater resources. One way to provide better information about groundwater resources related to eskers is to develop multidisciplinary characterization approach to better understand these aquifer systems.

This paper is related to a project aiming to develop such a characterization approach using the aquifer of the Saint-Mathieu/Berry esker located near the city of Amos as a natural hydrogeological laboratory (Figure 1). Groundwater is actively exploited from this esker, which has been initially characterized (Bolduc et al., 2004; Riverin, 2006). By integrating geological, geophysical, geochemical and hydrogeological methods, this project intends to better assess this aquifer system. More specifically, the project intends to make a more accurate estimation of groundwater recharge, better understand the flow dynamics in the esker and define the geochemical evolution of groundwater in the esker. This better assessment of the esker aquifer system should form the basis for the development of more realistic groundwater flow numerical models. Such models are important tools to quantitatively understand aquifers and thus better support groundwater resource management.

As part of the general study related to the segment of the Saint-Mathieu/Berry esker being studied, an initial hydrochemical characterization was carried out. As part of that characterization, rain, snow and groundwater samples were collected in 2009 and 2010 and chemically characterized, including physico-chemical parameters, complete chemical analyses and selected isotopic analyses. This paper presents the results of this geochemical characterization with three main objectives: 1) depict the spatial variability of groundwater chemistry, 2) relate this variability to the sampling depth (and thus residence time) in the esker and, 3) use geochemistry as a natural tracer to help constrain the conditions of groundwater flow dynamics. This initial characterization will guide further work needing to be carried out for the development of the general hydrogeological assessment approach developed on the Saint-Mathieu/Berry esker.

2 SITE DESCRIPTION

The study area comprises the southern portion of Saint-Mathieu/Berry esker, which is more than 20 km long from Beauchamp Lake, to the north, to the municipality of La Motte, to the south (Figure 1). The visible surface of the esker varies from 0.3 to 3 km in width, and more than 65 % of its surface is cover by forest. A significant part of the esker, which is from 1.2 to 5.6 km wide, is buried under clay and organic deposits. The esker thickness varies from 20 to 50 m (Bolduc et al., 2004). Numerous activities occur on this esker segment: municipal water pumping wells, bottled water pumping wells, sand and gravel pits, outdoor and recreational activities, as well as old waste dump sites. Most of the few houses using the esker groundwater as water supply are located around the Lac des Hauteurs in the municipality of Saint-Mathieu-d'Harricana (Figure 1).

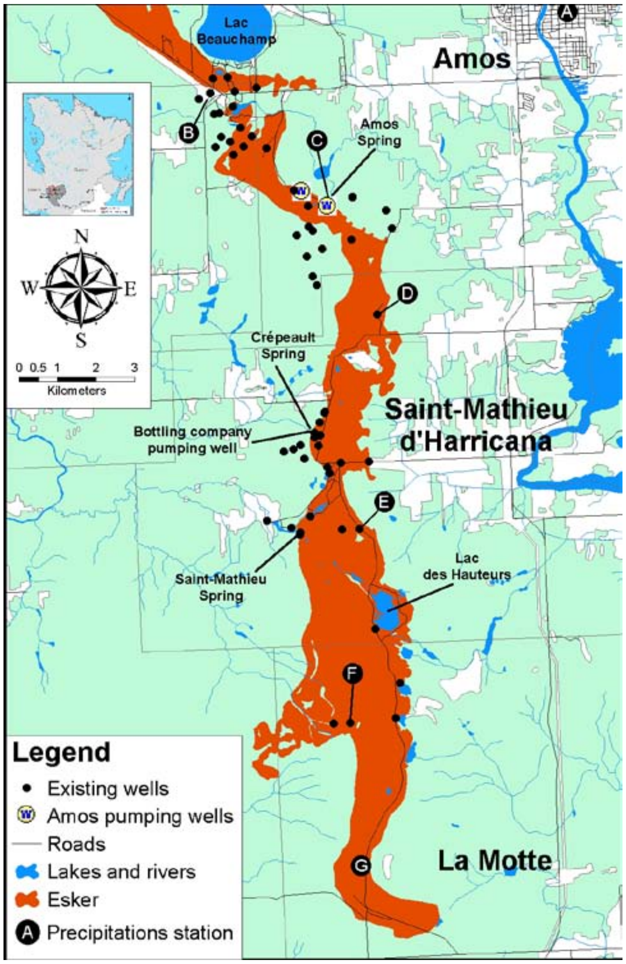

Figure 1: Study area. The exposed surface of the esker is mostly forested. Surrounding areas are either forested (green) or urban and farm land (white)

The Saint-Mathieu/Berry esker is located within the area where glaciolacustrine clay was deposited by the Barlow-Ojibway Lake that was formed during the continental glacier retreat (Nadeau, 2011). This clay sedimentation led to the deposition of clay over the esker flanks, thus maintaining an important saturated sediment thickness within the esker. The esker material being made up of sand and gravel, it has excellent porosity and permeability. Since a wide part of the esker surface is aerially exposed, there can be significant infiltration of precipitations in the esker, thus leading to important aquifer recharge. The combination of the partial burial of the esker and its excellent hydraulic properties thus lead to an important aquifer potential to this esker.

Figure 2 presents a hydrogeological conceptual model that further explains the aquifer potential of the studied segment of the Saint-Mathieu/Berry esker, and summarizes our general understanding of its geological setting. This esker segment overlies bedrock mostly composed of granite and volcanic rock and some metasedimentary rock. At some locations, glacial till separates the esker from the bedrock. Sediments located at the exposed surface of the esker were restructured by waves as sublittoral sand and deposited on top of the esker and above the clay covering the flanks of the esker. The bedrock, composed of fractured Canadian Shield rocks, has a very low primary porosity and a low aquifer potential. Bedrock is thus considered as an underlying impermeable boundary of the esker. The bedrock surface is not flat; rock uplift can occur and play the role of an hydraulic barrier. This may contribute to the segmentation of the esker aquifer in many sub-basins as noted by Riverin et al. (2005) and Riverin (2006) (Figure 3b). The clay has also a low hydraulic conductivity, so its presence on the esker flank restrains the seepage of groundwater through the flanks and allows the accumulation of groundwater within the esker, making it an aquifer. The extent of clay also controls the elevation of the water table in the esker. The unconfined extent of the esker surface exposed to the atmosphere allows groundwater recharge from the infiltration of precipitations or snow melt water.

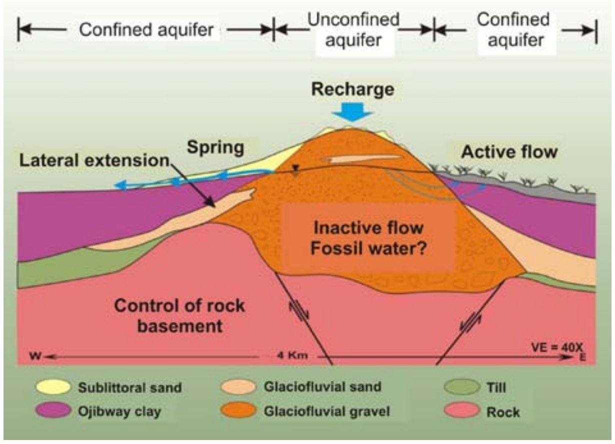

Figure 2: Hydrogeological conceptual model (modified from Riverin, 2006)

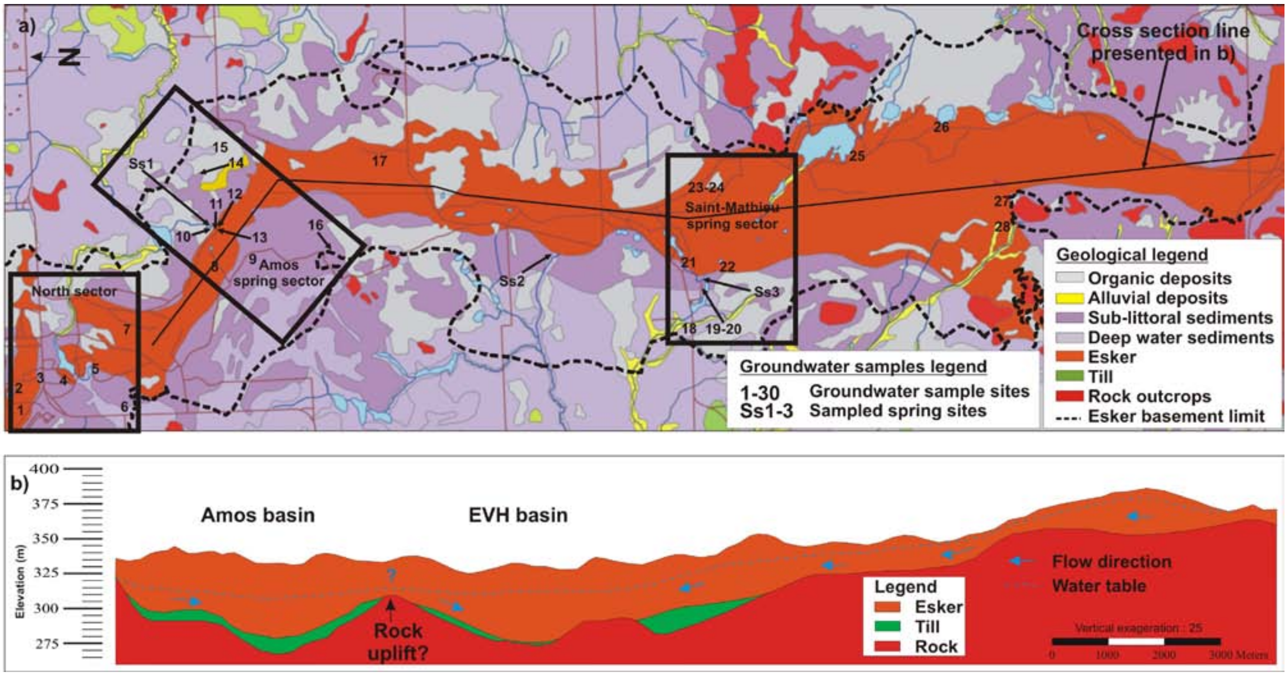

Figure 3: Longitudinal cross section of the study area: a) location of the North-South section and of the study sectors on the surficial geology (geology from Veillette, 2004 and Thibaudeau et Veillette, 2005; modified from Riverin, 2006), b) cross-section from the 3 D geological model (modified from Riverin, 2006, 3D model from Bolduc et al., 2004)

The hydrogeological conceptual model (Figure 2), implies the presence of distinct types of groundwater within the esker. The groundwater above the elevation of the confining clay is considered as young groundwater that evolves in an active flow zone; groundwater recharging from the esker surface should flow toward the esker flanks. This active groundwater feeds springs located at the esker-clay contact, which form creeks and wetlands adjacent to the esker. Below this active flow zone, it is considered that groundwater evolves in a low or inactive flow zone where fossil water would be present. This fossil water would originate from the Barlow-Ojibway Lake that flooded the area several thousand years ago. A mixing zone should separate the active and inactive flow zones. Besides this flow pattern from the crest to the edge of the esker, there is also a longitudinal groundwater flow component controlled by the rock topography along the axis of the esker (Figure 3b), the southern part of the esker segment covering bedrock at a higher elevation.

3 GENERAL APPROACH

The general approach of the study is meant to answer some key questions arising from the hydrogeological conceptual model and previous work of Riverin (2006). These questions regard the relation between the active flow and inactive flow zones. Is there a mixing zone located between them? How groundwater age is vertically distributed from the top of the water table to the base of the aquifer? Is the groundwater emerging at springs a mixture of newly recharged water with older water having some circulation in the aquifer lower part? The study approach aims to trace groundwater from precipitation recharging the aquifer to its discharge. For that purpose, it is necessary to sample groundwater through the entire thickness of the esker, including the unsaturated zone. Furthermore, samples have to be taken along the entire representative paths of groundwater flow. For that purpose, we proceeded to the installation of transverse well profiles which permit to follow the water on the direction of the transverse flow from the crest through the flanks and parallel to longitudinal flow (Figures 2 and 3b).

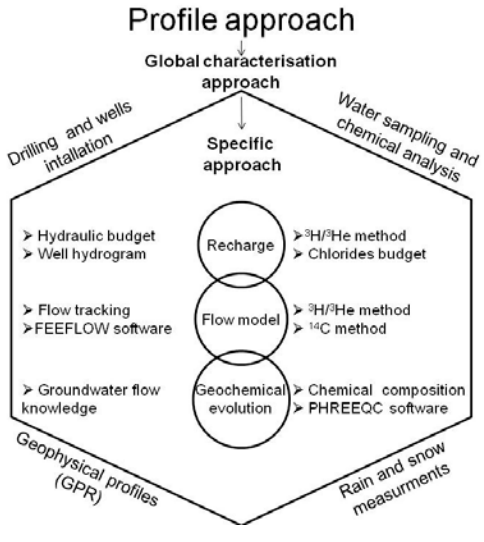

Figure 4: Overview of the general approach

This approach using sampling profiles is part of a global characterization approach, which feeds into numerical modeling efforts and the understanding of the geochemical evolution of groundwater (Figure 4). The global characterization approach regroups field work, which includes drilling and well installation, ground penetrating radar profiles (GPR), rain and snow measurements as well as water sampling. Once the field work is completed, results are use in the specific approach to be treated and analyzed to estimate more precisely groundwater recharge and help develop models aiming to provide an understanding of flow dynamics and groundwater geochemical evolution in the studied esker.

4 WATER SAMPLING METHODOLOGY

Sampling of rain and snow started in 2009 with the use of standard rain gauge during warm months and with pales during cold months. To avoid evaporation during warm months, which would affect stable isotopes, mineral oil lighter than water was introduced in standard rain gauges. Seven sites (A through G, Figure 1) were equipped for precipitation sampling for the establishment of the Amos meteoric water line (AMWL; Figure 5) and to verify the spatial variability of the chemical composition of precipitations that fall over the study area. Site A is installed on the roof of the Université du Québec en Abitibi-Témiscamingue (UQAT) in Amos, approximately 12 km to the north-east of the esker. Precipitation sampling occurs at this site since September 2009. Site B refers to the Amos airport located on the esker to the southwest of Lac Beauchamp (Figure 1). Precipitations were sampled from July 2009 and stopped in January 2010 due to technical problems. All samples collected at the Amos airport and at UQAT were analyzed for stable isotopes of water δ^2H and δ^{18}O at the GÉOTOP-UQAM-McGill laboratory to initiate the AMWL. Other samples collected at UQAC are currently being analyzed. These analyses will allow the establishment of the AMWL for a period of almost 1.5 year. Sites C through G were operated from December 2010 until March 2011. Collection of samples from these sites and the Amos Airport provide a verification of the spatial variability of the chemical composition of rain and snow.

Groundwater samples were collected in 2009 and 2010 in three springs (Ss1 to Ss3) and 28 wells (1 to 28, Figure 3a). Springs samples were collected at the source of the spring with the containers. When the water table in the well was less than 7 m depth, a low flow method was used to sample groundwater. In these wells, water samples were collected after a minimum purge of one well water volume after achieving stability of *in situ* temperature, pH, electrical conductivity at 25°C, dissolved oxygen and redox potential. When low flow sampling was not possible, a Hydrolift pump was used and the sample was collected after a minimum purge of three well water volumes and stability of i*n situ* parameters. *In situ* parameters of spring water were measured directly at the spring outlet.

All water samples were analyzed for major, minor and trace constituents at Exova and Maxxam laboratories in Montreal. Only samples collected in 2009 have been analyzed for water stable isotopes δ^2H and δ^{18}O. Samples collected in 2010 are currently in the process of δ^2H, δ^{18}O, δ^{13}C, enriched tritium and ^{14}C analyses. PHREEQC (V. 2.18; USGS, 2011) was used to establish the quality of laboratory analysis from the electronic balance and to determine the concentrations of HCO_3 and CO_3 using total Alkalinity as an input. Using an electronic balance limit of ±10 %, three samples were rejected (5, 27, 28; Figure 3a). Due to concentrations below detection limits for some major constituents, electronic balance was not suitable for precipitations samples and they were all considered to verify the spatial variability of the chemical composition of rain and snow.

The main focus being on groundwater, the parameters used for this characterization are pH, Eh, and chemical parameters who were detected above their detection limit on 75 % or more of the groundwater samples: Ca, Mg, Si, Na, Sr, SO_4, HCO_3+CO_3 (total Alkalinity), K, Cl, Cr. Due to technical problems with electrical conductivity instruments, this parameter is replaced by total dissolved solids (TDS) calculated from the sum of all constituents and Si as SiO_2 (Hounslow, 1995). The values associated to station B are means based on 3 to 4 samples collected during summer and fall 2009. Values for stations E, F and G are from a single sample collected at each station in December 2010.

5 CHEMICAL ANALYSES RESULTS

5.1 Precipitation samples

Table 1 shows the chemical composition of precipitations at stations B, E, F and G (see Fig. 1 for station locations). No samples for stations C and D have been submitted for the analysis of this set of parameters. As for stations B, E, F and G, samples of these stations are currently in the process of δ^2H and δ^{18}O analyses.

Table 1: Chemical composition of precipitations

Precipitations station	B	E	F	G
pH	4.99	5.01	5.09	5.23
Eh (mV)	390	nd	nd	nd
Ca (mg/L)	0.098	0.37	1.60	2.40
Mg (mg/L)	0.013	<0.10	<0.10	<0.10
Na (mg/L)	<0.5	0.21	0.26	0.35
K (mg/L)	<0.5	<0.10	<0.10	0.28
HCO_3+CO_3 (mg/L)	<1.22	<1.22	1.22	6.10
Cl (mg/L)	0.43	<0.3	0.40	1.00
SO_4 (mg/L)	0.67	1.9	3.90	2.30
Si (mg/L)	<0.02	<0.10	<0.10	<0.10
Sr (mg/L)	<0.01	<0.0020	<0.0020	<0.0020
Cr (mg/L)	<0.001	0.00067	0.00070	0.00070
calculated TDS (mg/L)	1.69	2.99	7.46	12.6

nd: no data

Table 1 indicates that precipitations are slightly acidic with very low concentrations for all the constituents relative to groundwater (Table 2). Also, it appears that pH and concentrations of Ca, Na, K, HCO_3+CO_3 and TDS increase southward. This is an important observation because it suggests that different input concentrations of geochemical tracers will have to be used as initial concentrations for the definition of the geochemical evolution in different locations of the esker segment.

On Figure 5, the Amos Meteoric Water Line (AMWL) compares well with the Canadian meteoric water line (CMWL; Clark and Fritz, 1997) and the Basses-Laurentides meteoric water line (BLMWL; Cloutier *et al*., 2006), which is from a region located about 575 km SSE from Amos. This indicates that results from July 2009 to January 2010 for precipitation from stations A and B (Figure 1) are coherent, so the AMWL can be used for the initial hydrochemical characterization.

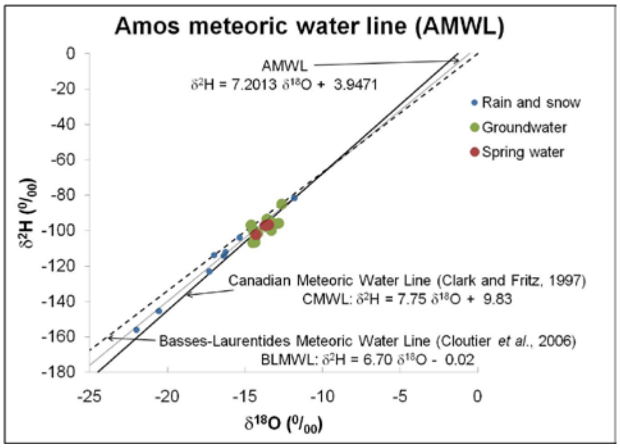

Figure 5: Initial data defining the AMWL

5.2 Groundwater samples

Table 2 presents the distributions of chemical parameters for the 28 groundwater samples retained for this hydrochemical characterization, including spring samples. As stated before, results for groundwater are very different from those of the rain and snow samples. The fact that groundwater concentrations are higher than those of precipitations would confirm that water-rock interactions are the dominant geochemical processes influencing groundwater chemical composition and geochemical evolution. However, 16 groundwater and 3 spring samples plot close to the AMWL (Figure 5), which would suggest a recent precipitations origin for the groundwater present in the studied esker segment.

To study the spatial variability of the *in situ* and chemical parameters over the esker segment, three major sectors were delineated based on the spatial distribution of samples (Figure 3a). The North sector regroups samples associated to wells 1 to 7 (the well 5 sample was rejected due to poor electronic balance). The Amos spring sector regroups wells 8 to 16. Finally, the sector of the Saint-Mathieu spring regroups wells 18 to 24. Since springs represent the end of flow paths, their samples are treated separately from groundwater samples (Table 3).

Table 2: Chemical results for groundwater and spring samples (n = 28)

Parameters	Minimum	25%	Median	75%	Maximum
pH	4.68	6.63	7.54	7.69	7.97
Eh (mV)	70	174	301	322	669
Ca (mg/L)	4.36	10.4	15.0	22.8	56.8
Mg (mg/L)	0.50	1.75	3.18	4.61	10.9
Na (mg/L)	1.50	1.70	2.10	2.95	5.20
K (mg/L)	<0.5	0.58	0.70	0.83	1.90
HCO_3+CO_3 (mg/L)	13.5	44.4	60.0	91.5	249
Cl (mg/L)	<0.3	<0.3	0.60	0.73	10.0
SO_4 (mg/L)	1.20	4.63	6.00	7.18	12.0
Si (mg/L)	3.68	4.6525	5.735	7.11	13.0
Sr (mg/L)	0.02	0.03	0.04	0.05	0.26
Cr (mg/L)	<0.0005	0.001	0.002	0.002	0.003
calculated TDS (mg/L)	39.1	75.1	101	144	346

<: Less than detection limit

Table 3 presents the means and standard deviations of chemical parameters for the sectors shown in Figure 3a and for springs. For the calculations of statistics, values below detection limit (<DL) were set to half of the DL (Farnham et al., 2002). Highest means are mostly found in the North sector whereas the lowest are generally related to spring waters. Two other interesting facts are the high mean for chlorides in the North sector relative to other sectors and springs and the increasing concentrations of Ca, Mg, HCO_3+CO_3 and TDS going North from the Saint-Mathieu spring sector.

Table 3: Means and standards deviation by sector

Location	North sector (n = 6)		Amos spring sector (n = 9)		Saint-Mathieu spring sector (n = 7)		Springs (n = 3)	
Statistics	**μ**	**s**	**μ**	**s**	**μ**	**s**	**μ**	**s**
pH	6.54	1.06	7.58	0.47	6.82	0.99	7.42	0.68
Eh (mV)	440	227	200	78.85	291	31.5	392	59.0
Ca (mg/L)	22.7	9.52	19.12	14.78	11.7	3.42	12.2	3.43
Mg (mg/L)	3.88	1.78	3.66	2.98	2.98	1.60	1.71	0.56
Na (mg/L)	2.42	0.58	2.28	1.16	2.53	1.16	1.70	0.17
K (mg/L)	0.79	0.28	0.80	0.46	0.66	0.29	0.37	0.20
HCO_3+CO_3 (mg/L)	81.9	34.3	80.4	66.1	50.0	9.24	46.0	12.1
Cl (mg/L)	5.02	3.97	0.52	0.22	0.46	0.65	0.70	0.10
SO_4 (mg/L)	7.48	1.95	5.47	2.50	7.09	2.32	4.83	0.61
Si (mg/L)	5.43	1.32	5.35	1.16	7.03	1.79	4.85	0.32
Sr (mg/L)	0.058	0.017	0.061	0.076	0.031	0.004	0.023	0.006
Cr (mg/L)	0.0018	0.0004	0.0018	0.0005	0.0013	0.0009	0.0023	0.0006
calculated TDS (mg/L)	138	50.3	124	87.5	90.5	14.7	72.5	9.53

Green shaded values: highest mean of the parameter

Gray shaded values: lowest mean of the parameter

Figure 6 shows the variability of calculated TDS with sampling depth for the sectors defined in Figure 3a. TDS is considered as an integrated parameter representative of the overall groundwater geochemistry.

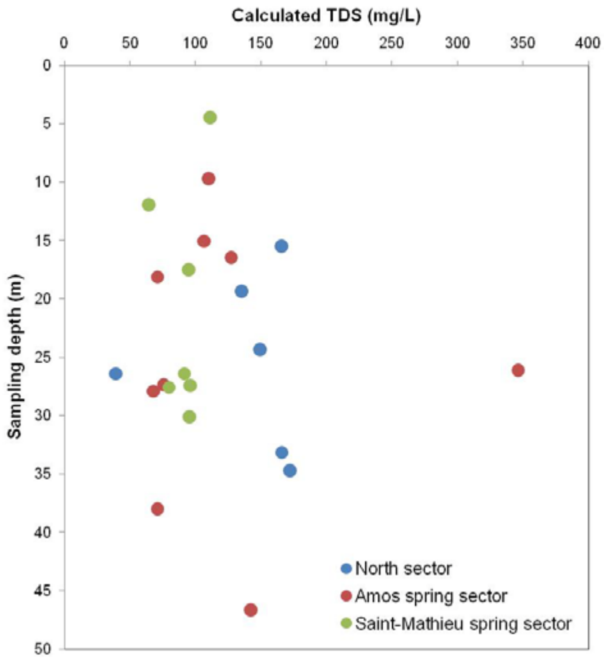

Figure 6: Relation between calculated TDS and the sampling depth for each sector

Based on TDS alone, there are no clear indications that the global chemical composition of groundwater varies with the sampling depth for each sector. However, when chemical parameters are considered individually, some decreasing concentrations with depth are observed for Eh and SO_4 in the Amos spring sector and for Mg, Na, Cl and Si in the Saint-Mathieu spring sector. Since these different trends are observed locally within sectors, this could indicate the presence of some heterogeneity in the spatial distribution of redox conditions, mineralogy of esker sediments or provenance of groundwater between sectors.

Concerning sediment mineralogy, Castelli (2008) characterized two sediment samples collected on top of the esker near the Lac Beauchamp using X-ray diffraction (Table 4). Based on these results, silicate minerals such as Quartz (SiO_2) and Albite ($NaAlSi_3O_8$) compose more than 90% of the esker sediments. Other minerals present, in decreasing concentration, are oxides (Rutile, Magnetite, Ilmenite), carbonates (Dolomite) and sulphides (Pyrite, Marcasite, Chalcopyrite, Sphalerite). This mineralogy is interesting because minerals that incorporate HCO_3, CO_3 and Cl, some of the dominant chemical species in the groundwater, have a very low fraction or were not detected in sediments. Thus, other sources than esker minerals such as precipitations and the organic cover can contribute to the groundwater chemistry along the flow path.

Table 4: Mineralogical composition of Saint-Mathieu/Berry esker sediments (from Castelli, 2008)

Minerals	**Chemical composition (Pellant, 1993)**	**Samples**	
		Esker-1	Esker-2
		Mass fraction (%)	
Quartz	SiO_2	41.3	25.81
Albite	$NaAlSi_3O_8$	41.19	44.54
Muscovite	$KAl_2(Si_3Al)O_{10}(OH,F)_2$	8.16	10.53
Actinolite	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$	4.38	9.2
Chlorite	$(Fe,Mg,Mn)_2Al_4Si_2O_{10}(OH)_4$	2.01	3.55
Rutile	TiO_2	1.54	1.91
Dolomite	$CaMg(CO_3)_2$	1.33	1.92
Magnetite	Fe_3O_4	nd	0.88
Pyrite	FeS_2	nd	0.67
Marcasite	FeS_2	nd	0.43
Chalcopyrite	$CuFeS_2$	nd	0.23
Ilmenite	$FeTiO_3$	nd	0.18
Sphalerite	ZnS	nd	0.15

nd: not detected

6 DISCUSSION

This hydrochemical characterization of precipitations and groundwater provided new information that will guide further work to develop a better understanding of groundwater flow dynamics and geochemical evolution in the Saint-Mathieu/Berry esker segment under study.

Available results for precipitations suggest an increasing trend from north to south for their global chemical composition. However, further rain and snow sampling has to be done to confirm this apparent trend, which could have an impact on the geochemical evolution. Since groundwater recharge occurs over the entire length of the esker segment under study, a different recharge composition has to be accounted for, if present. Also, the meteoric water line needs to be better defined to avoid misinterpretation about groundwater origin.

The comparison of precipitation and groundwater composition indicates that water-rock interactions are the dominant processes providing dissolved solutes in this system. Nevertheless, the limited available data on sediment mineralogy does not fully explain the presence of some chemical constituents at the concentrations measured in groundwater, such as Cl. It is essential to improve the mineralogical characterization of sediments as well as their chemical composition to better understand the origin of dissolved constituents and constrain the processes responsible for groundwater geochemical evolution.

For the different sectors of the esker (Figure 3a), a spatial variability of the groundwater chemical composition was found along the longitudinal axis of the esker. The installation of new wells at the crest of the esker and parallel to this axis will allow a better characterization of the spatial variability of the chemical composition in the esker, both from the crest to the flanks and longitudinally between sectors. These data should allow the definition of the geochemical evolution of groundwater along all flow paths and better constraints on the flow dynamics of the esker aquifer system.

Finally, stable isotope results and the variation of groundwater chemical composition with sampling depths suggest the presence of relatively young water over the entire saturated esker thickness and the absence of an inactive flow zone containing fossil water. This is very important because this preliminary conclusion is not coherent with our present hydrogeological conceptual model of groundwater flow in the esker aquifer system. However, groundwater age tracers currently being analyzed, ^{14}C and $^{3}H/^{3}He$, should provide a firmer basis to assess the presence or not of fossil groundwater and its potential spatial distribution.

7 CONCLUSION

This initial hydrogeochemical characterization of a segment of the Saint-Mathieu/Berry esker has shown that geochemistry can be used to get a better insight about the hydrogeology of this aquifer system. However, results also show that geochemistry alone cannot provide all the necessary information to understand the complex hydrogeological context of this esker. A quantitative assessment of the dynamics of this aquifer system requires the integration of various methods and specialties of earth sciences, as planned for the general approach of this project.

ACKNOWLEDGEMENTS

Funding for the study came from Fonds de recherche sur la nature et les technologies (FQRNT) du gouvernement du Québec, as well as the Ministère du Développement Durable, de l’Environnement et des Parcs (MDDEP) and regional partners (Conférence régionale des élus de l’Abitibi-Témiscamingue, MRC d’Abitibi, MRC de la Vallée-de-l’Or, Ville de Rouyn-Noranda) through the Programme d’acquisition de connaissances sur les eaux souterraines (PACES). Authors would like to acknowledge the contribution of the City of Amos, Les Fermes Truites Saint-Mathieu, Eaux Vives Water Inc. and the Ministère des Ressources naturelles et de la Faune (MRNF) du Québec for their collaboration to the project as well as the people of the municipalies of Amos, Saint-Mathieu-d’Harricana and La Motte. Thanks go to all those who have contributed to this study through their time and funding.

REFERENCES

Bolduc, A. M., Riverin, M.-N., Lefebvre, R., Paradis, S. J.Fallara, F. 2004. Modélisation de l'architecture 3D du segment sud de l'esker Saint-Mathieu - Berry reliée à la circulation de l'eau souterraine, région d'Amos, Abitibi, *GeoQuébec 2004*, 57 ième Congrès Canadien de Géotechnique 5ième Congrès Conjoint SCG/AIH – CGG, Québec, Québec Canada.

Castelli, S. 2008. *Caractérisation de la phase minéralogique de sédiments prélevés à l'esker Saint-Mathieu – Berry, Amos*, Cours Minéralogie appliquée à l'étude des minerais et leur traitement GNM1001, Université du Québec en Abitibi-Témiscamingue, Rouyn-Noranda, Québec Canada.

Clark, I., Fritz, P. 1997. *Environmental isotopes in hydrogeology*, CRC Press, Boca Raton London New York, U.S.

Cloutier, V., Lefebvre, R., Savard, M. M., Bourque, E., Therrien, R. 2006. Hydrogeochemistry and groundwater origin of the Basses-Laurentides sedimentary rock aquifer system, St. Lawrence lowlands, Quebec, Canada. *Hydrogeology Journal*, 14(4): 573-590.

Farnham, I. M., Singh, A. K., Stetzenbach, K. J., Johannesson, K. H. 2002. Treatment of nondetects in multivariate analysis of groundwater geochemistry data. *Chemometrics and Intelligent Laboratory Systems*, 60(1-2): 265-281.

Hounslow, A. W. 1995. *Water quality data; analysis and interpretation*, Lewis Publishers, Boca Raton, Florida, U.S.

Nadeau, S. 2011. *Estimation de la ressource granulaire et du potentiel aquifère des eskers de l’Abitibi-Témiscamingue et du sud de la Baie-James (Québec)*, Mémoire de maîtrise, Département de géographie, UQAM, Montréal, Québec Canada.

Pellant, C. 1993. *Roches et Minéraux*, Bordas, Paris, France.

Riverin, M.-N., Lefebvre, R., Bolduc, A., Paradis, S., Paradis, D. 2005. Characterization and modeling of flow dynamics in the Saint-Mathieu/Berry esker, Abitibi, Quebec, *GeoSaskatoon 2005*, 58th Canadian Geotechnical Conference and 6th Joint CGS/IAH Conference, Saskatoon, Saskatchewan Canada.

Riverin, M.-N. 2006. *Caractérisation et modélisation de la dynamique d'écoulement dans le système aquifère de l'esker Saint-Mathieu / Berry, Abitibi, Québec*, Mémoire de maîtrise, INRS-ETE, Québec, Québec Canada.

Thibaudeau, P., Veillette, J.J. 2005. *Géologie des formations en surface et histoire glaciaire, Lac Chicobi, Québec*, Commission géologique du Canada, Carte 1996A, échelle 1 : 100 000.

Veillette, J.J. 2004. *Géologie des formations en surface et histoire glaciaire, Cadillac, Québec*, Commission géologique du Canada, Carte 2019A, échelle 1 : 100 000

USGS, 2011. *PHREEQC Interactive v. 2.18.0.5314*, http://wwwbrr.cr.usgs.gov/projects/GWC_coupled/phreeqc/.