REGIONAL HYDROGEOCHEMISTRY OF GROUNDWATER IN FRACTURED CANADIAN SHIELD ROCK AND GLACIOFLUVIAL FORMATIONS IN ABITIBI, QUÉBEC

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ABSTRACT
Groundwater hydrogeochemistry in fractured Canadian Shield rocks and in glaciofluvial formations was studied as part of a regional hydrogeological project in Abitibi. The objectives of the study were to understand the processes controlling groundwater geochemistry, to determine groundwater origin and to evaluate groundwater quality. Groundwater samples were collected at 80 sites, both from fractured rock aquifers and from granular aquifers in eskers. Groundwater was analyzed for inorganic constituents, and 20 samples were analyzed for $\delta^{18}O$, $\delta^{2}H$, and tritium. Initial results indicate significant chemical differences between the excellent groundwater quality of esker aquifers and that of the more variable quality of water in fractured rocks aquifers overlain by Lake Ojibway clay in the broad zones between eskers.

RÉSUMÉ
L'hydrogéochimie de l'eau souterraine des roches fracturées du Bouclier canadien et des formations fluvioglaciaires est étudiée dans le cadre d'un projet d'hydrogéologie régionale en Abitibi. Les objectifs sont de comprendre les processus contrôlant la chimie de l'eau souterraine, de déterminer l'origine de l'eau et d'évaluer sa qualité. Des échantillons d'eau ont été prélevés à 80 sites, tant dans les aquifères rocheux fracturés et que dans les aquifères granulaires des eskers. L'eau souterraine a été analysée pour les constituants inorganiques, ainsi que $\delta^{18}O$, $\delta^{2}H$, et tritium pour 20 échantillons. Les résultats initiaux montrent des différences significatives entre l'excellente qualité de l'eau des eskers et celle plutôt variable des aquifères rocheux fracturés couverts par l'argile du Lac Ojiway dans les zones entre les eskers.

1 INTRODUCTION

Groundwater is a very important supply of freshwater for the administrative region of Abitibi-Témiscamingue, in north-western Québec (Figure 1). About 73% of its population depends on groundwater for their water supply. In the RCM (Regional County Municipality) of Abitibi, selected as the study area, the population depends exclusively on groundwater (MDDEP 2000).

The hydrogeochemical study aims to assess the regional quality of groundwater and to determine the influence of geological and hydrogeological conditions on groundwater geochemistry. It is part of a larger project to study the regional hydrogeology of the RCM of Abitibi that was initiated by the Université du Québec in Abitibi-Témiscamingue (Veillette et al. 2004; Veillette et al., this volume; Cloutier et al. in prep). A partnership with the Geological Survey of Canada and INRS-ETE allowed the realisation of a 3D geological model of St-Mathieu – Berry esker near Amos (Bolduc et al. 2004), and the numerical modeling of groundwater flow in this esker (Riverin 2006).

2 THE STUDY AREA

The RCM of Abitibi covers approximately 7950 km^2 (Figure 1) and straddles two large hydrographic basins. Most rivers and streams drain north into the James Bay basin, except for the south-western part of the study area, where surface waters drain southward into the St. Lawrence drainage basin.

Figure 1. Location of the RCM of Abitibi

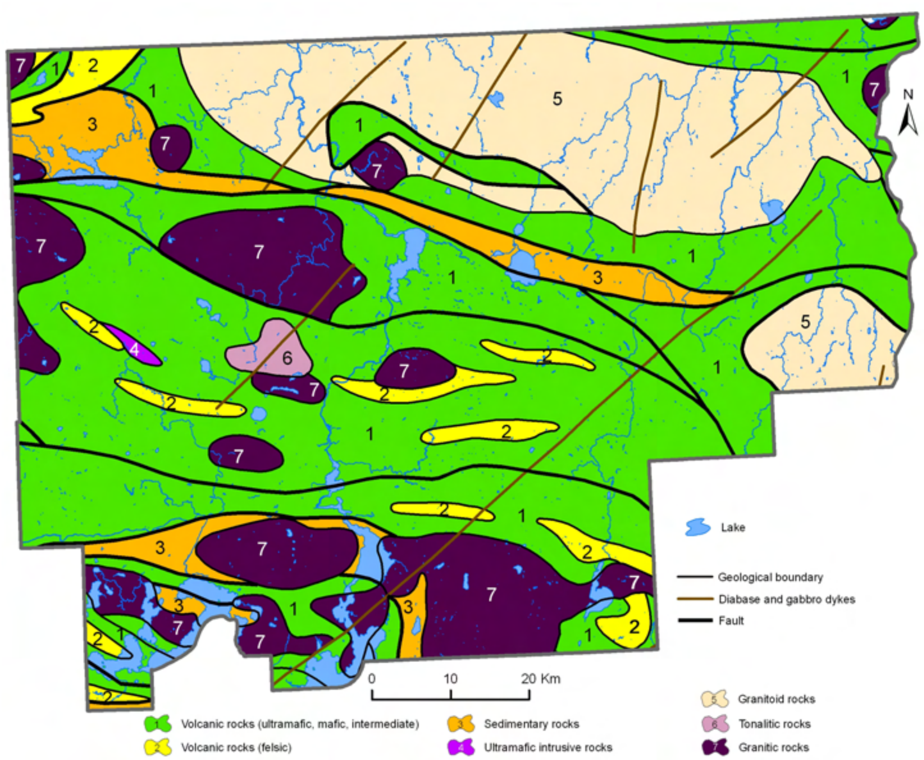

Figure 2. Bedrock geology of the RCM of Abitibi (adapted from MRN 2002)

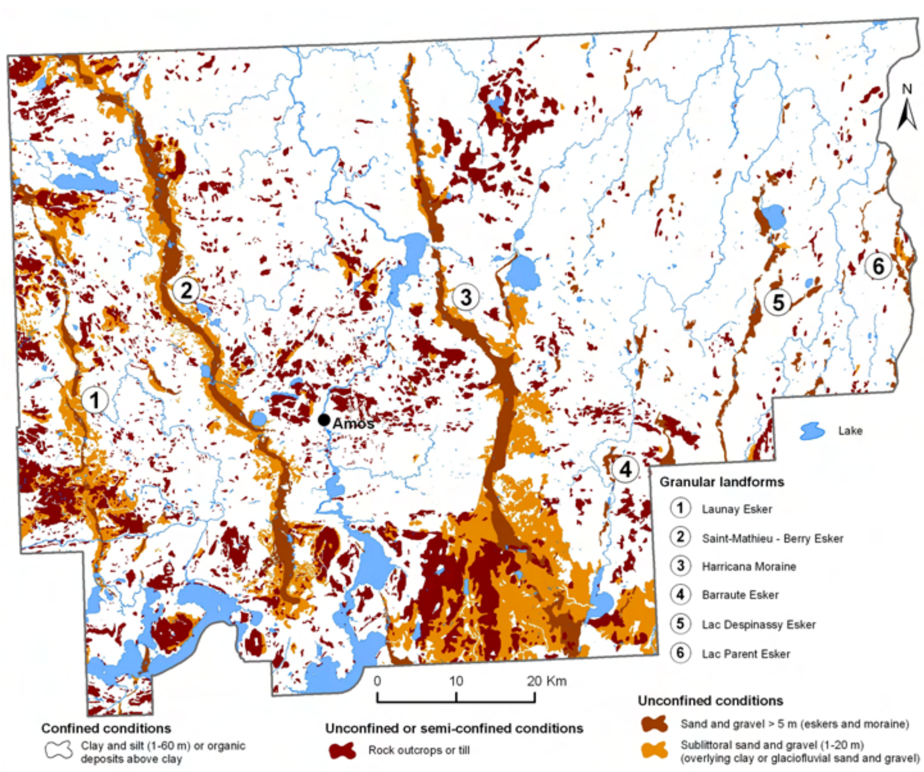

Figure 3. Surficial geology of the RCM of Abitibi and hydrogeological conditions inferred from the deposits. Geology from Veillette et al. (2003) and hydrogeological parameters from Cloutier et al. (in prep).

2.1 Bedrock and Quaternary Geology

Precambrian rocks of Archean age from the Superior geological Province of the Canadian Shield underlie the study area (Figure 2). Rock units consist mainly of north-west – south-east elongated belts of metamorphosed volcanic and sedimentary rocks, intruded by granitoids and granitic rocks. Proterozoic diabase and gabbro dykes are more or less perpendicular to the Archean rocks and faults. The chemical evolution of groundwater is influenced by rock types. As water moves along its flow paths, its chemistry is altered by geochemical processes causing groundwater to acquire dissolved constituents.

The last glaciation and ice retreat left a strong imprint on the landscape and contributed to the hydrogeological potential of the region. Regionally, the main granular deposits are the Launay esker, the St-Mathieu – Berry esker, the Harricana Moraine, the Barraute esker, the Lac Despinassy esker, and the Lac Parent esker (Figure 3). The portion of these glaciofluvial formations outcropping above the clay plain, represents about 4% of the study area but the deposits are more extensive below the clay cover. Fine-grained glaciolacustrine deposits covering about 60% of the Abitibi RCM are the most extensive with peat (20%). Till and bedrock, and littoral granular deposits occupy the rest of the area.

2.2 Aquifers and Aquitards

The nature of Quaternary sediments and their depositional environment are key elements to understand the aquifer potential of the geological formations. The hydrogeological units of the region are subdivided into high-potential granular aquifers, and fractured rock aquifers of lower potential (Figure 4). Having a very low primary porosity, the Canadian Shied rocks have a variable aquifer potential that is related to the presence and characteristics of fractures. Thus, there are two main sources for groundwater in the RCM of Abitibi: 1) the aquifer systems associated with glaciofluvial sands and gravels as the eskers, and 2) the fractured Canadian Shield rocks.

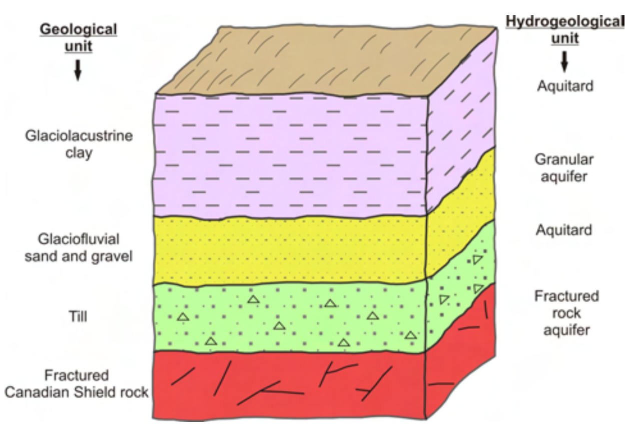

Figure 4. Hydrostratigraphic model of the study area (modified from Cloutier at al. in prep). The units appear in their order of deposition but are not necessarily found together everywhere throughout the study area.

The eskers contain aquifers supplying groundwater of excellent quality to several municipalities, and to a water bottling company. This high groundwater quality was recognized several times at the Berkeley Springs International Water Tasting in West Virginia, USA. The hydrogeological conditions illustrated on Figure 3 were interpreted from the surficial geology map. When outcropping above the clay cover, the eskers are aquifers under unconfined conditions, which are preferential recharge areas. The aquifer potential of eskers of the Clay Belt is closely related to the association between the sands and gravels of eskers and the younger glaciolacustrine clays. The depositional environment of eskers from north-western Québec is described by Veillette et al. (this volume). Two types of eskers are found in the RCM of Abitibi. Eskers of Type C are covered in part by clay deposited on the flanks of eskers. This is the case for the St-Mathieu – Berry esker and for the Harricana Moraine where the clay confines groundwater within the esker. Eskers of Type D, like the Barraute esker were deposited at lower elevation and are totally buried by clay deposited in glacial Lake Ojibway.

An important part of the population historically settled in the glaciolacustrine clay plain between eskers. Most of these inhabitants, as well as some municipalities and industries, have their wells installed in fractured Canadian Shield rocks below the clays, under confined conditions (Figure 3). Generally found in areas of elevated topography, rock outcrops and till are under unconfined or semi-confined conditions and could represent local recharge zone to the fractured rock aquifers (Figure 3).

The conceptual cross-section of Figure 5 illustrates the hydrogeological model of the region. It shows the transition from a Type C esker under unconfined conditions to the clay plain where the glaciolacustrine clay aquitard confines the fractured rock aquifer. Under unconfined conditions (P1 zone), infiltration of precipitation recharges the granular aquifer. Groundwater discharges as springs at the contact between esker and clay. The flanks of the esker are under confined conditions (P2 zone). In the clay plain, the fractured rock aquifer is confined by glaciolacustrine clay (P3 zone). Locally, some wells are installed in permeable sediments above bedrock, below the clay aquitard (P4 zone).

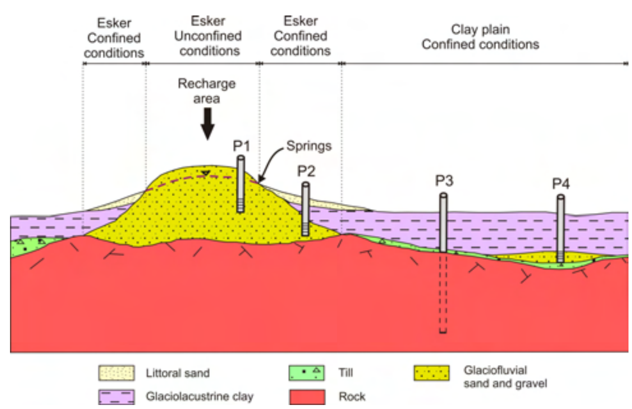

Figure 5. Conceptual cross-section of hydrogeological conditions (modified from Cloutier at al. in prep)

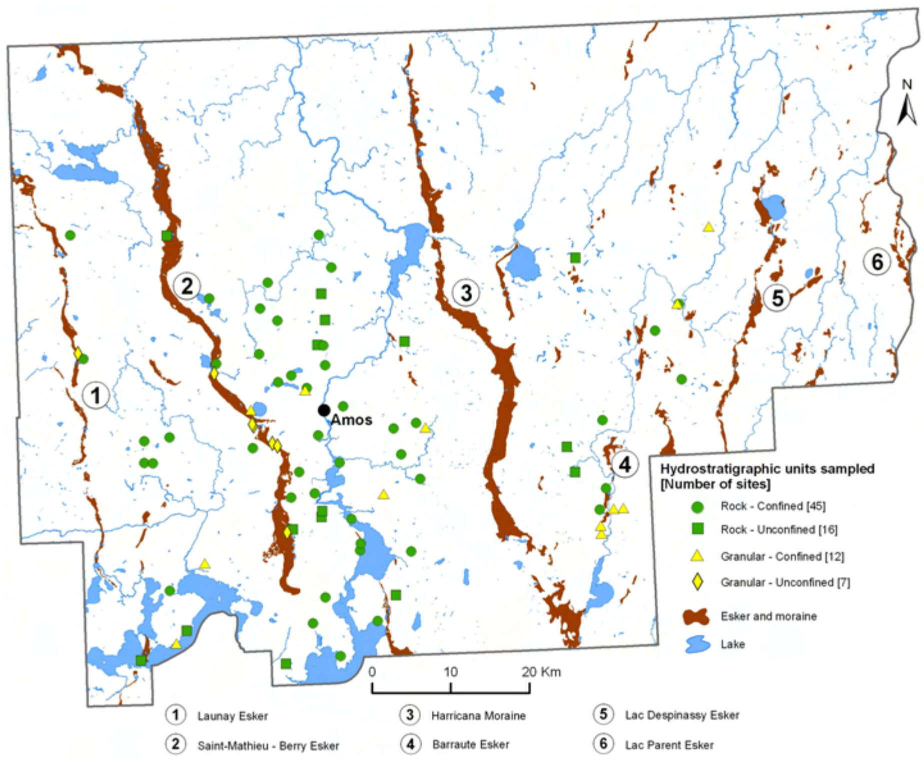

Figure 6. Location of the groundwater sampling sites (surficial geology from Veillette et al. 2003)

3 METHODS OF INVESTIGATION

The approach used in this study was to determine the hydrogeochemistry of groundwater for both the granular and fractured rock aquifers in all hydrogeological conditions as defined in Figure 5. The regional groundwater sampling was performed in 2006 in 8 municipal wells, and 72 domestic wells. Stratigraphy and construction details of wells were known in most cases. The location of the 80 sampled wells shows that the sites cover all permeable hydrostratigraphic units (Figure 6): a) 45 samples from confined fractured rocks aquifers (P3 Figure 5), b) 16 samples from unconfined fractured rocks aquifers, c) 12 samples from confined granular aquifers (including 4 wells installed in the buried Barraute esker, 7 wells in permeable sediments between bedrock and clay aquitard, P4 of Figure 5, and 1 well in the flank of St-Mathieu – Berry esker, P2 of Figure 5), and d) 7 samples from unconfined granular aquifers, P1 of Figure 5 (including 6 wells in the St-Mathieu – Berry esker and 1 well in the Launay esker). In situ field measurements were recorded on groundwater samples using an YSI 556 Multi-Probe System for temperature, pH, specific conductivity, dissolved oxygen and redox potential. Wells were purged until stabilization of field parameters was reached before sampling.

Samples for inorganic constituents were collected in plastic bottles. Sampling bottles and appropriate preservatives were provided by the laboratory Maxxam Analytics Inc. Samples for dissolved metals were filtered in the field prior to acidification. Samples were stored at 4ºC and shipped twice a week to the laboratory. Duplicate samples (6% of the total), as well as field and trip blanks, were also submitted to verify data quality and accuracy. The method of analysis of the laboratory were the following: ICP-MS for dissolved metals, Spectro/Colorimetry for sulphide anions, titrimetric method for total alkalinity, ion chromatography for anions (bromide, chloride, nitrate and nitrite, sulphate) and ion specific electrode for fluoride. Electro-neutrality was calculated to verify the analysis reliability. For the 80 groundwater samples, 47 have an electro-neutrality below 5%, 30 between 5% and 10%, and 3 between 10% and 12%. Twenty samples were submitted for $\delta^{18}O$ and $\delta^{2}H$ at the G.G. Hatch Isotope Laboratories of the University of Ottawa and for enriched tritium at the Environmental Isotope Laboratory of the University of Waterloo. Stables isotopes results will not be discussed in this paper.

4 REGIONAL GROUNDWATER GEOCHEMISTRY

Table 1 presents descriptive statistics of selected measured and calculated parameters for the 80 groundwater samples. For calculation of the descriptive statistics, the elements with concentrations lower than the detection limit were replaced by the value of the limit. For the measured parameters of the 80 groundwater samples, health-base guidelines of Health Canada (2007) are slightly exceeded for 2 parameters: As (2 samples) and F (1 sample). Values above the aesthetic objectives of Health Canada (2007) were observed for Fe (27 samples), Mn (50 samples), S (3 samples), and pH (5 samples). Total hardness was above 200 mg/L for 24 of the 80 samples.

Table 1. Descriptive statistics of selected measured and calculated parameters for groundwater (80 samples)

Parameters	DL[1]	Units	N[2]	Min.[3]	Max.[4]	Mean
Dissolved metals						
Al	<1	µg/L	39	1	100	9.52
Sb	<1	µg/L	80	—	—	—
Ag	<0.1	µg/L	78	0.1	0.4	0.15
As	<1	µg/L	44	1	31	2.61
Ba	<0.002	mg/L	3	0.002	0.42	0.04
Cd	<0.2	µg/L	80	—	—	—
Cr	<0.5	µg/L	27	0.5	9.2	1.59
Cu	<0.5	µg/L	44	0.5	170	7.08
Mn	<0.0004	mg/L	7	0.0004	1.1	0.21
Ni	<1	µg/L	70	1	59	2.1
Na	<0.03	mg/L	0	1.2	33	9.33
Zn	<1	µg/L	4	1	500	24.13
B	<0.005	mg/L	25	0.005	0.11	0.02
Fe	<0.03	mg/L	27	0.03	4.1	0.46
Mg	<0.01	mg/L	0	1	37	12.8
Li	<10	µg/L	78	10	12	10.03
K	<0.1	mg/L	0	0.3	6.5	1.95
Se	<1	µg/L	80	—	—	—
Sr	<0.002	mg/L	0	0.031	3	0.27
Ca	<0.05	mg/L	0	3.5	120	45.07
Si	<0.1	mg/L	1	0.1	14	8.08
Pb	<0.1	µg/L	57	0.1	2	0.51
Conventionals						
S	<0.02	mg/L	71	0.02	0.16	0.02
F	<0.08	mg/L	26	0.08	1.8	0.15
T. Alk.[5]	<2	mg/L	0	13	410	189.7
Br	<0.1	mg/L	75	0.1	0.5	0.11
Cl	<0.05	mg/L	0	0.05	38	4.34
NO_3[6]	<0.02	mg/L	31	0.02	4.9	0.22
SO_4	<0.1	mg/L	2	0.01	62	7.15
Field						
pH	—	—	—	5.39	8.82	7.59
Sp. Cond[7]	—	mS/cm	—	0.081	0.797	0.38
Calculated						
T. Hard.[8]	—	mg/L	—	12.86	398.5	165.3

[1]Detection Limit
[2]Number of samples under detection limit
[3]Minimum [4]Maximum
[5]Total alkalinity as $CaCO_3$
[6]Nitrate and nitrite as N
[7]Specific conductivity
[8]Total hardness as $CaCO_3$

Figure 7 shows the major ions composition of the groundwater samples on a Piper diagram. The Piper diagram illustrates that samples are concentrated mainly in the Ca-Mg-HCO_3 zone of the diamond shaped field. Thus groundwater of the different units can not be distinguished based on their groundwater types alone.

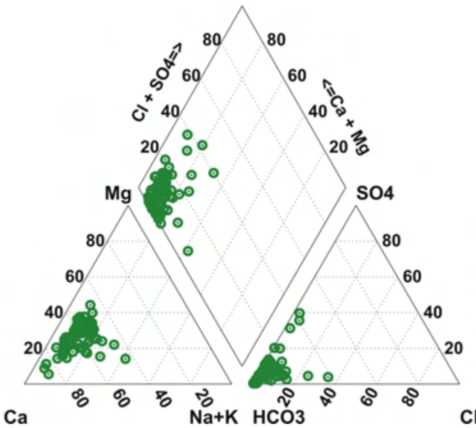

Figure 7. Piper diagram illustrating the major ions chemistry of the 80 groundwater samples

Figures 8 to 10 present the regional distribution of selected geochemical parameters. The distribution of specific conductivity shows lower values in groundwater of the St-Mathieu – Berry esker (Figure 8). Values in the clay plain between eskers and in the buried Barraute esker are higher and variable. The confined conditions of the Barraute esker may explain these higher values. The same trend is observed for the distribution of major elements Ca, Mg, Na, K, Alkalinity, and Cl (Cloutier et al. in prep). A large range of pH (7.39 to 8.82) is observed in the St-Mathieu – Berry esker compare to the Barraute esker. The three sites with pH above 8.5 are from the St-Mathieu – Berry esker (Cloutier et al. in prep).

Figure 9 shows that the sampling sites with aesthetic objectives exceeding in Fe and Mn are distributed throughout the region. Even though higher concentrations are found in the fractured rock units, some were observed in granular aquifers of eskers. As for Fe and Mn, most of samples having a high total hardness are from wells installed in the fractured rock units found between eskers and could highly be influenced by the bedrock geology.

The problem of arsenic contamination in domestic wells of Abitibi-Témicamingue was studied by Poissant (1997). The natural origin of As in groundwater could be related to the presence of Archean sedimentary rocks. Figure 10 shows the distribution of As in groundwater with bedrock geology as background. The site with the highest value in As is from a well installed in the confined fractured rock aquifer, located just north of the sedimentary rocks (unit 3 on Figure 10). Geology could also explain the higher concentrations in F of groundwater from the rock units in the south-western region of the RCM of Abitibi (Cloutier et al. in prep). The presence of F in groundwater could be related to the presence of the mineral fluorite in granitic rocks (unit 7 on Figure 10). The interaction between groundwater and fluorite could have triggered the processes that generated these higher concentrations in F in wells installed in this geological unit or close to it.

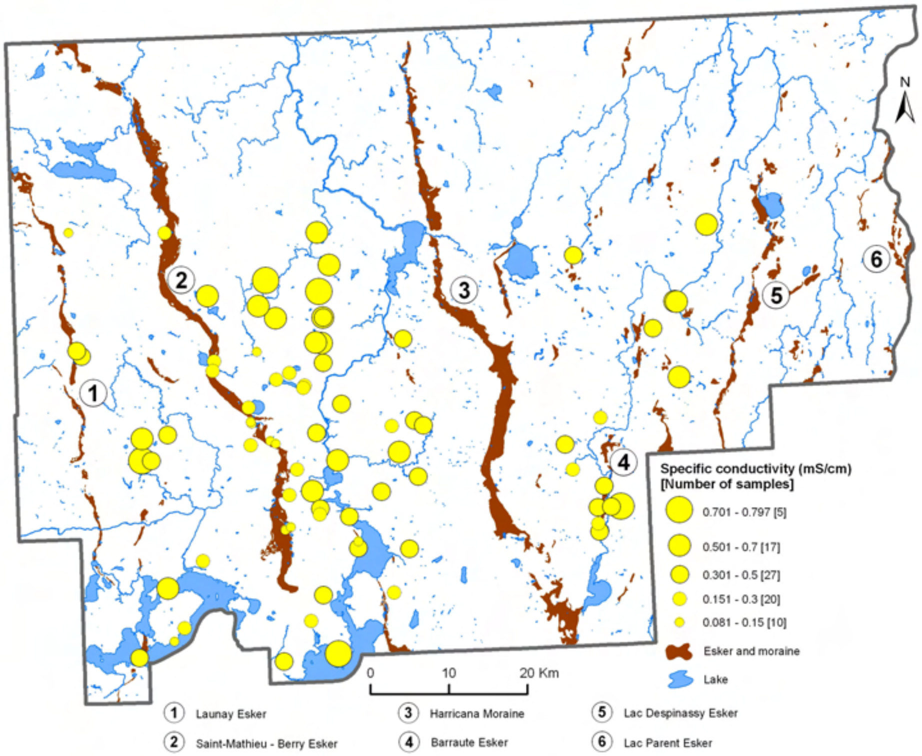

Figure 8. Regional distribution of specific conductivity in groundwater (surficial geology from Veillette et al. 2003)

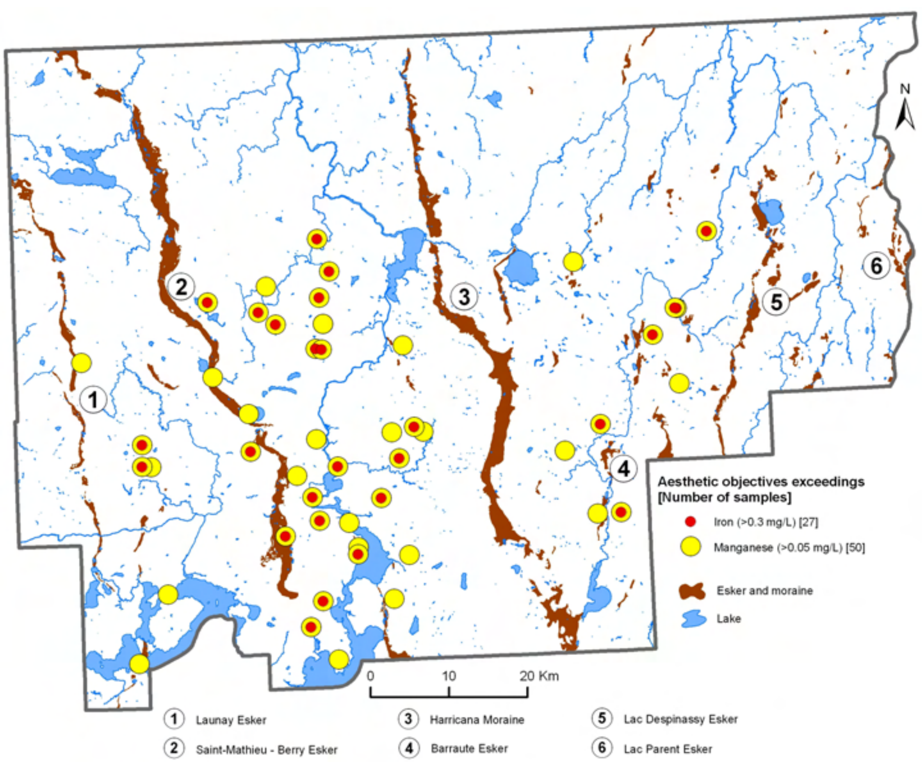

Figure 9. Sampling sites with aesthetic objectives exceeding in Fe and Mn (surficial geology from Veillette et al. 2003)

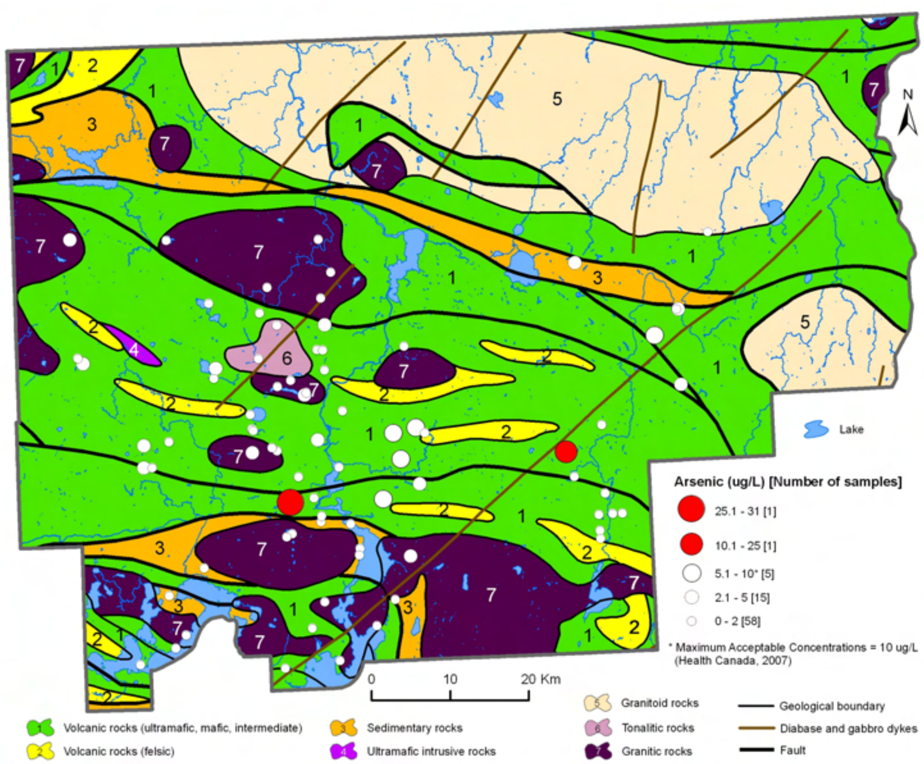

Figure 10. Regional distribution of arsenic in groundwater (geological map adapted from MRN 2002)

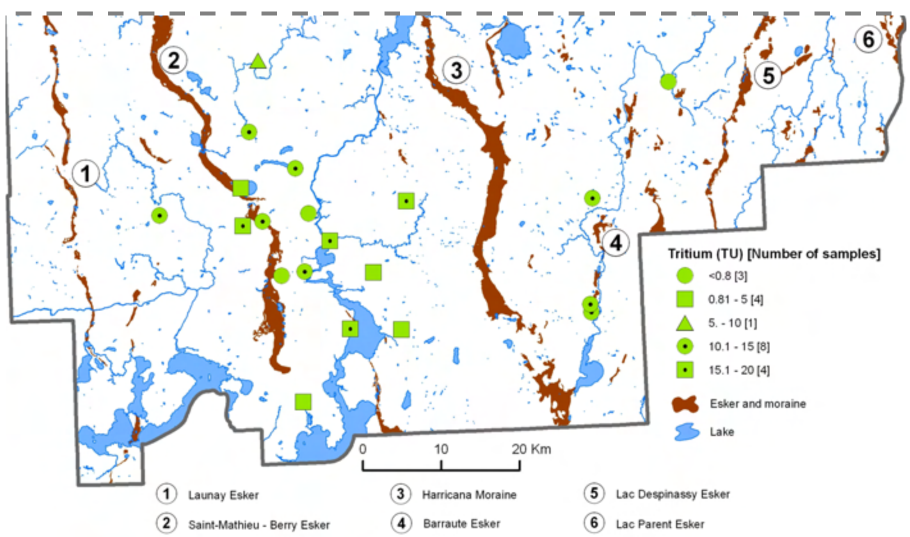

Figure 11. Regional distribution of tritium in groundwater (surficial geology from Veillette et al. 2003)

4.1 Tritium Dating

Twenty samples were analyzed for enriched tritium to evaluate the mean residence time of groundwater. The samples were chosen to represent the different hydrogeological conditions: a) 14 samples in confined fractured rocks aquifers, b) 5 samples in confined granular aquifers (including 2 wells installed in the buried Barraute esker, 2 wells in the clay plain, and 1 well in the flank of St-Mathieu – Berry esker), and c) 1 well in unconfined granular aquifers of the St-Mathieu – Berry esker. The tritium concentrations of the sampling sites, expressed as tritium units (TU) are shown on Figure 11.

The following qualitative interpretation of the tritium data is based on the presence of tritium in groundwater, and allows division of groundwater into modern, mixture between recent recharge and submodern, and submodern, i.e. recharged prior to 1952 (Clark and Fritz 1997). Three samples from the confined rock unit have tritium concentrations <0.8 TU. These tritium-free samples are considered as submodern water older than

1952. Four samples have tritium values from 0.8 to 5 TU, and could result from the mixing between modern and older groundwater. Two of these samples are from the confined rock unit, one from confined granular aquifers in the clay plain, and one from the confined granular aquifers in the flank of St-Mathieu – Berry esker. The last thirteen samples have modern tritiated water (5 to 20 TU), and are considered as recently recharged groundwater. One of these wells is from the St-Mathieu – Berry esker in unconfined conditions, two from the buried Barraute esker, nine from the confined rock unit, and one from confined granular deposits. These data indicate the input of modern groundwater in the confined rock aquifer. The recharge of modern water could occur in areas of elevated topography, with rock outcrops and thin till cover, as presented on Figure 3.

5 SUMMARY AND CONCLUSION

This paper presents initial results obtained from a regional hydrogeochemical characterization in Abitibi. The geochemical data for 80 groundwater samples were presented within the geological and hydrogeological contexts of the study area. For the parameters analyzed, the groundwater quality is generally good in the region. Drinking water quality of wells installed in the clay plain (in fractured rock unit or permeable sediments below the clay aquitard) is affected mainly by aesthetic parameters, as hardness, Mn and Fe. The samples that exceed health criteria, two samples for As and one for F, indicate that rock/water interaction influences geochemistry of groundwater from the fractured Canadian Shield rock aquifers. The presence of minor and trace constituents, as F and As, is thus influenced by the geological units. With no sample exceeding health-base guidelines, groundwater quality associated to the glaciofluvial formation as eskers is superior to the one of the fractured Canadian Shied rock aquifers.

The geochemical data and the distribution maps of parameters show that groundwater chemistry is influenced by geological contexts for parameters as Fe, Mn, pH, hardness, As and F. Other parameters are also controlled by the hydrogeological contexts including the specific conductivity and major ions. The study shows the chemical differences between groundwater of eskers and the one of the fractured rock units. The study also indicates that the water chemistry can be significantly different between eskers, as for the St-Mathieu-Berry esker and the buried Barraute esker, and that the water quality could be variable within the same esker, as for the St-Mathieu-Berry esker. The geochemical processes affecting groundwater are still being investigated. Details geochemistry of the different types of eskers is required to explain the hydrochemical variability between eskers.

The qualitative interpretation of the tritium concentrations in groundwater is generally consistent with the hydrogeological conditions. These results show the presence of submodern and modern groundwater in the confined rock aquifer. The detection of tritium in groundwater is a qualitative indication of the aquifer vulnerability. Additional groundwater dating would better constrain the activity of the groundwater flow systems of the St-Mathieu-Berry and the buried Barraute eskers. The geochemical data set establishes the natural chemical background in the region, and will be used in conjunction with the larger hydrogeological project to elaborate management strategies for the groundwater resource.

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