POTENTIAL IMPACTS OF SAND AND GRAVEL EXTRACTION ON GROUNDWATER RESOURCES: SUGGESTED SOLUTIONS

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1. Introduction

Depending on the prevailing hydrogeological conditions, sand and gravel deposits can host significant aquifers. These environments are frequently mined for the production of construction aggregates and of backfill materials. Such operations often involve (1) the removal of vegetation and soil cover, (2) the modification of natural surface slopes, (3) a reduction in the unsaturated layer thickness and (4) increased risks related to the spill of polluting substances during mechanical operations. As a result, groundwater quantity and quality can be impacted (see **Hatva, 1994; Markle et al., 2007; Smerdon et al., 2012**). The sustainable development of sand and gravel resources therefore implies to adapt land management strategies in an effort to prioritize groundwater protection. In this scope, the present study aims at developing strategies intended to minimize the potential impacts of sand and gravel extraction on groundwater resources stored in eskers on the basis of quantitative hydrogeological and cartographic data. Specific objectives include (1) the definition of a groundwater resource sensitivity index and (2) a regional scale evaluation of the pressure induced by sand and gravel extraction on the groundwater resources. These calculations are used to suggest solutions for allowing the sustainable management of sand and gravel extraction.

2. Study area

The study area (**Figure 1**) covers 25 750 km^2 and encompasses the Barlow-Ojibway Clay Belt region in western Quebec, Canada. The geomorphological features of the region are inherited from the Canadian Shield irregular surface and from the sediments deposited during and following the last glaciation. A detailed description of the regional geological setting can be found in **Nadeau (2011)**. Here, the focus is set on the unconfined granular aquifers found in eskers and moraines, the latter constituting significant groundwater resources within the study region, both in terms of water quality and quantity (**Cloutier et al., 2013a; 2013b; 2014**). Considering the similarities between the eskers and moraines within the region, both terms are jointly called "eskers" below. The outcropping esker segments were mapped on the basis of data from the Geological survey of Canada (GSC). This allowed defining 594 distinct polygons, altogether covering 1 100 km^2 of the study region (**Figure 1**). An exhaustive inventory of sand and gravel extraction sites was developed based on the compilation of pre-existing governmental databases and complemented by the analysis of aerial photographs (see **Cloutier et al., 2013c**). This allowed identifying 588 extraction sites altogether covering approximately 2% of the areal extent of outcropping eskers (**Figure 1**).

Figure 2 (a through f) illustrates the sequence of glaciofluvial, glaciolacustrine and postglacial processes that led to the development of eskers within the Barlow-Ojibway proglacial lake. Subaqueous fans first developed at the emergence of subglacial meltwater at the ice-front (figure **2a; 2b**). Silt and clay sediments were then deposited within lake Barlow-Ojibway up to elevations of approximately 320 m (**Figure 2c**). As the lake level dropped, wave action has partly reworked the sediments (**Figure 2d**). Wind and water action along with peatland and vegetation development subsequently led to the shaping of the landscape as it appears today (**Figure 2e; 2f**). Most of the eskers found within the study region were formed under these (or somewhat similar) conditions.

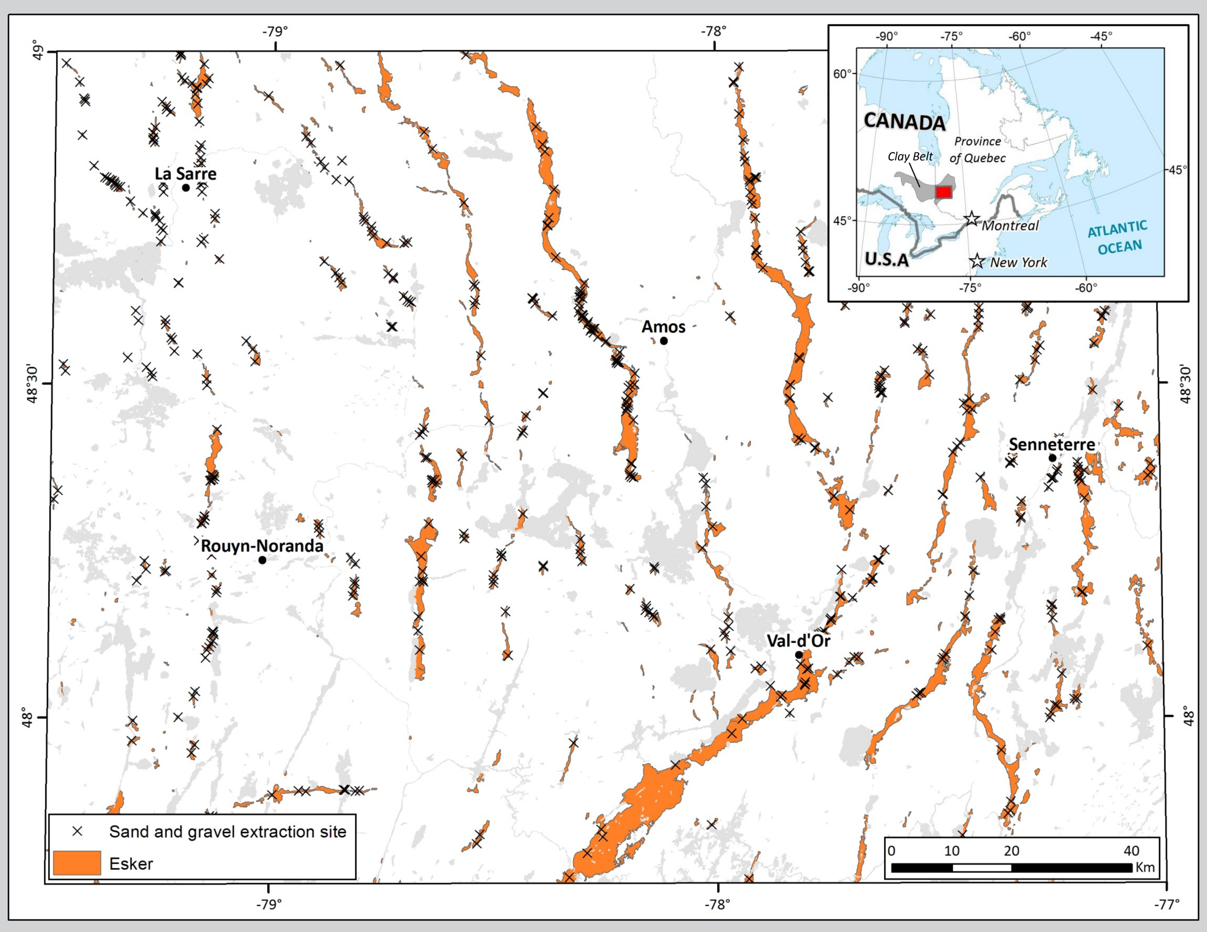

Figure 1. Eskers and sand and gravel extraction sites within the study area

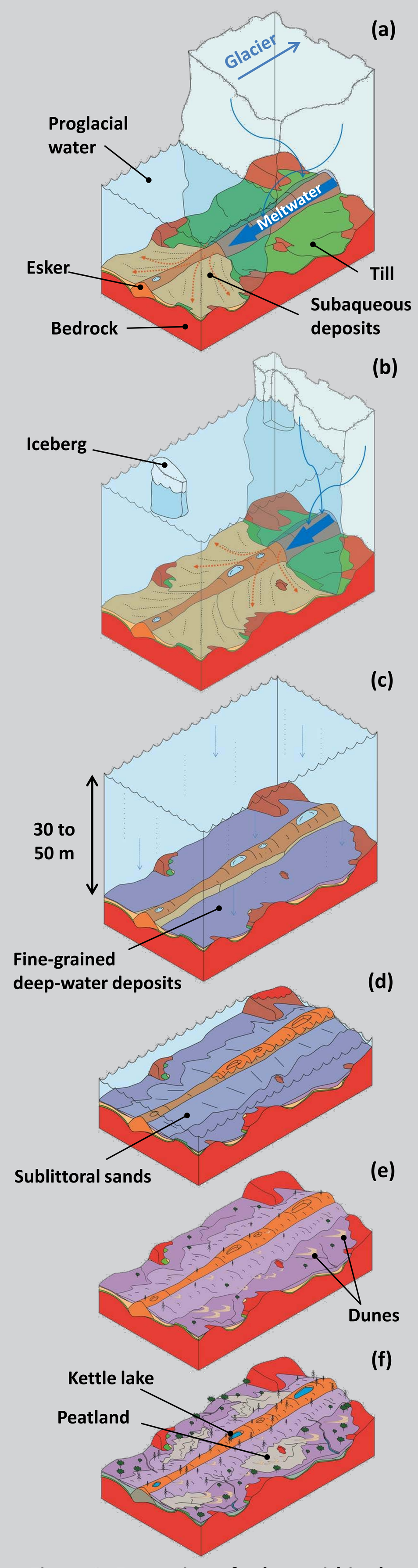

Figure 2. Formation of eskers within the study region

3. Methods

3.1. Definition of a reference surface

Figure 3a shows an esker segment, bordered on its sides by finer sediments and overlying older sediments or sitting directly on the bedrock, consistent with the regional hydrogeological framework. **Figure 3b** illustrates the hydrogeological unit defined by eskers in terms of regional resources. We assume that the volume of material contained between the bedrock surface and the maximal potential elevation of the water table comprises the potential groundwater reserve stored in eskers, whereas the volume of material contained between the water table and the ground surface consists in the granular resource. The maximum potential elevation of the water table is therefore used as a reference surface for defining the limit between both resources. The approach relies the hypothesis that the maximum height of the water table that can be maintained within the eskers is imposed by the elevation of the hydrogeological units defining their limits (assumed to be characterized by lower hydraulic conductivities).

The position of the reference surface is evaluated by linearly interpolating the elevations of reference points delineating the lateral extent of eskers. It is interpreted as the maximal potential elevation of groundwater within these formations. The reference points used for the interpolation are generated using the extremities of linear segments defining eskers in the GSC maps. The elevations of reference points are extracted from topographic data interpolated using the Anudem algorithm (Topo to raster tool) in ArcMap.

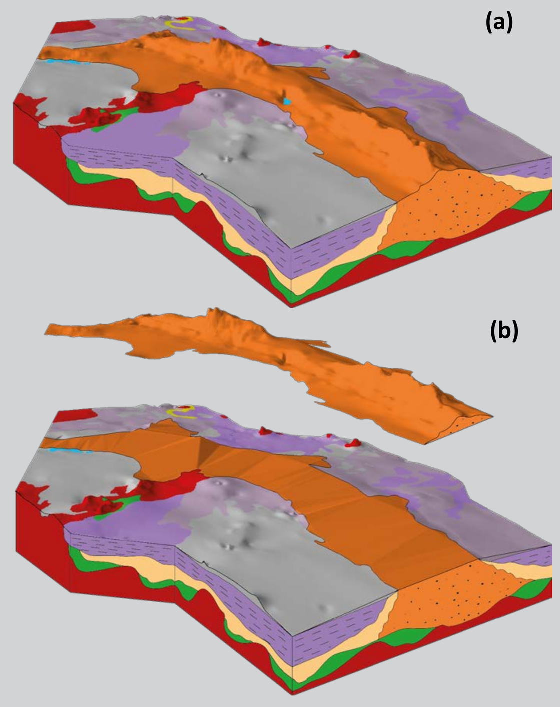

Figure 3. Schematic representation of an esker (a) in terms of hydrogeological setting and (b) in term of exploitable resources

3.2. Evaluation of potential groundwater and granular resources

Estimates of Aquifer Potential Levels (**APL**) are proposed on the basis of geomorphological observations following the approach developed by **Nadeau, (2011)**, as summarized in **Figure 4a-b** and **Table 1**. The thickness of the unsaturated sand and gravel layer (**Figure 4c**) is evaluated by subtracting the elevation of the reference surface (**Section 3.1**) from ground surface elevations using a 100 m x 100 m grid.

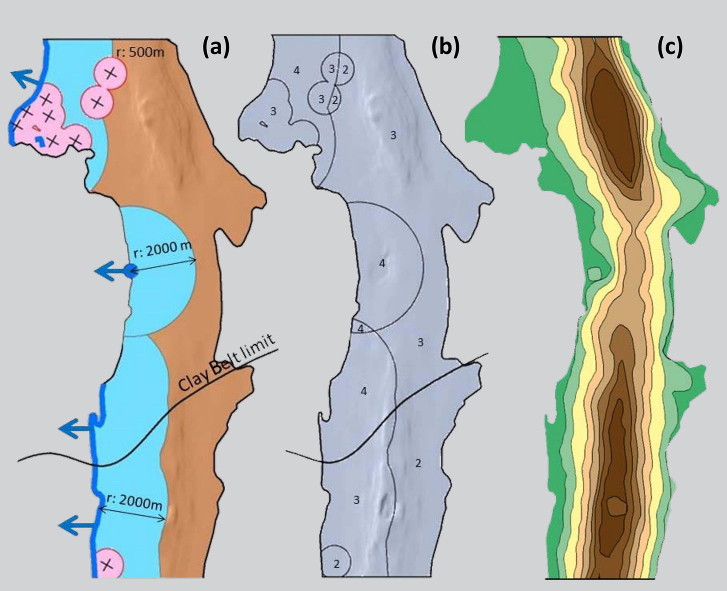

Figure 4. (a-b) Illustration of the method used for evaluating APL values (refer to Table 1); (c) schematic representation of the unsaturated layer thickness (brown = greater thicknesses)

Fine grained sediments on the eskers flanks	Bedrock or till outcrops within a 500 m radius	Springs or diffusive seepage zones within a 2000 m radius	Aquifer potential level (APL)
Yes (1)	Yes (0)	Yes (2)	APL-3
		No (1)	APL-2
	No (1)	Yes (2)	APL-4
		No (1)	APL-3
No (0)	Yes (0)	Yes (2)	APL-2
		No (1)	APL-1
	No (1)	Yes (2)	APL-3
		No (1)	APL-2

Table 1. Aquifer potential level (APL) evaluation strategy

3.3. Definition of a groundwater resource sensitivity index (GRSI) for groundwater resources stored in eskers

Two main aspects were retained for evaluating groundwater sensitivity towards sand and gravel extraction based on a spatial approach:

1- How likely is a given esker parcel to store a significant groundwater volume;
2- How vulnerable is the resource stored in this given esker parcel.

The first aspect is evaluated solely on the basis of the previously defined aquifer potential levels (APL) (**Figure 4 a-b; Table 1**). The second aspect is estimated based on an adaptation of the DRASTIC method (**Aller et al., 1987**). It is assumed that the term «D» of the DRASTIC method (depth to water) constitutes the key parameter for differentiating the vulnerability of aquifers within eskers as the six other parameters («R», «A», «S», «T», «I», «C») are most likely to be fairly constant at the regional scale within these formations. The vulnerability of the groundwater resource stored within eskers is therefore evaluated on the basis of the reference surface depth (**Figure 4c**). Based on these assumptions, the Groundwater Resource Sensitivity Index (GRSI) is defined as:

$$GRSI = \frac{APL}{4} + \frac{R_{RSD}}{50}$$ **Equation 1**

Where the *APL* and R_{RSD} terms represent the aquifer potential level as defined in section 3.2 and the rating (*R*) given to the reference surface depth (*RSD*) according to the DRASTIC method . **Equation 1** was applied to every 100 m x 100 m parcel of eskers, allowing a representation of the **GRSI** at the regional scale. Based on this approach, esker sectors that are unlikely to store significant volumes of groundwater and that are likely to present an important unsaturated layer thickness show the lowest **GRSI**, and vice-versa.

4. Results and discussion

Figure 5 illustrates the **GRSI** as evaluated using equation 1 (**Section 3.3**) for each 100 m x 100 m parcel of esker within the study region. In the context of this study, the concept of groundwater resource sensitivity refers to the potential impacts on groundwater resources (in terms of quantity and quality) that may result from human activities conducted on eskers. It is proposed here that the more a sector is characterized by a high **GRSI**, the more sand and gravel extraction activities will represent a risk of compromising groundwater resources. Based on this approach, esker margins appear to present the highest sensitivity. This is partly explained by the position of the reference surface (**Section 3.1**), the latter being closer to the ground surface on the eskers flanks (**Figure 4c**).

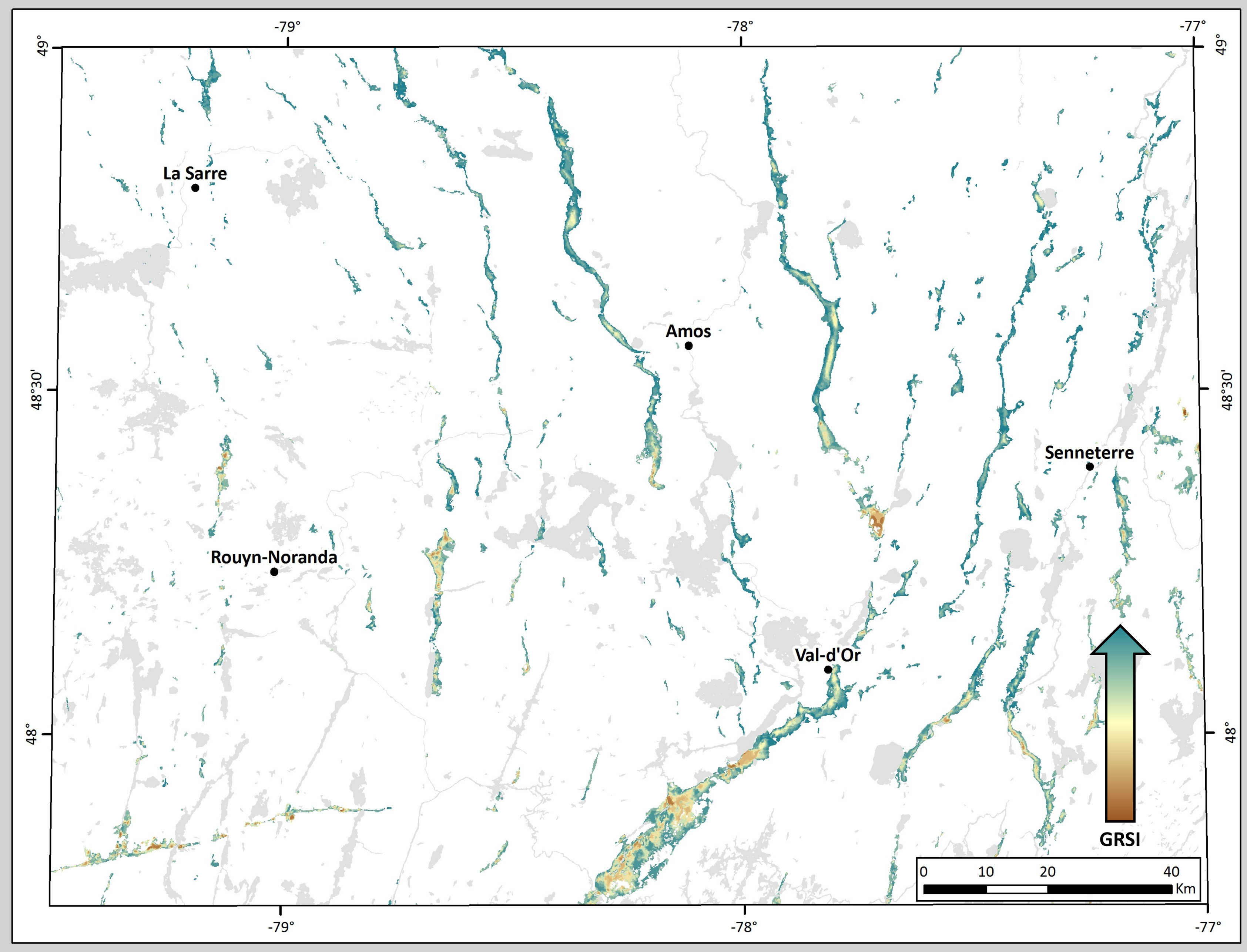

Figure 5. GRSI values evaluated at the regional scale

Based on the pre-established **GRSI** (**Figure 5**), a sand and gravel Extraction Pressure Index (**EPI**) can be defined in order to provide a picture of the present-day situation with respect to the pressure exerted on the groundwater resource. The strategy used for calculating the **EPI** is illustrated in **Figure 6**. For each esker parcel (on a 100 m X 100 m grid), the proportion of the area exposed to extraction was calculated within a 500 m radius. This proportion (with values ranging from 0 to 1), is then multiplied by the value of the **GRSI** corresponding to the same parcel to obtain the first term needed to evaluate the **EPI**:

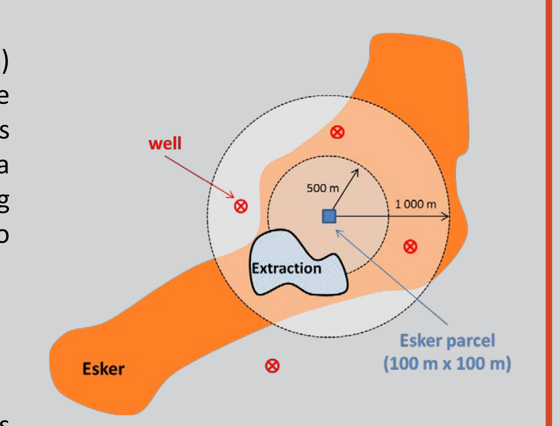

Figure 6. EPI evaluation strategy

$$Term\ \#1 = \left[\frac{APL}{4} + \frac{R_{RSD}}{50}\right]\varphi$$ **Equation 2**

Where the terms in brackets correspond to the **GRSI** as reported in **Equation 1** and φ represents the spatial density of sand and gravel extraction sites within a 500 m radius of the parcel.

Subsequently, the number of wells within a radius of 1 000 m is evaluated for each esker parcel. The result is used for calculating the second term needed to evaluate the **EPI**:

$$Term\ \#2 = \left[\frac{APL}{4} + \frac{R_{RSD}}{50}\right]\varphi n$$ **Equation 3**

Where n represents a quote (with values ranging between 0 and 1) corresponding to the density of wells within a 1 000 m radius of the parcel. Based on this approach, the **EPI** corresponds to the value of *Term #2* when the result of **equation 2** is >0 and to the value of *Term #1* everywhere else (**Figure 7**). This approach allows highlighting sectors where sand and gravel extraction operations are concentrated in the vicinity of potentially sensible aquifers or wells used for water supply. Simply said, the higher the **EPI**, the higher the risk towards groundwater resources stored in eskers. We propose that the **GRSI** and **EPI** maps could be used as tools for orienting land management strategies in an effort to protect groundwater resources. From a groundwater protection perspective, the location of future sand and gravel extraction sites should be chosen in a manner (1) to avoid sectors characterized by high **ERSI** values and (2) to minimize future **EPI** values.

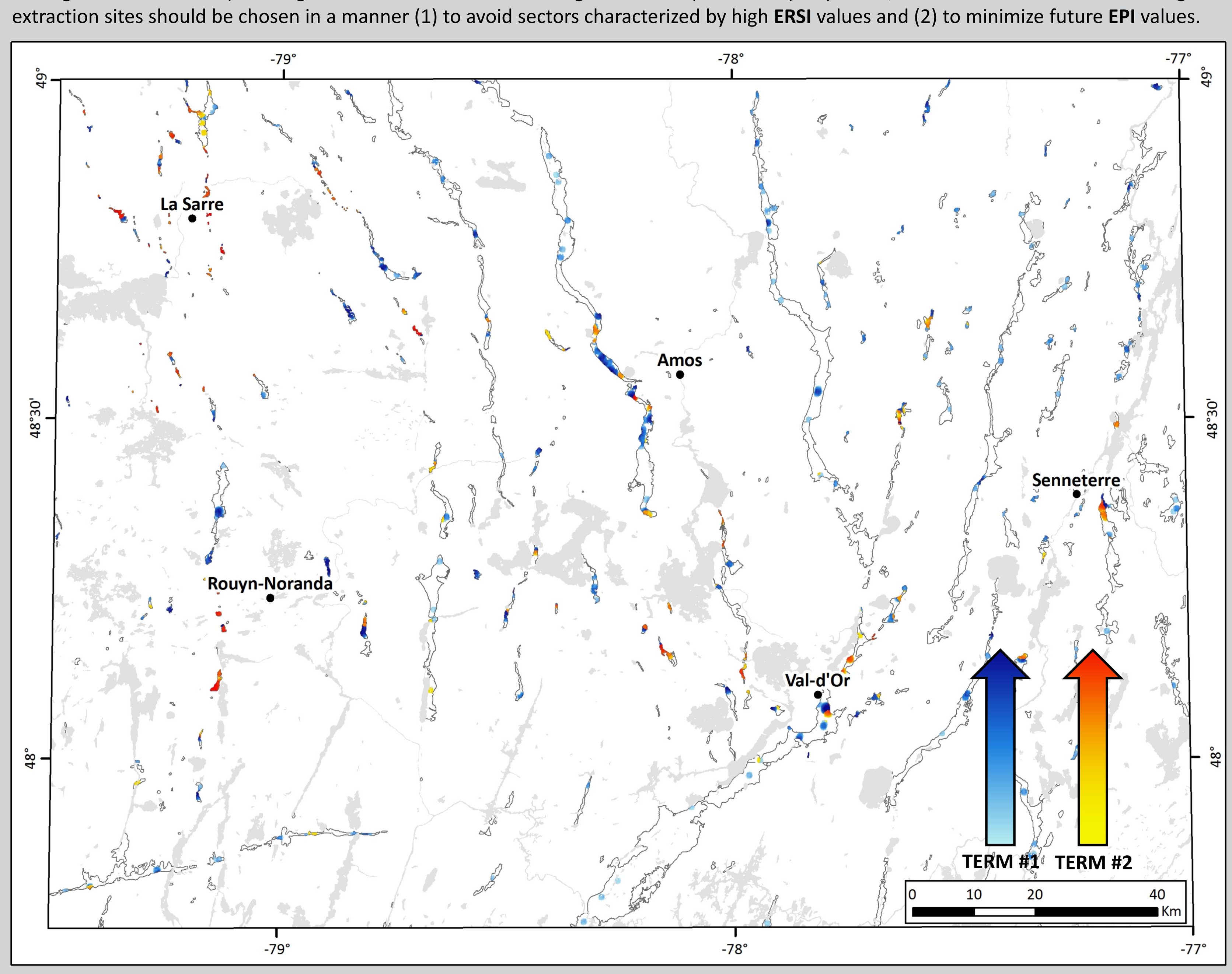

Figure 7. EPI values evaluated at the regional scale

5. Concluding remarks

This study aimed at developing strategies intended to minimize the potential impacts of sand and gravel extraction on groundwater resources stored in unconfined granular aquifers. The focus was set on the aquifers found in eskers, the latter constituting significant groundwater resources within the study region. Esker segments were subdivided using a 100 m x 100 m grid in order to allow calculations based on a cartographic approach. A groundwater resource sensitivity index (**GRSI**) was defined on the basis of (1) an indirect evaluation of granular aquifer volumes and (2) estimates of the parameters included in the DRASTIC method. The pressure induced by sand and gravel extraction (**EPI**) on the groundwater resources was evaluated for each 100 m x 100 m esker parcel on the basis of (1) the predefined resource sensitivity index and (2) the spatial density of sand and gravel extraction sites and groundwater wells. These calculations were used to suggest solutions for allowing the sustainable management of sand and gravel extraction activities in an effort to protect groundwater resources.

6. References and acknowledgements

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