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A GIS-based approach for supporting groundwater protection in eskers: Application to sand and gravel extraction activities in Abitibi-Témiscamingue, Quebec, Canada

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ABSTRACT

Study region: Part of Abitibi-Témiscamingue in northwestern Quebec (25,750 km^2), within the Quebec/Ontario Clay Belt, Canada.
Study focus: The focus is set on the unconfined granular aquifers found in eskers, the latter containing significant groundwater resources, both in terms of water quality and quantity. Yet, these glaciofluvial deposits also constitute the main source of exploitable sand and gravel and are therefore frequently at the roots of land use conflicts.
New hydrological insights: Methods and indices based on the use of geographic information systems (GIS) were developed in support of land management strategies oriented towards the protection of groundwater resources in eskers of northwestern Quebec. A groundwater resource sensitivity index was defined for each 10 × 10 m parcel of esker on the basis of (1) an evaluation of the aquifer potential based on three geomorphological parameters observable on well-known granular aquifers and (2) estimates of the parameters included in the DRASTIC method. The pressure induced by sand and gravel extraction on the groundwater resources was subsequently evaluated on the basis of (1) the resource sensitivity index, and (2) the spatial density of sand and gravel extraction sites and groundwater wells. These calculations are used to suggest solutions for supporting the sustainable management of sand and gravel extraction activities at the regional scale and for highlighting sectors where field data acquisition is most needed.

1. Introduction

The sustainable exploitation of natural resources requires the adaptation of land management strategies to ensure groundwater protection. Shallow, unconfined aquifers found in surficial deposits are likely to be especially vulnerable to human pressures. In that sense, the protection of groundwater resources stored in eskers must be prioritized. Eskers consist of sand and gravel deposits formed by meltwaters in contact or in the vicinity of a glacier (Banerjee and McDonald, 1975; Brennand,

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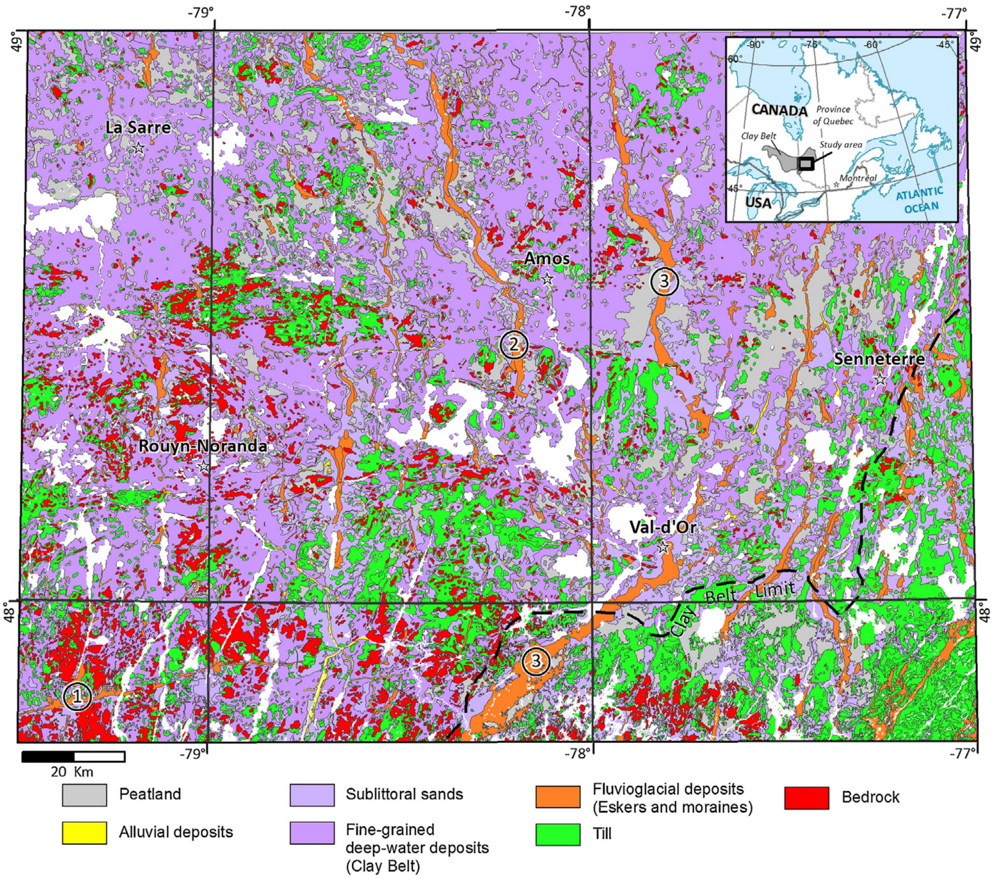

Fig. 1. Surficial geology of the study area based on maps from the Geological Survey of Canada (see text for details). The inset shows the extent of the Clay Belt. (1) Roulier Moraine, (2) Saint-Mathieu/Berry esker, and (3) Harricana Moraine. As a complement to this figure, the files «Study_area.kmz» and «Eskers_study_area.kmz» provided as Supplementary geospatial data illustrate the limits of the study region and the spatial distribution of eskers.

2000). From a geomorphological perspective, these formations consist of straight or sinuous linear accumulations of glaciofluvial deposits that can reach several kilometers in length and several tens of meters in thickness in the glaciated terrain of Nordic countries. Depending on the prevailing hydrogeological conditions, eskers can host significant aquifers (Väisänen, 1997; Okkonen and Kløve, 2012) that are likely to interact with surrounding surface waters (Ala-aho et al., 2013; Okkonen and Kløve, 2011) and peatlands (Comas et al., 2005; Rossi et al., 2012). In Abitibi-Temiscamingue (Fig. 1), glaciofluvial formations formed in contact with the proglacial waters of Lake Barlow-Ojibway are partly, and in some rare cases, totally buried by glaciolacustrine sediments. Such conditions allow eskers to host aquifers containing significant groundwater resources, both in terms of water quality and quantity, and some are exploited for water supply (Bolduc et al., 2005; Riverin, 2006; Veillette et al., 2007; Cloutier et al., 2013). One noticeable example is that of the Saint-Mathieu/Berry esker (no.2 on Fig. 1), which is used extensively, including a commercial bottling company and water wells supplying Amos, a city of 13,000 persons. Yet, in populated areas, borrow pits in eskers are frequently at the roots of land use conflicts. The extraction of sand and gravel for construction purposes stands out as a major concern with respect to groundwater protection. Sand and gravel extraction activities commonly 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, quality and temperature can be impacted, along with dependent ecosystems (see Hatva, 1994; Markle and Schincriol, 2007; Smerdon et al., 2012). Smerdon et al. (2012) proposed that the potential impacts of sand and gravel extraction on groundwater dependent ecosystems (GDE) could be investigated and minimized during planning studies on the basis of simple quantitative analyses. This study was initiated with the purpose of developing a regional scale GIS-based approach intended to support land management strategies oriented towards the protection of groundwater resources stored in eskers. The specific objectives include the establishment of spatial calculation methods aimed at (1) quantifying the outcropping sand and gravel resources associated with eskers, (2) evaluating the position of the water table within eskers, and (3) classifying esker segments based on their potential to host groundwater resources. The methods rest on hydrological data and measurements and geomorphological information obtained from surficial geology maps. The results associated with the predefined specific objectives are discussed in the perspective of evaluating a groundwater resources sensitivity index (GRSI). The latter is used for evaluating a spatial index

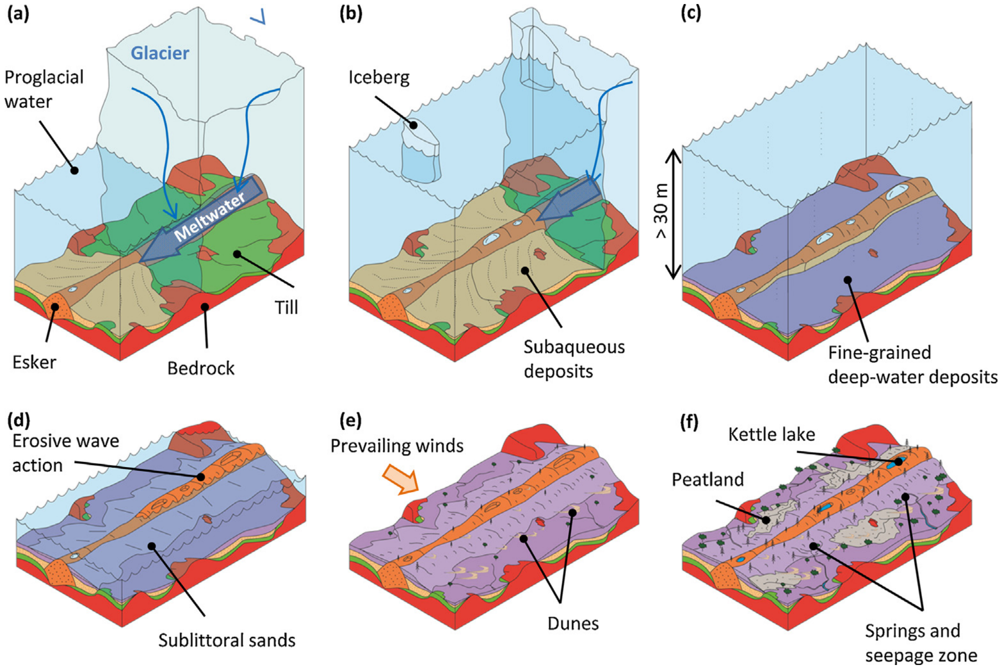

Fig. 2. Sequence of glaciofluvial, glaciolacustrine and postglacial processes that led to the development of eskers within the Barlow-Ojibway proglacial lake (adapted from Nadeau (2011); see Section 2 for details).

related to the pressure induced by sand and gravel extraction on groundwater resources. These indices will hopefully assist managers concerned with the protection of groundwater resources in eskers.

2. Study area

The study region includes part of Temiscamingue and Abitibi counties in northwestern Quebec and covers a total area of 25,750 km^2, accounting for approximately 20% of the Quebec/Ontario Clay Belt (Fig. 1). Over most of the study area, the bedrock essentially consists of Archean intrusive, plutonic, volcanic and metasedimentary rocks of the Superior Province, whereas younger rocks, predominantly gneissic, of the Grenville Province are found in the southern part of the area (MERQ-OGS, 1983). The geomorphological features of the region are inherited from the rugged Precambrian Shield topography, the latter being covered in places by accumulations of glacial, glaciofluvial and/or glaciolacustrine deposits. The result is a featureless clay plain broken up locally by wave-washed bedrock knobs, higher hills covered by a thin cover of till and glaciofluvial deposits, with eskers and moraines rising above the surrounding terrain. These eskers form a vast network converging toward a large interlobate landform (Harricana Moraine) roughly oriented north-south (no.3 on Fig. 1). The Harricana-Lake McConnell glaciofluvial system was the expression used by Veillette (1986a) to refer to the southern component of this extensive and complex landform. In its northern part (north of Val-d'Or), several indicators point to the interlobate nature of the feature and its esker-like characteristics (see Veillette, 1986a for a review of the literature). It was deposited in deep proglacial waters and as observed in the study of Brennand and Shaw (1996) carried out in that part of the feature, shares similarities with eskers in terms of depositional processes. Similarly, borrow pits in the Roulier Moraine (no.1 on Fig. 1), a distinct frontal feature also deposited in contact with deep proglacial waters, show stratified, water-laid, granular sediments that, from a hydrogeological perspective, do not differ significantly from esker deposits. The moraines of the study region are considered here as similar to eskers in terms of hydrogeological characteristics and are therefore referred to as "eskers" from here on. For simplification purposes, the portion of an esker that stands above the surrounding terrain is hereafter referred to as its «outcropping» portion. A detailed description of the regional geological setting and glacial history is found in the maps produced by the Geological Survey of Canada (GSC) (Veillette, 2004; Thibaudeau and Veillette, 2005; Paradis, 2005, 2007; Veillette, 1986b, 1987a,b) (hereafter referred to as GSC maps).

Veillette (1994) described the evolution of glacial Lake Barlow-Ojibway, with an emphasis on the impact of water depth variations on the composition and distribution of glaciofluvial and glaciolacustrine deposits. Fig. 2 (a through f) is based on interpretations of the glacial and post-glacial history and illustrates the sequence of glaciofluvial, glaciolacustrine and postglacial processes that led to the development and evolution of eskers as they occur today within the study area. The coarse, granular core of eskers (flanked by subaqueous fans) first developed at the emergence of subglacial meltwater at the ice front, within proglacial lake Barlow-Ojibway (Fig. 2a and b). Fine-grained deep-water sediments (silt and clay) were then deposited on glaciofluvial sediments in the deepest parts of the lake basin, up to approximately 320 m asl (above sea level)

(Fig. 2c) in central Abitibi region, concealing the base of the large eskers. As the lake level dropped, wave action reworked the eskers crests into broad, nearly flat surfaces and distributed the sediments as aprons of sand and gravelly sand overlying the fine-grained deep water deposits (Fig. 2d). Wind action and fluvial erosion were the main processes active in early postglacial time followed by paludification and vegetation development beginning in mid-Holocene. This sequence of events led to the landscape as it appears today (Fig. 2e and f). Most of the eskers found within the study area are located in the deepest parts of the Barlow-Ojibway basin and were formed under such conditions.

Hereafter, the focus is set on the unconfined granular aquifers identified in eskers (Cloutier et al., 2013, 2015) as the latter are most prone to land use conflicts. These contain (1) significant groundwater resources both in terms of quality and quantity and (2) the main source of sand and gravel deposits available for extraction within the study region. The outcropping esker segments of the region were identified on the basis of data from the GSC maps. This allowed defining 594 distinct polygons, altogether covering approximately, 1100 km^2. A total of 541 distinct sand and gravel extraction sites were identified within these esker segments using governmental databases (forest inventories, mining titles and surficial geology maps) and aerial photographs. Altogether, these sites cover approximately 2% of the areal extent of outcropping eskers (see supplementary geospatial data). Individual extraction sites range in size from 60 to 1,082,000 m^2, with average and median areas of 37,100 and 14,300 m^2, respectively. In addition, a total of 4310 groundwater wells included in the Quebec's provincial Hydrogeological Information System (HIS) database and 122 groundwater wells included in the directory of wells supplying more than 20 people (Provincial government database) are identified within the study region. Among these, 937 (with 895 from the HIS) are located inside or within a distance of 1000 m of polygons delineating eskers in the GSC maps.

3. Methods and data sources

3.1. Evaluation of outcropping sand and gravel resources

Digital topographic data from the Government of Quebec topographic database (1:20,000 scale) were used to construct a digital elevation model (DEM) of the study region on a 10 × 10 m grid. The DEM was constructed using the topo to raster tool in ArcGIS 10. A reference surface was subsequently defined by creating a triangulated irregular network (TIN) constructed from the elevation of the vertices of polygons defining eskers in the GSC maps. The TIN was converted to a 10 × 10 m raster to obtain the reference surface elevation (RSE). The volume of outcropping sand and gravel material associated with eskers was evaluated by calculating the difference between ground surface elevation and the RSE for each 10 × 10 m parcel of esker and accounting for area (outcropping volume associated with a parcel = [DEM elevation – RSE] × surface). For a given esker segment, the volume of outcropping material corresponds to the sum of volumes calculated for each included 10 × 10 m parcel. Fig. 3 illustrates the conceptual basis of the approach previously described.

3.2. Groundwater monitoring

Field data were acquired to support the application of spatial calculations. A total of 40 piezometers were installed within 13 eskers segments and instrumented with automated probes (Solinst Levelogger gold LT F30/M10 3001) in order to achieve temporal monitoring of water levels (see Supplementary geospatial data). The probes were lowered within the piezometers using a steel cable. The fluctuations in atmospheric pressure were monitored using 10 automated probes (Solinst Barologger LT F5/M15 Model 3001) installed within the protective casings of selected piezometers. The data from 14 piezometers installed within eskers and included in the groundwater monitoring network of the Government of Quebec were also used. In all cases, data were collected at regular intervals of 6 h (1 h;7 h;13 h;19 h).

3.3. Evaluation of aquifer potential levels

The subsurface extent of eskers (Fig. 3) is likely to be significant in terms of volume with respect to their outcropping portion (see Artimo et al., 2003; Bolduc et al., 2005; Veillette et al., 2007; Cummings et al., 2011). However, within the study region, the scarcity of drilling data precludes a straightforward quantitative evaluation of the volumes of eskers (and associated aquifers) below the ground surface. The main limitation is related to the assessment of the bedrock morphology underneath eskers. The near-absence of subsurface control prevents a precise quantitative regional-scale evaluation of aquifers set in eskers, since both the shape and extent of the reservoirs are partly dictated by the bedrock configuration. Field observations along with aerial photographs interpretation and data from the GSC surficial deposits maps were therefore jointly used for evaluating the potential of eskers to store groundwater based on three main parameters observable on well-known granular aquifers of the region (Bolduc et al., 2005; Veillette et al., 2007; Nadeau, 2011):

1. The potential of an esker to contain groundwater is closely related to its sedimentation environment. Eskers flanked by fine-grained glaciolacustrine sediments are most likely to contain groundwater because they occur in the low altitude sector (<320 m) of the region and are contained within relatively impervious sediments.
2. The potential of an esker to contain groundwater is related to the underlying bedrock topography. It is assumed that the presence of rock and till outcrops within and/or in the vicinity of eskers implies the absence of major bedrock depressions underneath the esker and hence of significant granular aquifers. Here, it is proposed that if an esker parcel (10 × 10 m) is

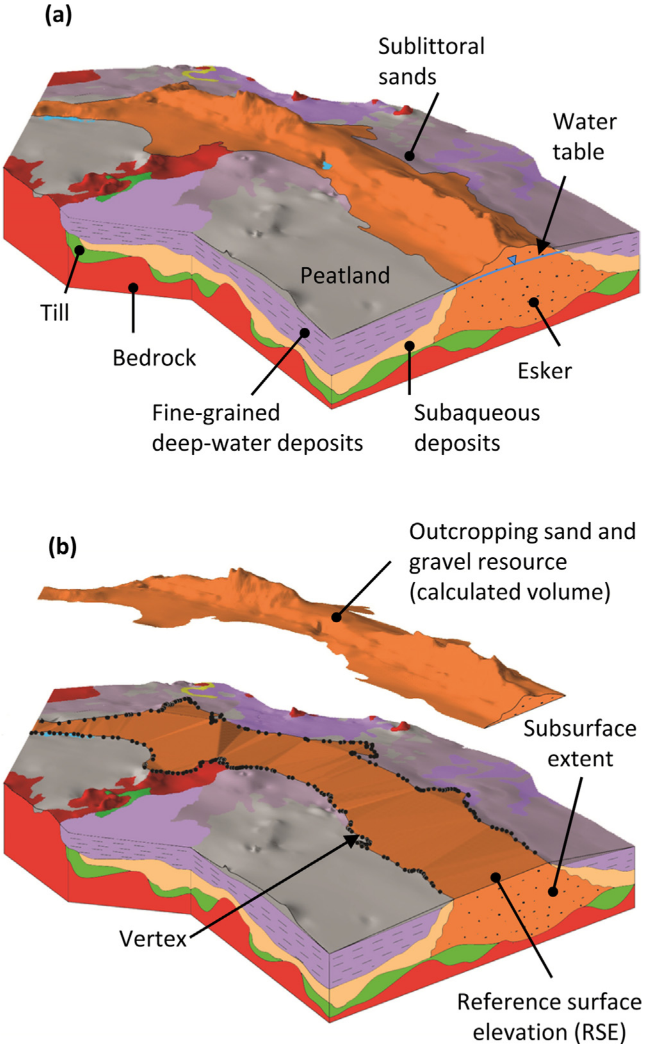

Fig. 3. Representation of an esker in terms of (a) hydrogeological framework and (b) associated reference surface. Dots along the esker margin correspond to the vertices of the polygon as defined from the Geological Survey of Canada maps (refer to Section 3.1 for details).

located within a distance of 500 m from a bedrock outcrop, the geological evidences suggest that the subsurface extent of glaciofluvial sediments (and associated aquifers) is limited. Although this criterion does not allow a quantitative assessment of the subsurface extent of eskers, it allows categorizing esker parcels on the basis of a straightforward spatial approach that is applicable even in region where subsurface data availability is limited.

3. The presence of springs and/or diffuse seepage zones associated with peatlands on the margins of eskers suggests the presence of groundwater within the glaciofluvial deposits. Stereoscopic analysis of aerial photographs (1:40,000 scale, taken between years 1970 and 1990) suggests that dendritic surface water networks developed on the flanks of eskers correspond to major groundwater seepage zones. Punctual springs were identified from aerial photographs and/or field visits. Here, it is proposed that the esker parcels located within a distance of 2000 m from a spring or diffuse seepage zone are most likely to host groundwater resources. The 2000 m radius roughly corresponds to the greatest width of glaciofluvial formations within the study region. It is therefore assumed that if an esker is characterized by a seepage zone on one of its lateral margins, it is likely to contain groundwater over its entire width.

The attribution of ratings related to these basic parameters allowed Nadeau (2011) to propose a classification of eskers according to their aquifer potential (Table 1). A modified version of this classification is presented here. Esker segments were subdivided using a 10 × 10 m grid and each cell was attributed an «aquifer potential level» (APL) ranging between 1 and 4 following the procedure summarized in Fig. 4:

1. APL-1: no geomorphological evidence of a groundwater reservoir.

Table 1
Summary of the evaluation strategy for aquifer potential levels (APL).

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

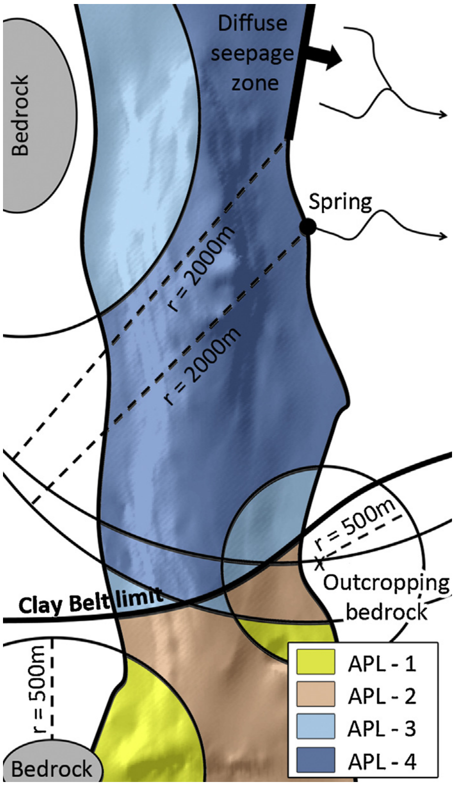

Fig. 4. Illustration of the parameters considered for evaluating the aquifer potential levels (APL). Corresponding APL values within the esker segment (with values ranging between 1 and 4) are also shown. Refer to Section 3.3 and Table 1 for further details. As a complement to this figure, the punctual springs and diffuse groundwater seepage zones identified within the study region are can be viewed from the files «Springs.kmz» and «Seepage_zones.kmz» provided as Supplementary geospatial data.

2. APL-2: geomorphological features suggest the possibility of a limited groundwater reservoir.
3. APL-3: most geomorphological features suggest the presence of a groundwater reservoir.
4. APL-4: all geomorphological features suggest the presence of a significant groundwater reservoir.

Based on the approach outlined above, esker segments characterized by the highest APL values are most likely to host significant groundwater reservoirs within the study region.

4. Results

4.1. Evaluation of outcropping sand and gravel resources

The DEM indicates elevations ranging between 250 and 604 m in the study region, with eskers generally defining crests within the landscape. Fig. 5 illustrates the spatial distribution of the calculated outcropping granular thicknesses (i.e., height of esker material lying above surrounding terrain). At the regional scale, the calculated outcropping esker thicknesses reach

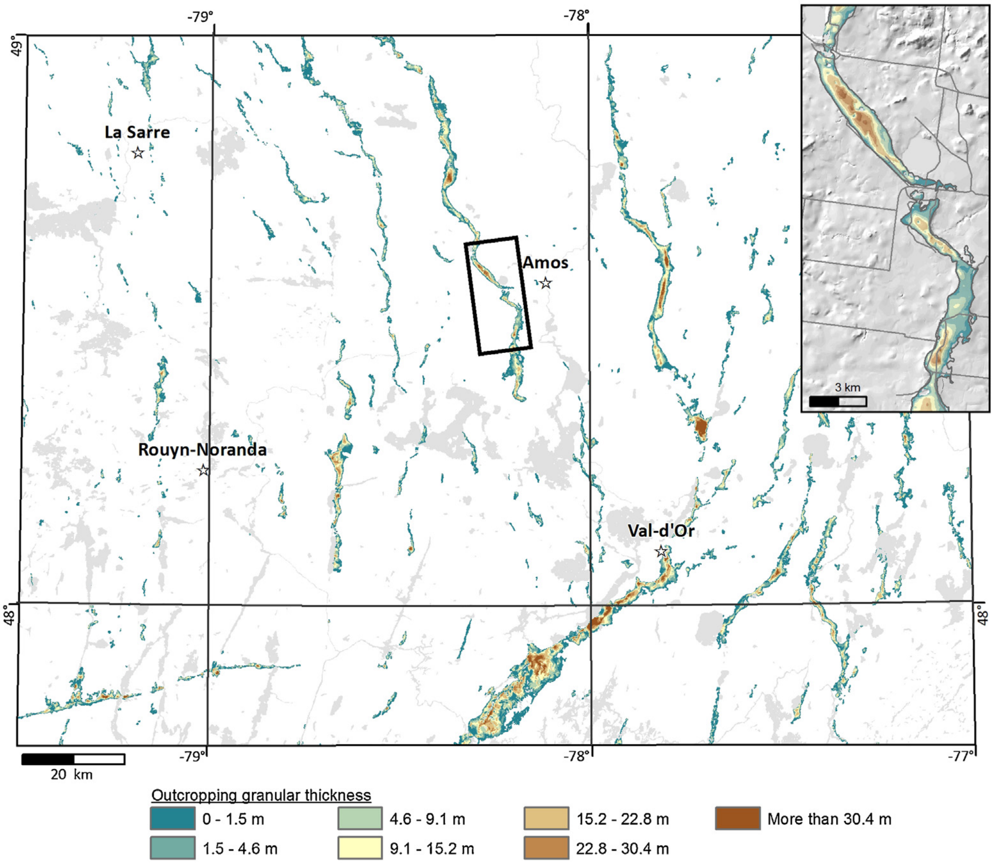

Fig. 5. Regional distribution of the outcropping granular material thickness values evaluated for each 10 × 10 m esker parcel using the approach outlined in Section 3.1 (Fig. 3). The proposed thickness classes correspond to limit values associated with the «*D*» factor (depth to water) of the DRASTIC method. The data can also be viewed from the file «Outcropping_granular_thickness.kmz» provided as Supplementary geospatial data.

a maximum value of 77 m with average and median values of 7.2 m and 4.2 m, respectively. In sectors where the calculated reference surface elevation is greater than the corresponding values of the DEM (due to local morphological features), the thickness of outcropping sand and gravel deposits is considered equal to zero. Based on this data, it is estimated that outcropping sand and gravel resources represent a total volume of 6.3 km^3 within the study region.

4.2. Groundwater monitoring

Supplementary Table 1 provides a summary of groundwater levels monitored within eskers. The data allow calculating groundwater elevations ranging between 294 and 358 m at the regional scale, with temporal fluctuations ranging between 0.4 and 4.8 m over the study period.

4.3. Evaluation of aquifer potential levels (APL)

The approach described in Section 3.3 is used for highlighting the esker segments where the resource is most likely to be significant in terms of volume. The calculations were conducted on 594 distinct esker segments subdivided according to a 10 × 10 m grid. The geological and geomorphological features used for the calculations include:

1. a total of 4241 linear km of eskers flanked by clay, accounting for 66% of the cumulated perimeters of esker segments.
2. a total of 3,220,519 cells identified within 500 m of a bedrock or a thin till outcrop and representing 29% of the cumulated area of esker segments.
3. a total of 117 punctual springs and 1428 linear km of mapped diffuse groundwater seepage zones accounting for 35% of the cumulated perimeters of esker segments.

Fig. 6 illustrates the spatial distribution of the calculated APL. Overall, 41% of the areal extent of eskers corresponds to an APL-4 value, 40% corresponds to an APL-3 value, 16% corresponds to an APL-2 value, and 1% to an APL-1 value. The remaining

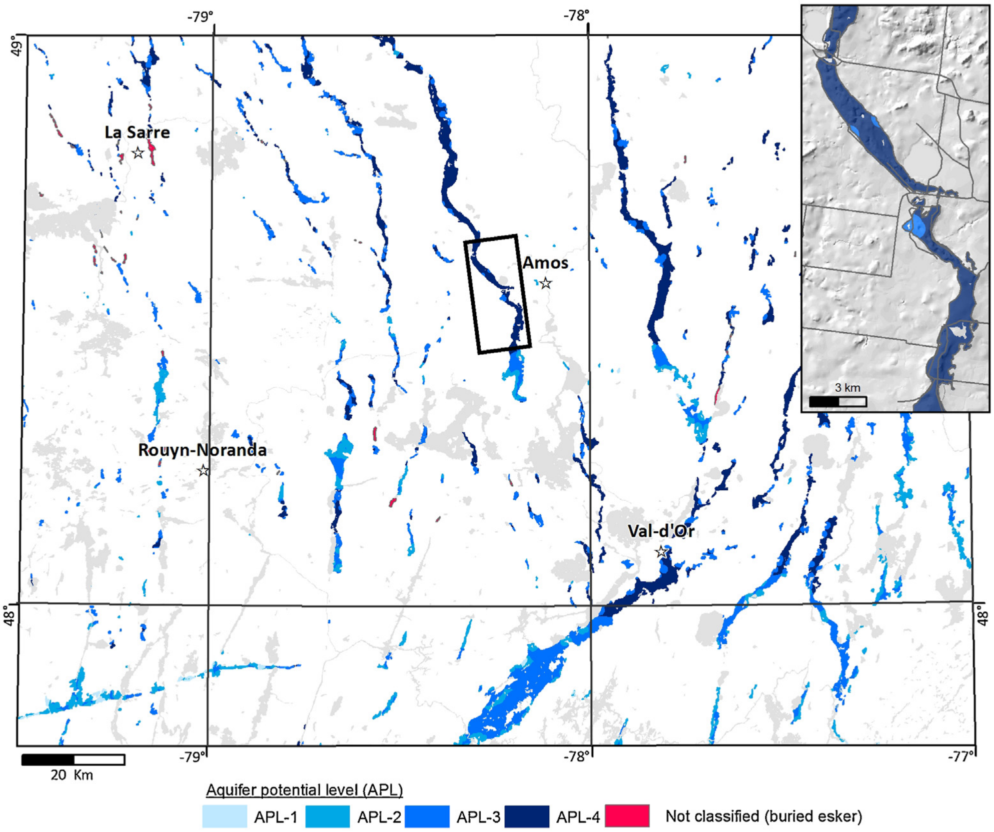

Fig. 6. Regional distribution of aquifer potential level (APL) values evaluated for each 10 × 10 m esker parcel using the approach outlined in Section 3.3 (Fig. 4; Table 1). Higher APL values correspond to sectors presenting geomorphological evidence suggesting for the presence of a groundwater reservoir. The data can also be viewed from the file «APL.kmz» provided as Supplementary geospatial data.

2% refers to totally buried esker segments that could not be classified using the approach proposed here. It is assumed that esker sectors characterized by higher APL values are more likely to contain significant aquifers (in terms of volume) than esker segments characterized by low APL values.

5. Proposition of spatial indices

The development of indices aimed at evaluating (1) the sensitivity of the groundwater resources stored in eskers and (2) the pressure induced by sand and gravel extraction on groundwater resources is central to the following Sections. The indices and related spatial calculations are exclusively based on the data and results presented in the previous Sections. Unless stated otherwise, all of the GIS-based calculations and associated values rely on a 10 × 10 m grid restricted to the polygons defining eskers as they appear on the GSC maps. The indices were developed with the objective of providing a useful management tool for the protection of groundwater contained in the glaciofluvial deposits at the regional and local scales.

5.1. Groundwater resources sensitivity index

Two basic questions were addressed for evaluating groundwater sensitivity towards sand and gravel extraction activities:

- How likely is a given esker parcel to store a significant groundwater volume?
- How vulnerable is the resource stored in this esker parcel?

The answer to the first question is solely based on the previously defined aquifer potential levels (APL) (Sections 3.3 and 4.3). The overall high APL values attributed to the Saint-Mathieu/Berry esker segment (Fig. 6; see Fig. 2 for location of the Saint-Mathieu/Berry esker) are consistent with the significant groundwater resources identified therein (Bolduc et al., 2005; Riverin, 2006).

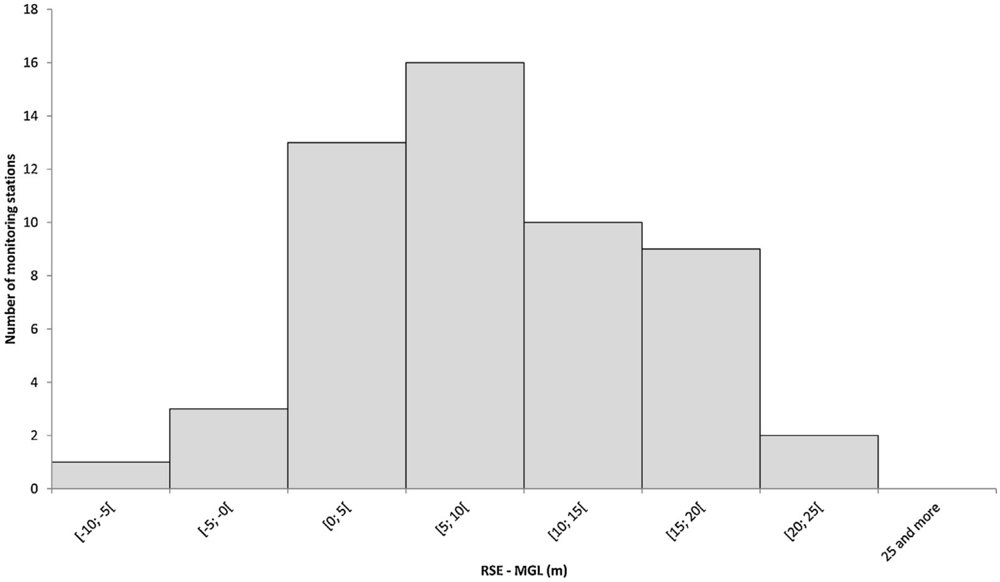

Fig. 7. Comparison of the reference surface elevation (RSE) with corresponding average monitored groundwater levels (MGL). Values on the *x* axis correspond to the difference between RSE and the corresponding MGL.

It contains the bulk of boreholes and geophysical data in the region directed towards the evaluation of the groundwater potential. Based on this, we suggest that the APL evaluations provide realistic estimates of aquifers potential within the eskers of the study region.

The answer to the second question is based on an adaptation of the DRASTIC method (Aller et al., 1987) which can be used to evaluate the pollution potential of hydrologic settings based on the seven factors forming the acronym DRASTIC: depth to water «*D*», net recharge «*R*», aquifer media «*A*», soil media «*S*», topography «*T*», impact of the vadose zone media «*I*» and hydraulic conductivity «*C*». Here, it is proposed that «*D*» constitutes the key factor for differentiating the vulnerability of groundwater within eskers as the 6 other parameters are known to be fairly constant at the scale of the study region within these formations (Cloutier et al., 2013). The vulnerability of the groundwater resource stored within eskers is therefore evaluated on the basis of the depth of the water table within eskers. However, given the limited available groundwater monitoring data (Sections 3.2 and 4.2), the precise evaluation of the water table within eskers at the scale of the study area remains challenging. Here, it is proposed that the reference surface elevation (RSE) as described in Sections 3.1 and 4.1 provides a reliable estimate of the maximum possible elevation of the water table within eskers. In that sense, the outcropping granular thicknesses illustrated in Fig. 5 correspond to the unsaturated layer thickness and allow identifying the minimum depth of the water table below surface. Although the above statements represent a simplification of the natural complexity of hydrogeological conditions, the following field observations, calculations and hypotheses tend to support the acceptability of the proposed strategy:

1. Eskers define topographic highs within the study area (Fig. 3). Their matrix is characterized by relatively high hydraulic conductivities (10^{-6} to 10^{-1} m/s, Cloutier et al., 2013). Therefore, in the absence of lower hydraulic conductivity units on their margins, eskers are unlikely to sustain high groundwater levels under the hydrogeological conditions prevailing within the study region;
2. Localized springs and diffuse groundwater seepage zones are frequently observed at the contact of eskers with surrounding geological formations, especially fine-grained glaciolacustrine deposits (Sections 3.3 and 4.3). This tends to indicate that water levels within eskers are partly controlled by the elevation of the surrounding geological units which present lower hydraulic conductivities. Above this elevation, groundwater flowing within the eskers is likely to form springs and diffuse seepage zones;
3. The data from the 54 groundwater monitoring sites available within the study area (Sections 3.2 and 4.2) reveal that the reference surface depth is, on average, 9.3 m above the average elevation of the monitored groundwater levels (MGL) (Fig. 7). This is consistent with the hypothesis that the RSE provides a reliable estimate of the maximum possible elevation of the water table within eskers.

Based on the previously discussed elements and assumptions, a Groundwater Resource Sensitivity Index (GRSI) is proposed:

$$\mathrm{GRSI} = \frac{\mathrm{APL}}{4} + \frac{R_{\mathrm{Ref}}}{10} \tag{1}$$

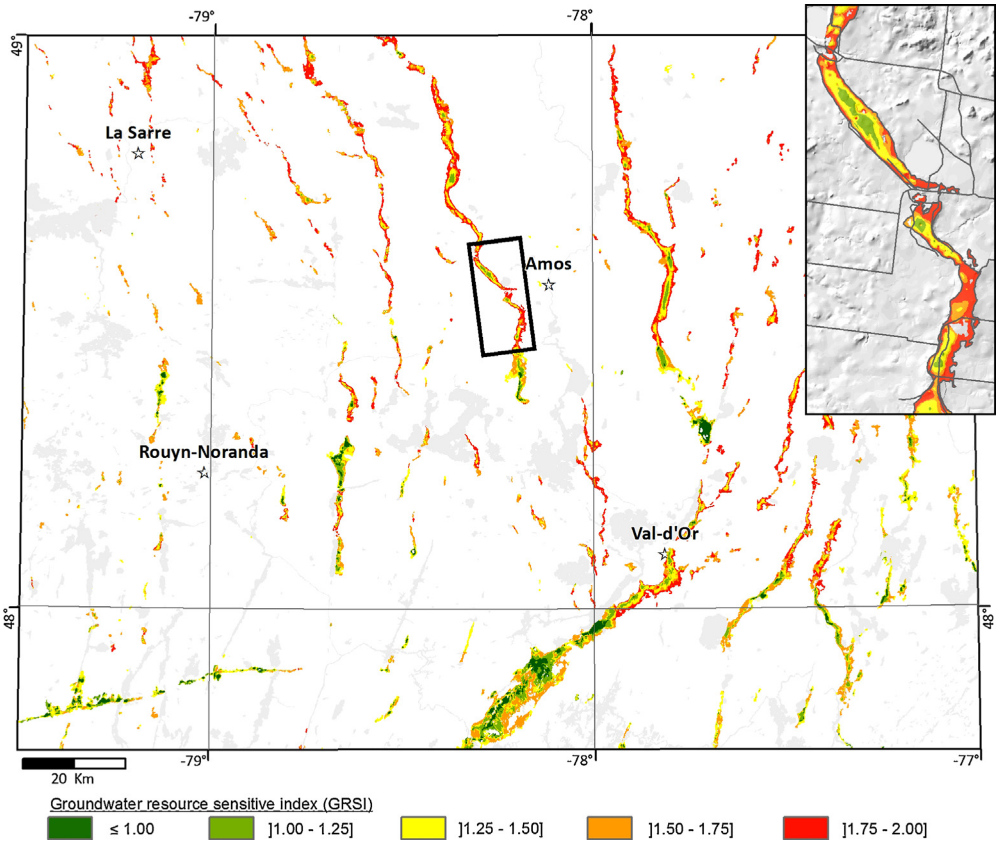

Fig. 8. Regional distribution of groundwater resource sensitive index (GRSI) values evaluated for each 10 × 10 m esker parcel using Eq. (1). Esker sectors coloured in red are considered to be most sensitive. The data can also be viewed from the file «GRSI.kmz» provided as Supplementary geospatial data.

Where the APL and R_{Ref} terms represent the aquifer potential level as defined in Section 3.3 (values ranging between 1 and 4) and rating given to the depth of the reference surface (as defined in Section 3.1) below the ground surface according to the DRASTIC method, assuming that it corresponds to the «*D*» factor of the DRASTIC method (with possible values ranging between 1 and 10, based on the approach proposed by Aller et al., 1987). The denominators used on the right side of Eq. (1) ensure that both terms can reach maximum values of 1, therefore restricting GRSI to dimensionless values ≤ 2. The regional scale spatial distribution of calculated GRSI values is illustrated in Fig. 8. Calculated GRSI values range from 0.45 to 2.00, with average and median values of 1.60 and 1.65, respectively. Based on the approach outlined above, esker parcels that are most likely to host significant aquifers in terms of volume (high APL values) and that correspond to sectors characterized by shallow groundwater depths (shallow reference surface position below ground surface) are considered most sensitive (higher GRSI values), and vice-versa. The large outcropping esker segments tend to present higher GRSI values on their margins. This is attributed to the reduction of the depth of the water table from eskers crests towards their flanks (Figs. 5 and 8). In that sense, the greater thickness of the unsaturated layer on eskers crests is assumed to act as a protection for groundwater. Smaller esker segments, which generally display shallower unsaturated thicknesses (Figs. 5 and 8), tend to present GRSI values >1.50.

5.2. *Sand and gravel extraction pressure index*

A sand and gravel Extraction Pressure Index (EPI) is proposed in order to provide an evaluation 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 Fig. 9. For each 10 × 10 m esker parcel, the proportion of area exposed to sand and gravel extraction was calculated within a 500 m radius. This spatial density (with values ranging from 0 to 1), is subsequently multiplied by the value of the GRSI (Section 5.1) corresponding to the same parcel in order to obtain the first term needed to evaluate the EPI:

$$\text{Term\#1} = \left[\frac{\text{APL}}{4} + \frac{R_{\text{ref}}}{10}\right]\varphi \tag{2}$$

Where the terms in brackets correspond to the GRSI as reported in Eq. (1) and φ represents the spatial density of sand and gravel extraction sites within a 500 m radius of the parcel used for calculating Eq. (2). The 500 m radius represents the

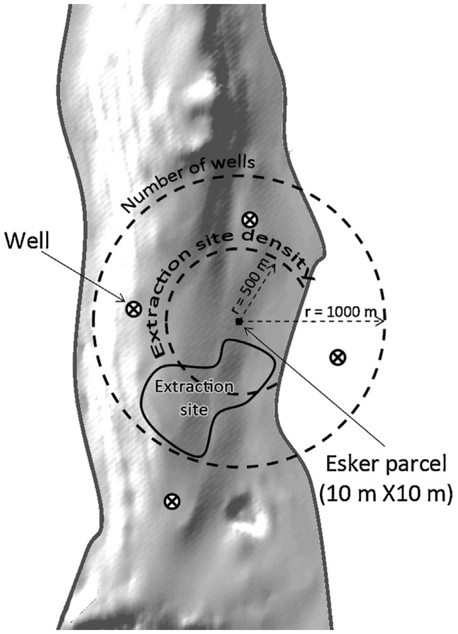

Fig. 9. Sand and gravel extraction pressure index (EPI) evaluation strategy. The proportion of 10 × 10 m cells included within sand and gravel extraction sites is evaluated within a 500 m radius of the selected cell (with cells located outside of the esker excluded from the calculation) ($\varphi \approx 0.2$ for the example illustrated here). The number of groundwater wells located within 1000 m of the selected cell is evaluated by including wells located beyond the esker limit ($n = 3$ for the example illustrated here). The entire procedure in repeated for each 10 × 10 m esker parcel.

Table 2
Quotes attributed with respect to the number of groundwater wells within a 1000 m radius of each esker parcel.

Number of groundwater wells identified	Attributed quote
0	0
[1–5]	0.2
[5–10]	0.4
[10–15]	0.6
[15–20]	0.8
≥20 or presence of a well supplying more than 20 people[a]	1

[a] Reference to the directory of groundwater wells supplying more than 20 people (see Section 2 for details).

maximal value that can be used for allowing φ values reaching 1 (with a larger radius, calculated φ values are systematically <1). The number of wells within a radius of 1000 m (radius used in provincial regulation respecting pits and quarries) is subsequently evaluated for each 10 × 10 m esker parcel. The result is used for calculating the second term needed to evaluate the EPI:

$$\text{Term\#2} = \left[\frac{\text{APL}}{4} + \frac{R_{\text{ref}}}{10}\right]\varphi n \tag{3}$$

where n represents a quote (with values ranging between 0 and 1) corresponding to the number of wells found within a 1000 m radius of the parcel (Table 2). Based on this approach, the EPI corresponds to the value of Term #2 when the result of Eq. (3) is >0 and to the value of Term #1 (result of Eq. (2)) everywhere else. The spatial distribution of calculated EPI values is illustrated in Fig. 10.

Based on the approach outlined above, EPI values allow highlighting sectors where sand and gravel extraction operations are concentrated in the vicinity of potentially sensitive aquifers (Term #1; Eq. (2); blue scale in Fig. 10) and/or wells used for water supply (Term #2; Eq. (3); red scale in Fig. 10): the higher the EPI, the greater the pressure exerted by sand and gravel extraction on groundwater resources stored in eskers. Quantitatively, it is estimated that 70% of existing extraction sites (in terms of area) are located within segments that are characterized by GRSI values >1.50, suggesting that sites selection strategies could be improved. Fig. 10 allows interpreting the data in terms of spatial distribution. The highest values calculated for Term #1 (Eq. (2); blue scale) allow the identification of esker segments where sand and gravel extraction sites are concentrated in the vicinity of esker parcels characterized by high GRSI values. At the regional scale, the highest Term #1 values tend to be concentrated in the vicinity of the most populated areas (La Sarre, Rouyn-Noranda, Amos and Val d'Or) (Fig. 10). In addition, high values of Term #2 (Eq. (3); red scale in Fig. 10) reveal that sand and gravel extraction sites are commonly observed within 1000 m of groundwater wells used for human consumption. This is the case, for example, for several of the esker segments located in the vicinity of the municipality of La Sarre (Fig. 10). At the regional scale, 196 of the

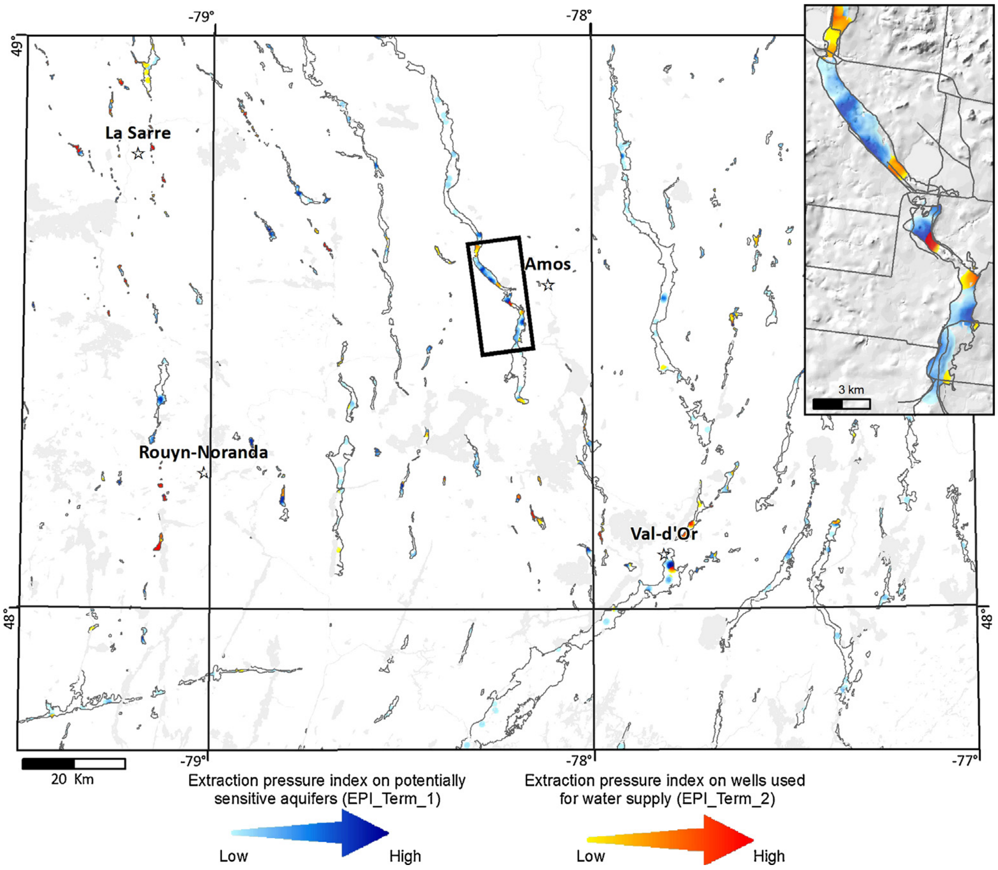

Fig. 10. Regional distribution of the extraction pressure index (EPI) values evaluated for each 10 × 10 m esker parcel using Eqs. (2) and (3). EPI values allow highlighting sectors where sand and gravel extraction operations are concentrated in the vicinity of potentially sensitive aquifers (Term #1; Eq. (2); blue scale) and/or wells used for water supply (Term #2; Eq. (3); red scale): the higher the EPI, the greater the pressure exerted by sand and gravel extraction on groundwater resources stored in eskers. The data can also be viewed from the files «EPI_Term_1.kmz» and «EPI_Term_2.kmz» provided as Supplementary geospatial data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

541 sand and gravel extraction sites are located within 1000 m of existing groundwater wells. Among the 122 groundwater wells supplying more than 20 people identified within the study region (see Section 2), 28 are located within 1000 m of sand and gravel extraction sites. It is proposed here that the sectors characterized by high EPI values (for one or both terms) should be prioritized for conducting field studies aimed at quantifying the impacts of sand and gravel extraction on groundwater resources. In addition, the examples discussed above suggest that within the study region, land management strategies related to sand and gravel extraction could be improved in an effort to protect groundwater resources.

6. Discussion

6.1. Suggested solutions at the regional scale

It is proposed that the GRSI and EPI maps (Figs. 8 and 10, respectively) could be used as tools for orienting land management strategies in an effort to protect groundwater resources. The location of future sand and gravel extraction sites should be chosen in such a way to (1) avoid segments characterized by high GRSI values and (2) minimize future EPI values. This would reduce the risk of contaminating groundwater stored within eskers and affecting existing groundwater wells. The calculated GRSI could be used as a preliminary regional tool for identifying esker segments where sand and gravel extraction represents a lower risk for the groundwater resource. Such segments should be preferred for performing further field measurements aimed at assessing the interpretations drawn from the GRSI map. The use of the GRSI map (Fig. 8) as a preliminary tool would reduce costly field measurements, given the large dimensions of the territory, by highlighting key esker segments where the groundwater resource is likely to be less at risk with respect to sand and gravel extraction activities. Finally, it is proposed here that the GRSI and EPI could be integrated (or used as a complement) to spatial multicriteria decision analysis strategies (see Malczewski, 2006) in an effort to prioritize groundwater protection in selecting area for new extraction sites.

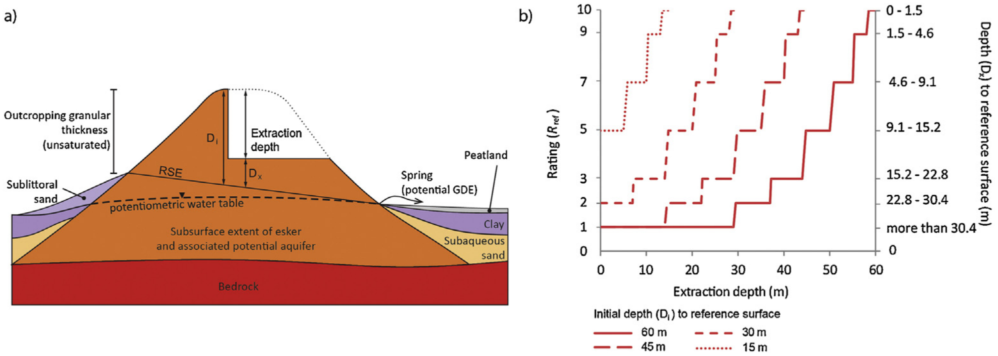

Fig. 11. (a) Conceptual representation of the impact of an extraction site on an esker segment. (b) Illustration of the stepwise increase of the rating attributed to the "*D*" factor of the DRASTIC method as a result of sand and gravel extraction.

6.2. *Suggested solutions at the local scale*

At the local scale, the effects of sand and gravel extraction on groundwater are likely to include impacts on water quantity, quality and temperature and associated effects on groundwater dependent ecosystems (see Hatva, 1994; Markle and Schincriol, 2007; Smerdon et al., 2012). However, there is currently no site-specific quantitative hydrogeological data permitting the quantification of such impacts within the study area. In this sense, the transition from regional to local scale in land management strategies aimed at protecting groundwater represents a challenge. Nevertheless, in an effort to be consistent with the regional approaches outlined above (Sections 5.1 and 5.2), the risk generated by sand and gravel extraction at the local scale could be assessed through an evaluation of the modifications of DRASTIC indices (Aller et al., 1987). Sand and gravel extraction activities are most likely to result in an increase of the ratings attributed to the «depth to water (*D*)», «soil cover (*S*)» and «topography (*T*)» factors of the DRASTIC method. As an example, Fig. 11 illustrates the stepwise increase of the rating attributed to the «*D*» factor of the DRASTIC method as a result of sand and gravel extraction. Under such circumstances, defining a DRASTIC index threshold value indicating when sand and gravel extraction should be stopped at the local scale could stand as a reliable approach. In addition, environmental restoration strategies that would reduce the quotes of the different parameters of the DRASTIC method should be prioritized.

Smerdon et al. (2012) proposed that knowledge of surficial geology, aggregate grade and lake elevations could provide sufficient information to develop simple quantitative analyses of the impacts of sand and gravel extraction on wetlands and lakes (and associated groundwater dependent ecosystems (GDE)). In connection with this, it is proposed here that the punctual springs and diffusive groundwater seepage zones (see Supplementary geospatial data) used for evaluating APL (Sections 3.3 and 4.3) should be targeted as potential GDE (see Fig. 11). As a complement, the elevation of the reference surface as defined in Section 3.1 could be used to identify lakes that are likely to interact with groundwater. The latter (along with springs and diffuse groundwater seepage zones) should be prioritized for the acquisition of local scale field data aimed at evaluating the capture zone where increased groundwater protection is required.

6.3. *Limits of the proposed approaches and indices*

The indices developed and the associated maps include a level of interpretation that may not account for the complexity of the hydrogeological environment at specific sites. Firstly, the proposed approaches do not account for temporal fluctuations in groundwater levels. Secondly, spatial calculations are performed using radial distances. This allows applying a straightforward approach based on conservative criteria, and proposing «critical distances» that can be used for orienting land management strategies. However, it does not allow accounting for groundwater flow directions. The proposed spatial approaches are therefore considered most suitable for regions where the scarcity of hydrogeological data prevents a robust evaluation of flow directions at the local scale but could be improved in sectors where groundwater flow directions are well-known. The proposed calculations are therefore not intended to replace field observations and data acquisition. It should rather be used as a preliminary tool (1) for evaluating the risk towards groundwater generated by sand and gravel extraction activities and (2) for identifying key esker segments where further field data acquisition should be prioritized. Such field investigations seem much needed for a better evaluation of the potential impacts of sand and gravel extraction on groundwater resources and related dependent ecosystems within the study region.

7. Conclusions

The need to develop tools to assist managers confronted with the potential land use conflict related to sand and gravel extraction activities on eskers, parts of which are also valuable, sensitive, unconfined aquifers, was the impetus for this study of a 25,750 km^2 area of northwestern Quebec. Using GIS-based methods and data from 54 piezometers recording water levels within eskers, the volume of unsaturated sand and gravel contained in the outcropping part (1100 km^2) of eskers was evaluated at 6.3 km^3. The potential of eskers to store groundwater (Aquifer Potential Level, APL) was expressed in 4 classes (levels) using criteria obtained from field observations, aerial photographs interpretations and surficial geology maps. The calculated APL values are consistent with the current knowledge of the regional scale hydrogeological setting.

These evaluations of the regional granular and groundwater reserves were jointly used for proposing an approach allowing the calculation of a groundwater resource sensitivity index (GRSI) for each 10 × 10 m esker parcel of the region. The spatial distribution of calculated GRSI indices was subsequently used along with inventories (1) of sand and gravel extraction sites and (2) of groundwater wells identified within governmental databases in order to develop a spatial index representing the pressure induced by sand and gravel extraction activities on groundwater resources (extraction pressure index, EPI). Both the GRSI and EPI were then displayed on maps showing the esker distribution for the entire study area.

The results allow identifying sectors where sand and gravel extraction activities are concentrated in the vicinity of sensitive aquifers and/or groundwater wells used for human consumption. Such sectors should be prioritized for the acquisition of field data aimed at quantifying the impacts on groundwater. It is proposed that the location of upcoming sand and gravel extraction sites should be chosen with the concern (1) to avoid sectors characterized by high GRSI values and (2) to minimize future EPI values. The proposed indices are not substitutes for field observations and data acquisition, but provide a regional framework for orienting the selection of sites for conducting field investigations prior to sand and gravel extraction. This approach could reduce the costs of field investigation in this vast territory. At the local scale, it is proposed that syn- and post exploitation actions aimed at limiting and/or reducing the DRASTIC indices associated with sand and gravel extraction sites should be prioritized. Punctual springs and diffuse groundwater seepage zones should be targeted as potential groundwater dependent ecosystems (GDE) and prioritized for the acquisition of field data aimed at evaluating the associated capture zone where increased groundwater protection is required. Further field work should be conducted in order to identify GDE associated with lakes. Given an adequate knowledge of the hydrogeological setting, the GIS approaches proposed here are suitable for vast regions, like the Clay Belt of Quebec and Ontario.

Conflict of interest

None.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejrh.2015.05.015.

References

Ala-aho, P., Rossa, P.M., Klove, B., 2013. Interaction of esker groundwater with headwater lakes and streams. J. Hydrol. 500, 144–156.

Aller, L., Bennett, T., Lehr, J.H., Petty, R.J., Hackett, G., 1987. DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings. United States Environmental Protection Agency, pp. 622.

Artimo, A., Makinen, J., Berg, R.C., Abert, C.C., ASalonen, V.-P., 2003. Three-dimensional geologic modeling and visualization of the Virttaankangas aquifer, southwestern Finland. Hydrogeol. J. 11, 378–386.

Banerjee, I., McDonald, B.C., 1975. Nature of esker sedimentation. In Glaciofluvial and Glaciolacustrine sedimentation. Society of Economic Paleontologists and Minerologists, no. 23, special publication, pp. 132–154.

Bolduc, A., Paradis, S.J., Riverin, M.N., Lefebvre, R., Michaud, Y., 2005. A 3D esker geomodel for groundwater research: the case of the Saint-Mathieu-Berry esker, Abitibi, Québec, Canada. In: Three-Dimensional Geologic Mapping for Groundwater Applications (Salt Lake City, UT). Geological Society of America, UT Geological Survey of Canada, Salt Lake City.

Brennand, T.A., 2000. Deglacial meltwater drainage and glaciodynamics: inferences from Laurentide eskers, Canada. Geomorphology 32, 261–293.

Brennand, T.A., Shaw, J., 1996. The Harricana glaciofluvial complex, Abitibi region, Quebec; its genesis and implications for meltwater regime and ice-sheet dynamics. Sediment. Geol. 102, 221–262.

Cloutier, V., Blanchette, D., Dallaire, P.-L., Nadeau, S., Rosa, E., et Roy, M., 2013. Projet d'acquisition de connaissances sur les eaux souterraines de l'Abitibi-Témiscamingue (partie 1). Rapport final déposé au Ministère du Développement durable, de l'Environnement, de la Faune et des Parcs dans le cadre du Programme d'acquisition de connaissances sur les eaux souterraines du Québec. Rapport de recherche P001. Groupe de recherche sur l'eau souterraine, Institut de recherche en mines et en environnement, Université du Québec en Abitibi-Témiscamingue, p. 135, 26 annexes, 25 cartes thématiques (1:100,000).

Cloutier, V., Rosa, E., Nadeau, S., Dallaire, P.-L., Blanchette, D., et Roy, M., 2015. Projet d'acquisition de connaissances sur les eaux souterraines de l'Abitibi-Témiscamingue (partie 2). Rapport final déposé au Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques dans le cadre du Programme d'acquisition de connaissances sur les eaux souterraines du Québec. Rapport de recherche P002. R3. Groupe de recherche sur l'eau souterraine, Institut de recherche en mines et en environnement, Université du Québec en Abitibi-Témiscamingue, p. 313, 15 annexes, 24 cartes thématiques (1:100,000).

Comas, X., Slater, L., Reeve, A., 2005. Stratigraphic controls on pool formation in a domed bog inferred from ground penetrating radar (GPR). J. Hydrol. 315, 40–51.

Cummings, D.I., Gorrell, G., Guilbault, J.-P., Hunter, J.A., Logan, C., Ponomarenko, D., Pugin, A.J.-M., Pullan, S.E., Russell, H.A.J., Sharpe, D.R., 2011. Sequence stratigraphy of a glaciated basin fill, with a focus on esker sedimentation. Geol. Soc. Am. Bull., 1478–1496, http://dx.doi.org/10.1130/B30273.1.

Hatva, T., 1994. Effect of gravel extraction on groundwater. Future groundwater resources at risk 222. pp. 427–434.

Markle, J.M., Schincriol, R.A., 2007. Thermal plume transport from sand and gravel pit—potential thermal impacts on cool water streams. J. Hydrol. 338, 174–195.

Malczewski, J., 2006. GIS-based multicriteria decision analysis: a survey of the literature. Int. J. Geogr. Inf. Sci. 20 (7), 703–726.

MERQ-OGS, 1983. Carte lithostratigraphique de la sous-province de l'Abitibi. Ministère de l'énergie et des ressources du Québec / Ontario Geological Survey. DV 83-16 (Québec) et Map 2484 (Ontario), échelle 1: 500,000.

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). MSc thesis. Département de géographie, Université du Québec à Montréal (UQÀM), Montréal, pp. 145.

Okkonen, J., Kløve, B., 2011. A sequential modelling approach to assess groundwater–surface water resources in a snow dominated region of Finland. J. Hydrol. 411, 91–107.

Okkonen, J., Kløve, B., 2012. Assessment of temporal and spatial variation in chemical composition of groundwater in an unconfined esker aquifer in the cold temperate climate of Northern Finland. Cold Reg. Sci. Technol. 71, 118–128.

Paradis, S.J., 2005. Géologie des formations en surface et histoire glaciaire, Lac Castagnier, Québec. Geological Survey of Canada, Map 1991A, scale 1:100,000.

Paradis, S.J., 2007. Géologie des formations en surface et histoire glaciaire, Lac Blouin, Québec. Geological Survey of Canada, Map 2017A, scale 1:100,000.

Riverin, M.N., 2006. Caractérisation et modélisation de la dynamique d'écoulement dans le système aquifère de l'esker Saint-Mathieu/Berry, Abitibi, Québec. MSc Thesis. Université du Québec, Institut national de la recherche scientifique, pp. 203.

Rossi, P.M., Ala-aho, P., Ronkanen, A.-K., Klove, B., 2012. Groundwater–surface water interaction between an esker aquifer and a drained fen. J. Hydrology 432–433, 52–60.

Smerdon, B.D., Mendoza, C.A., Devito, K.J., 2012. The impact of gravel extraction on groundwater dependent wetlands and lakes in the Boreal Plains, Canada. Environ. Earth Sci. 67 (5), 1249–1259.

Thibaudeau, P., Veillette, J.J., 2005. Géologie des formations en surface et histoire glaciaire, Lac Chicobi, Québec. Geological Survey of Canada, Map 1996A, scale 1:100,000.

Väisänen, U., 1997. Groundwater resources at risk in the glaciofluvial formation of Jokkavaara in Rovaniemi area, Northern Finland. Environ. Geochem. Health 19 (3), 127–134.

Veillette, J.J., 1986a. Former southwesterly ice-flows in Abitibi-Témiscamingue: implications for the configuration of the Late Wisconsinan ice sheet. Can. J. Earth Sci. 23, 1724–1741.

Veillette, J.J., 1986. Surficial geology, New Liskeard, Ontario-Quebec. Geological Survey of Canada, Map 1639A, scale 1:100,000.

Veillette, J.J., 1987. Surficial geology, Lac Simard, Quebec. Geological Survey of Canada, Map 1640A, scale 1:100,000.

Veillette, J.J., 1987. Surficial geology, Grand Lake Victoria North, Quebec. Geological Survey of Canada, Map 1641A, scale 1:100,000.

Veillette, J.J., 1994. Evolution and paleohydrology of glacial Lakes Barlow and Ojibway. Quat. Sci. Rev. 13 (9–10), 945–971.

Veillette, J.J., 2004. Géologie des formations en surface et histoire glaciaire, Cadillac, Québec. Carte 2019A. Commission géologique du Canada.

Veillette, J., Cloutier, V., de Corta, H., Gagnon, F., Roy, M., Douma, M., et Bois, D., 2007. A complex recharge network, the Barraute esker, Abitibi, Québec. In OttawaGeo2007/OttawaGéo2007 (Ottawa), p. 8. Ottawa.