

Assessing rock aquifer vulnerability using downward advective times from a 3D model of surficial geology: A case study from the St. Lawrence Lowlands, Canada

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RESUMEN

Se verifica en St. Lawrence Lowlands en SW Québec un método de evaluación de vulnerabilidad acuífera, el cual relaciona directamente la vulnerabilidad con el tiempo advectivo descendiente (DAT) a partir de un modelo geológico 3D. El objetivo fue evaluar la vulnerabilidad del acuífero regional, el cual es sobreyacido por unidades Cuaternarias discontinuas y no consolidadas. Parámetros hidrogeológicos como la recarga y la porosidad de cada unidad sobreyacente fueron integrados a una malla estratigráfica gOcad. Esta malla fue generada a partir de un modelo geológico hecho con superficies entrelazadas representando las fronteras de las unidades Cuaternarias y la topografía del basamento. Se hicieron cálculos usando un enfoque determinístico y valores de DAT fueron obtenidos para el 74 % del área en estudio. Los resultados son agrupados en 6 clases DAT, los cuales son interpretados en términos de un índice de vulnerabilidad relativa. La distribución espacial de este índice concuerda con el escenario hidrogeológico y los datos hidrogeoquímicos disponibles. Los resultados indican que 40 % del área evaluada cae en clases de moderadamente alta a muy alta vulnerabilidad. Una comparación entre este mapa y no DRASTIC de la misma área revelan algunas discrepancias significantes, particularmente en áreas de profundidad somera al basamento, las cuales son caracterizadas por rápidos DAT a través de la delgada zona vadosa. En estas áreas DRASTIC produce vulnerabilidades bajas mientras esta evaluación da valores altos de vulnerabilidad. Esta valoración provee bases legítimas para una planificación regional y la toma de decisiones.

PALABRAS CLAVE: Vulnerabilidad acuífera, modelo geológico 3D, hidrogeología regional, sedimentos Cuaternarios.

ABSTRACT

An aquifer vulnerability assessment method which relates vulnerability directly to groundwater Downward Advective Time (DAT) from a 3D geologic model is tested over a 1400 km² area in the St. Lawrence Lowlands in SW Québec. The goal was to assess the vulnerability of the regional rock aquifer which is overlain by discontinuous and unconsolidated Quaternary units. Hydrogeologic parameters such as groundwater recharge and porosity of each unit overlying the aquifer were integrated to a gOcad 3D stratigraphic grid. This grid was generated from a 3D geologic model made of interlocked surfaces representing the boundaries of Quaternary units and the underlying bedrock topography. Calculations were carried out using a deterministic approach and DAT estimates were obtained for 74% of the model area. Results are tentatively grouped into 6 DAT classes which are interpreted in terms of a relative vulnerability index. The spatial distribution of this index is in good agreement with the hydrogeological settings and available hydrogeochemical data. Results indicate that 40% of the evaluated area falls within the moderately high to very high vulnerability classes. Comparison between this map and a DRASTIC map of the same area reveals some significant discrepancies, particularly in areas of shallow depth to bedrock which are characterized by fast DAT through a thick unsaturated zone. In these areas DRASTIC produces low vulnerability scores while this assessment yields high vulnerability ranking. Overall, this assessment provides a sound basis for regional planning and decision making.

KEYWORDS: Aquifer vulnerability, 3D geologic modeling, regional hydrogeology, Quaternary sediments.

INTRODUCTION

The notion of groundwater downward time-of-travel (TOT) is implicit in many intrinsic vulnerability assessment methods such as in DRASTIC (Aller *et al.*, 1987) and GOD (Foster 1987) and it is sometimes used as the main indicator of vulnerability to transport of contaminants by natural

groundwater recharge (GSW 1991). With the AVI method (Van Stempvoort *et al.*, 1993), the aquifer vulnerability is considered to be inversely related to the bulk hydraulic resistance of the layered system above the aquifer. The parameter is usually estimated at well locations and interpolated between wells. As acknowledged by Van Stempvoort *et al.* (1993), this hydraulic resistance is not a true downward TOT,

but it provides an approximation of it based on a measurable property rather than on an empirical, and thus debatable, weighing scheme such as with the DRASTIC system. In another approach, vertical travel times are approximated for different soils and depth intervals and used in combination with 2D geologic maps and generalized hydrogeologic settings to map the aquifer vulnerability to accidental liquid spills (Maxe and Johansson, 1998). In any case, accessibility to consistent subsurface stratigraphic information is crucial to get fairly reliable TOT estimates. This is especially true for cases where the aquifer is overlain by several discontinuous layers, including aquitards, but accessibility to such information is often the missing link at regional scales.

In the last decade, however, geoscientific databases as well as different geomodeling tools (e.g., gOcad, EarthVision) and approaches have been developed to allow the construction of detailed 3D geologic models (e.g., Soller *et al.*, 1999; Ross *et al.*, in press, a) in a way that standard GIS or CAD tools simply cannot do (e.g., Mallet 2002). This has opened a new perspective in regional hydrogeology and many geological surveys have started 3D mapping programs to provide the most detailed and consistent stratigraphic information in rapid growth regions where the population mainly relies on groundwater for its water supply (e.g., Berg *et al.*, 2000; Berg *et al.*, 2004; [http://www.isgs.uiuc.edu/...](http://www.isgs.uiuc.edu/)). Few regional 3D models are available in Canada but it is expected to increase in the near future. These 3D geologic models have the potential to provide more consistent data for unit distribution and thickness than the GIS-based multi-layered models and they can also integrate information about soil properties and hydrogeologic parameters at various scales of resolution. Therefore, once it is available, a 3D geologic model can be used to estimate the groundwater downward time-of-travel (TOT) through the layers overlying the targeted aquifer and, hence, to evaluate its vulnerability to contamination. The main benefit of using such an approach is that the vulnerability assessment is based on a detailed and consistent stratigraphic model as well as on a parameter (downward TOT) that expresses a physical process.

The objectives of this paper are: 1) to present an approach to map aquifer vulnerability at regional scale from Downward Advective Times (DAT) estimated using a 3D geologic model that integrates a few key input parameters; 2) to demonstrate the applicability of the approach in areas where the regional aquifer is overlain by several discontinuous units, including aquitards. In this case study, the groundwater DATs are estimated from the surface through discontinuous and unconsolidated Quaternary units to an underlying fractured rock aquifer. Results are tentatively grouped into 6 DAT classes and interpreted in terms of a relative vulnerability index. In contrast with the AVI method (Van Stempvoort *et al.*, 1993), which could also be easily applied on a 3D geologic model, this method aims at estimating the

DAT based on Darcy's law rather than on the hydraulic resistance factor.

A CONCEPTUAL FRAMEWORK FOR ASSESSING AQUIFER VULNERABILITY

Groundwater or aquifer vulnerability to contamination is a concept for which several definitions and assessment methods are available (Civita *et al.*, 1990; USEPA, 1993; NRC, 1993; Vrba and Zaporozec, 1994; Gogu and Dassargues, 2000). Therefore, it is useful to make a clear statement about the adopted conceptual framework for assessing aquifer vulnerability.

For the purpose of this work, aquifer vulnerability to contamination is defined as the relative ease with which dissolved contaminants can reach the upper boundary of an aquifer by downward advective, unretarded and non-reactive transport following the introduction of a contaminant at or near the land surface. It is a conservative definition of aquifer vulnerability since all the processes which could potentially limit the impact of contamination, such as adsorption and dispersion, are not considered. In this sense, vulnerability is an intrinsic characteristic of the natural environment, which is independent of contaminant type and source as well as specific land-use and management practices. It is very close to the definition of "aquifer sensitivity" developed by the USEPA (1993), which also considers sensitivity as "a function of the intrinsic characteristics of the geologic materials in question, any overlying saturated materials, and the overlying unsaturated zone". With this concept, the goal is to provide insights on the potential of a natural setting overlying an aquifer to act as an efficient contaminant downward migration route to the aquifer rather than trying to map the vulnerability at a given location (e.g., well screen) within the aquifer system (e.g., Frind and Molson 2002). Several methods such as DRASTIC, GOD and AVI are based on this concept and use the water table as the reference location. With the method presented here, the reference location is the upper boundary of the evaluated aquifer, which can be below another aquifer in some cases. The vulnerability of the aquifer to contamination is interpreted from estimates of groundwater DAT along a vertical travel distance from the land surface down to this reference location. Therefore, the fate and transport of contaminants once they have reached the aquifer under evaluation are not taken into account in the above conceptual framework. As a consequence, information provided by such a vulnerability assessment should be combined with other methods (e.g., well vulnerability mapping) to determine whether a particular well is vulnerable to contamination on the basis of its location in the flow system and with respect to its capture zone or to evaluate the impact of contamination in the aquifer (e.g., the aquifer volume which may be at risk in the case the aquifer becomes polluted). Aquifer vulnerability maps are thus only one of many tools

required for groundwater protection and management at regional scale.

STUDY AREA

The study area is located in Eastern Canada, more specifically in the St. Lawrence Lowlands where it extends between the Laurentian Highlands and the Ottawa River and other St. Lawrence tributaries (Figure 1). Elevations range from 25 m above sea level (ASL) close to the St. Lawrence River to 90 m a.s.l. at the northern limit and up to 250 m in the Oka Hills. The rural and semi-rural population of the region depends largely on fractured-rock aquifers for water supply. Figure 2 shows the regional hydrostratigraphic framework. The regional aquifer system is largely confined and consists of fractured Cambro-Ordovician sedimentary rocks (Figure 2). The uppermost part of the fractured rock aquifer was found to be more permeable than rock layers at greater depth (Nastev *et al.*, 2001). Also, overlying discontinuous and highly permeable Quaternary sediments of variable thickness are partly connected to the fractured rock unit and, thus, contribute to the regional system (Figure 2; Ross *et al.*, in press, a). Aquifer layers connectivity is limited by the till and the marine clay which act as the regional aquitard and aquiclude, respectively (Figure 2). Therefore, the Quaternary succession largely controls the confining conditions of the regional aquifer as well as its recharge and offers a great variety of hydrogeologic settings (Ross *et al.*, in press, a). Moreover, thin regressive sands commonly overlie marine

clay (Bolduc and Ross, 2001a, 2001b), thus forming an upper unconfined aquifer of variable extent.

METHODS

3D geologic modeling

Many approaches to 3D geologic modeling exist and theoretical background as well as currently-used methods are described in a few texts (e.g., Turner 1992; Mallet, 2002). The model used in this work was constructed using the geomodeling software gOcad 2.0.4 and subsequent versions (Earth Decision Sciences, 2001). The model covers an area of about 1400 km² and is made of interlocked discontinuous triangulated surfaces representing the top of each of the main Quaternary units of the basin as well as bedrock topography. It is a grid independent model which may be internally meshed in different ways. For a full description of the procedure to construct the model, the reader is referred to Ross *et al.* (in press, a).

The aquifer vulnerability method

The method used in this study makes use of a 3D geologic model and allows for a relative regional estimate of aquifer vulnerability to downward transport of dissolved and persistent contaminants based on groundwater DAT. It usually requires a full 3D numerical flow model to estimate groundwater time-of-travel (TOT) but these sophisticated nu-

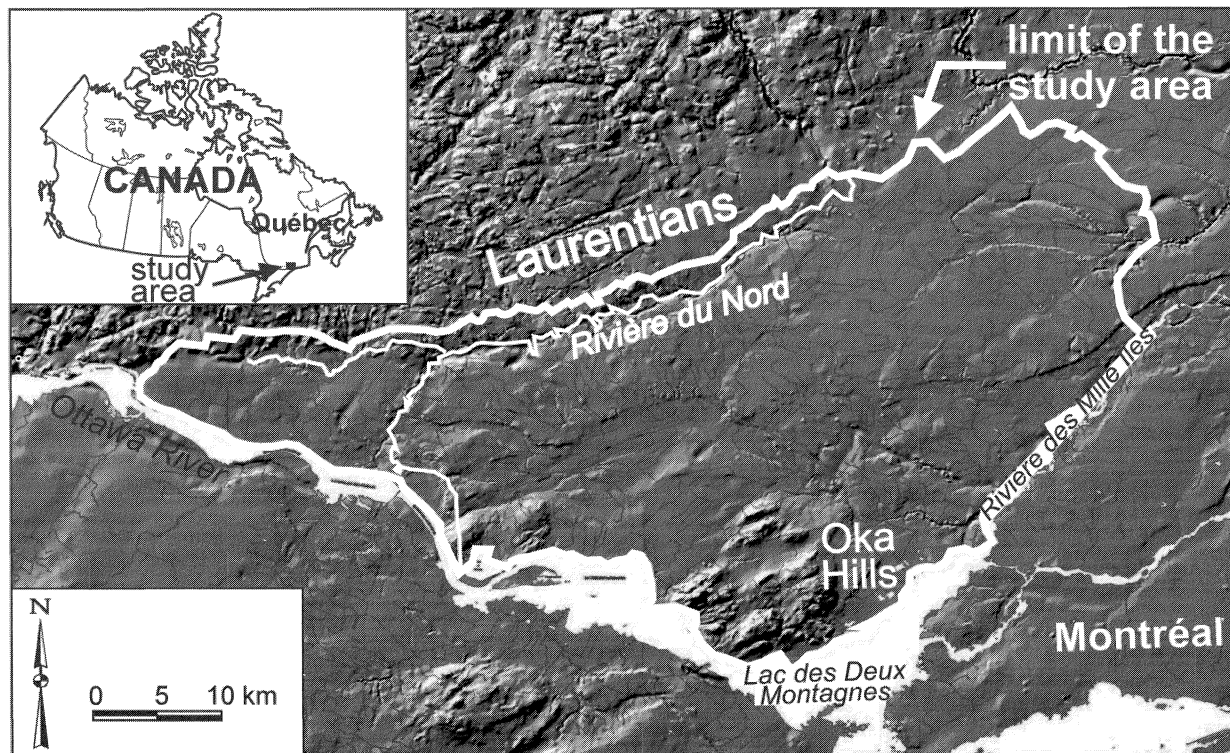


Fig. 1. Location of study area.

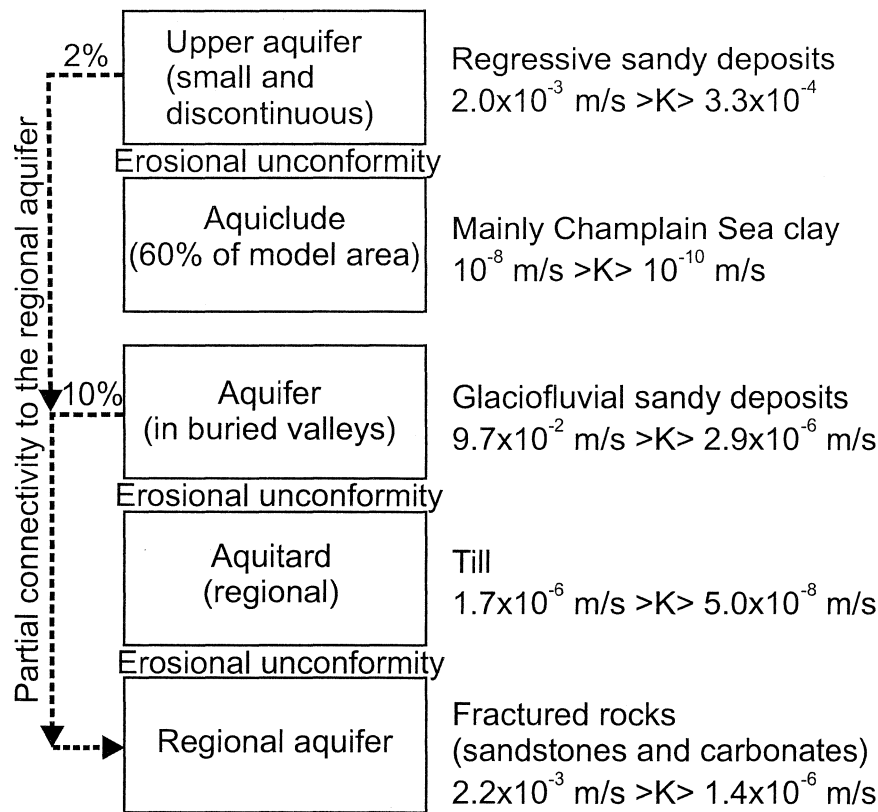


Fig.2. General hydrostratigraphic framework. A total of 12% of the model area shows direct vertical hydraulic connection between discontinuous granular aquifers and the regional rock aquifer.

merical models would be difficult to implement as a groundwater vulnerability evaluation tool on a regional scale and it may not necessarily provide more reliable outputs to specifically estimate vulnerability. Moreover, in many instances the assessment complexity can be greatly reduced by treating the TOT estimation as a one-dimensional advective flow problem with contaminant moving vertically downward. Here, the aim is to estimate groundwater DAT from the surface through a regional geologic model to the underlying regional aquifer. It is apparent that such an approach is a simplification of the real complexity of the system but it is assumed that reasonable estimates are possible as long as the interpretation of the results is made within the limitations of the adopted simplifying assumptions. The main assumptions are summarized below:

- 1) The relative vulnerability of an aquifer can be obtained by estimating DAT using geologic and hydrogeologic information;
- 2) Factors that may change over time such as land use or seasonal effects are not considered;
- 3) Contaminant behavior is the same as water;
- 4) Contaminants are released at the land surface;

- 5) Groundwater flow is vertical along the entire length considered for DAT estimation.

The main advantages of this approach are that few input parameters are needed and the method can be applied on a detailed 3D geologic model without significant transformation or adaptation. Furthermore, the results are not based on an empirical weighing scheme.

The one-dimensional advective, nonreactive, solute time-of-travel or, more simply, the DAT through an unsaturated layered system can be approximated by the following equation:

$$DAT = \frac{1}{q} \sum_{i=1}^n m_i \theta_i, \quad (1)$$

where q (m/s) is the groundwater recharge rate, m_i (m) and θ_i (mL cm⁻³) are the thickness and volumetric water contents, respectively, of layers at every location where the calculation is applied (Haith and Laden 1989; Wösten et al., 1986; Kalinski et al., 1994). The sum of m_i is limited by the travel distance D (m), which is usually from the land surface to the

top of the evaluated aquifer. Also, when assuming saturation through D , θ is replaced in Eq. 1 by the porosity n ($\text{cm}^3 \text{cm}^{-3}$). This applies when the targeted aquifer is largely overlain by saturated low permeability units.

Travel distance and parameter estimation

In the study area, till and marine clay are by far the most abundant Quaternary sediments and they are generally less permeable than the underlying fractured rocks. The rocks act as the regional aquifer, thus, forcing near vertical flow within the saturated overlying less permeable units. Such a process was demonstrated in the classical work of Freeze and Whitherspoon (1967). Therefore, considering vertical flow through the saturated zone above the rock aquifer is a reasonable assumption and DAT were thus estimated for a travel distance starting at the land surface through the Quaternary sequence to the regional fractured rock aquifer. Also, it was found that the specific discharge exceeds the infiltration rate in all units, except for the regional confining layer (marine clay). Therefore, q was considered equal to the infiltration rate of the uppermost unit except where the marine clay is present and is more than 1 m thick. In this case, q was determined according to the following equation that is equivalent to Darcy's law:

$$q = K_{cl} \frac{\partial h}{TH_{cl}}; \text{ where } \partial h = h_{surf} - h_r, \quad (2)$$

where TH_{cl} (m) is the thickness of the confining layer (marine clay), K_{cl} is the hydraulic conductivity of the confining layer, and ∂h is the hydraulic head loss between the surface and the bedrock aquifer. h_{surf} (m) is the topographic eleva-

tion minus 2 meters, which is the approximated hydraulic head in the surface aquifer or aquiclude (this assumption is in good agreement with observed conditions in the field), and h_r (m) is the hydraulic head of the rock aquifer (Paradis 2002). Finally, since the saturated zone is much thicker through the travel distance D than the unsaturated zone, the unsaturated downward flow was approximated by saturated flow. A typical porosity value was assigned to each unit and considered constant throughout the study area (Table 1). This may result in rough downward DAT approximations only, but it fulfills the primary purpose of testing the method. Another approach, which is being tested as part of a new mapping phase, is to randomly choose some of the input parameters within their estimated range values and generate multiple DAT estimates (Ross *et al.*, in press, b).

Geologic model discretization and data processing

The 3D geologic model is primarily defined by a series of interlocked surfaces representing the boundaries of geological objects. With the geomodeling package gOcad, such a framework can be further discretized in different ways to adapt to the specific needs of various applications. In this work, the initial geologic framework was used to generate a curvilinear regular 3D grid that maintains the geometric integrity defined by the interlocked surfaces. Node spacing used in the x and y directions is 200 m and their x and y locations are identical to the grid which provided h_r values used in Eq. 2. After "deactivating" the grid cells located over areas of upward flow and in incomplete 3D model parts, a script command was applied to automatically populate the remaining "active" cells with the input parameters. This process was achieved for each unit (Table 1) while considering the rules

Table 1

Mean infiltration rates (Hamel, 2002) and homogeneous porosity from literature used as input parameters in Eq.(1). Each sediment type corresponds to one unit in the model

Sediment type	Mean infiltration (mm / yr)	Porosity ($\text{cm}^3 \text{cm}^{-3}$)
Regressive sands (upper aquifer)	240	0.3
Marine clay (aquiclude)	150	0.45
Glaciofluvial sand and gravel (aquifer layer 2)	300	0.35
Till (aquitard)	200	0.10
"Pre-till" sediments (aquifer layer 2)	N/A*	0.30
Fractured rocks (aquifer layer 1)	300	0.01

*This unit was only recognized in the subsurface.

previously described. Finally, Eq. 1 was applied to generate DAT estimates on the rock aquifer meshed layer (33 808 cells). The total number of "active" cells in this layer is 24 920. Figure 3 shows the general procedure.

RESULTS

The histogram of DAT results is clearly bimodal (Figure 4). This is, in fact, the expected log- distribution in areas

where the confining unit is discontinuous but generally thick when present. The results were also grouped in different DAT classes and interpreted in terms of a relative vulnerability index (Table 2). The proposed index allows for a practical, albeit subjective, ranking of the classes, which is adapted from the one proposed by the Geologic Sensitivity Workgroup (1991). The choice of such large classes is an attempt to take into account the high uncertainty inherent to this type of assessment. The spatial distribution of DAT classes and the

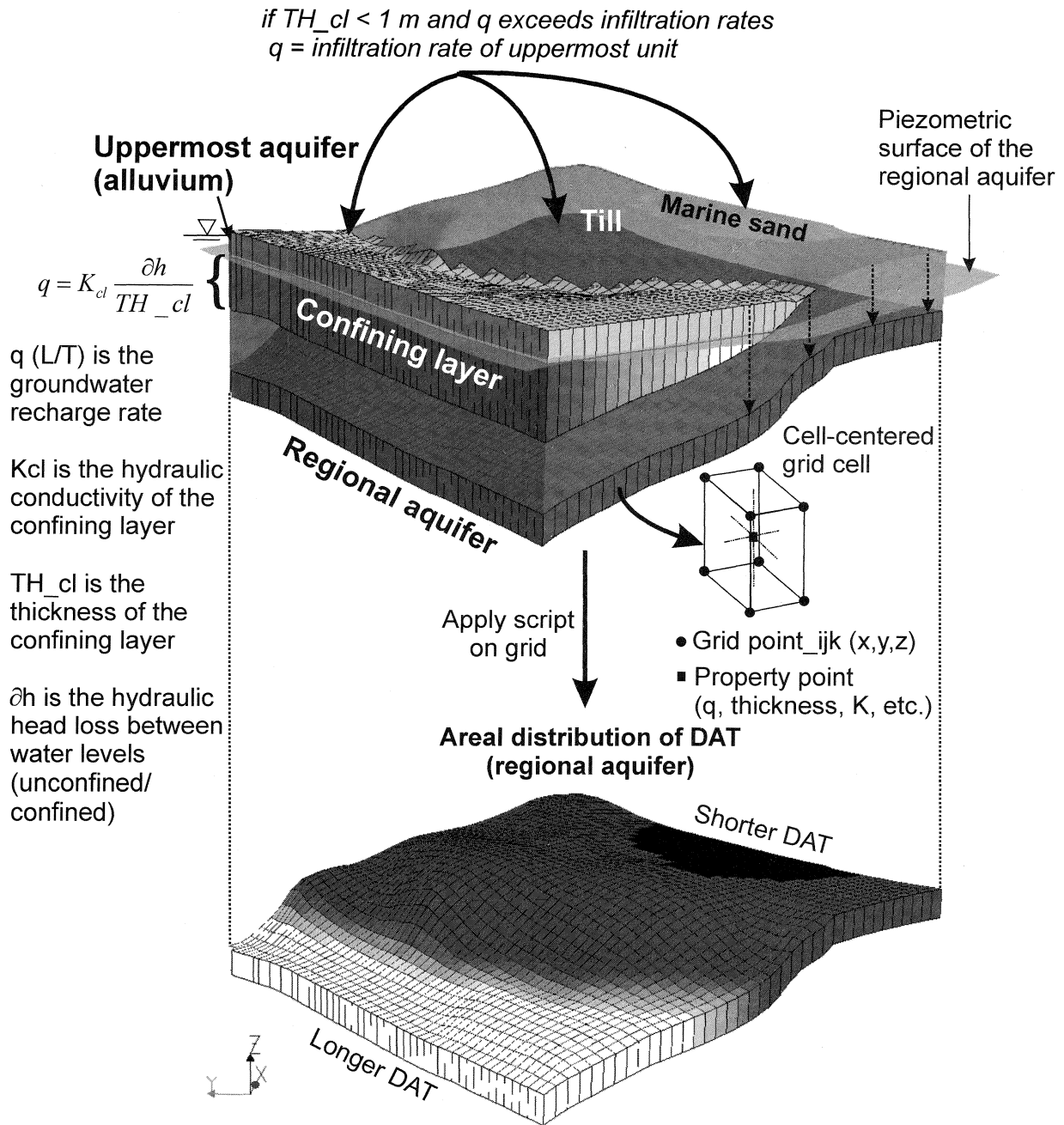


Fig. 3. A 3D grid is generated from the geologic model and a script command is applied to populate the grid with the input parameters and to estimate DAT from the surface to the underlying regional aquifer (modified from Ross et al., 2004).

corresponding relative vulnerability estimates are shown in Figure 5, whereas the percentage of areas covered by each class respectively is shown in Table 2. The remaining 26% (Table 2) represents the area of the model for which no DAT estimates were generated. This includes areas of upward flow and incomplete 3D model parts (most of the Oka Hills and parts of the Laurentian Highlands). According to this assessment, at least 40% of the evaluated area (cf., Table 2) should be considered as being moderately high to highly vulnerable (class 3 to 1). It is also important to note that almost half of the area which falls into class 4 (moderate vulnerability) has a thin clay cover indicating that some portions of the "confining layer" does not offer adequate protection to the under-

lying rock aquifer, at least with the parameter values used in this assessment (cf. Table 1).

DISCUSSION

Comparison with DRASTIC and hydrogeochemical data

Results were compared with a DRASTIC map of the same area (Murat, 2002) as well as with hydrogeochemical data (Simard, 1977; Cloutier *et al.*, 2001; Cloutier and Bourque, 2002) of groundwater samples taken in the upper part of the fractured rock aquifer. However, it is important to note that the 3D geologic model was not available for the

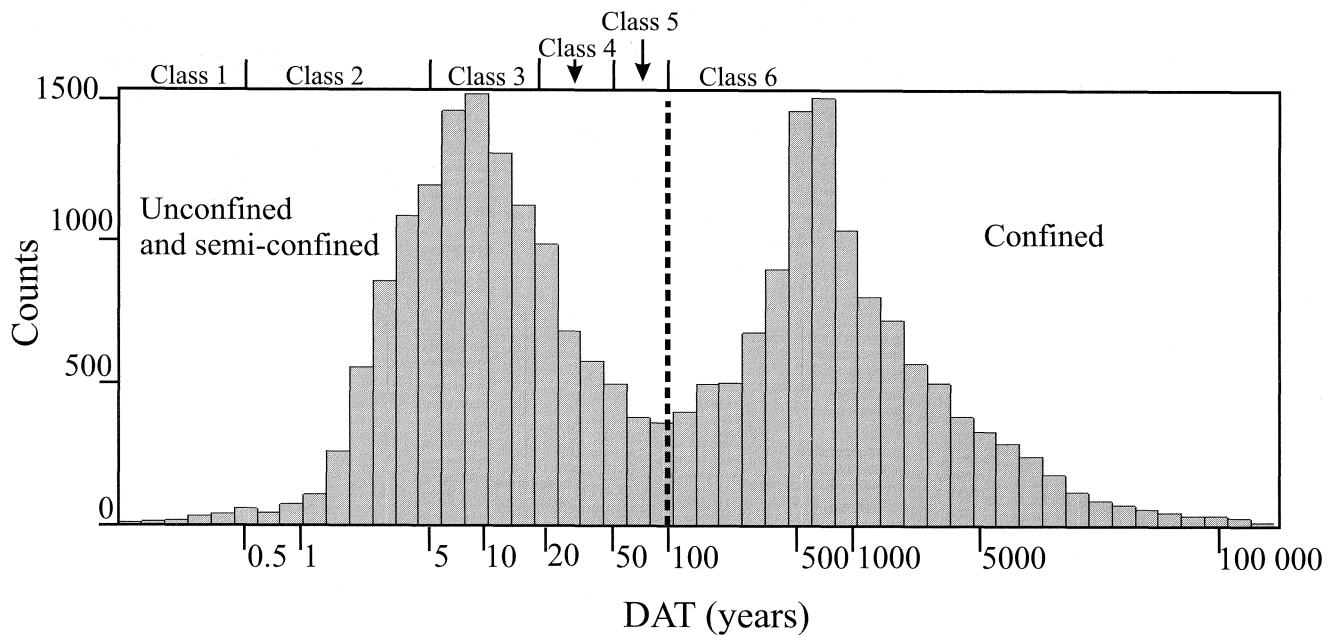


Fig. 4. Log-distribution of DAT results. The first mode is associated with recharge zones and DAT classes from 1 to 5, whereas the second mode is associated with confined areas and DAT class 6 (see also Table 3).

Table 2

Results are grouped into 6 classes of groundwater downward TOT and their percent areas have been calculated. A relative vulnerability index is also proposed that allows for a practical, although subjective, ranking of the classes.

Groundwater downward TOT	Relative vulnerability index	Percent area
Less than 6 months (class 1)	Very High	1%
6 months to 5 years (class 2)	High	23%
5 years to 2 decades (class 3)	Moderate to high	13.5%
2 decades to 50 years (class 4)	Moderate	4.5%
50 years to a century (class 5)	Low	2%
More than a century (class 6)	Very low	34%
Areas of upward flow	Very low	11%
Remaining areas	N/A	11%

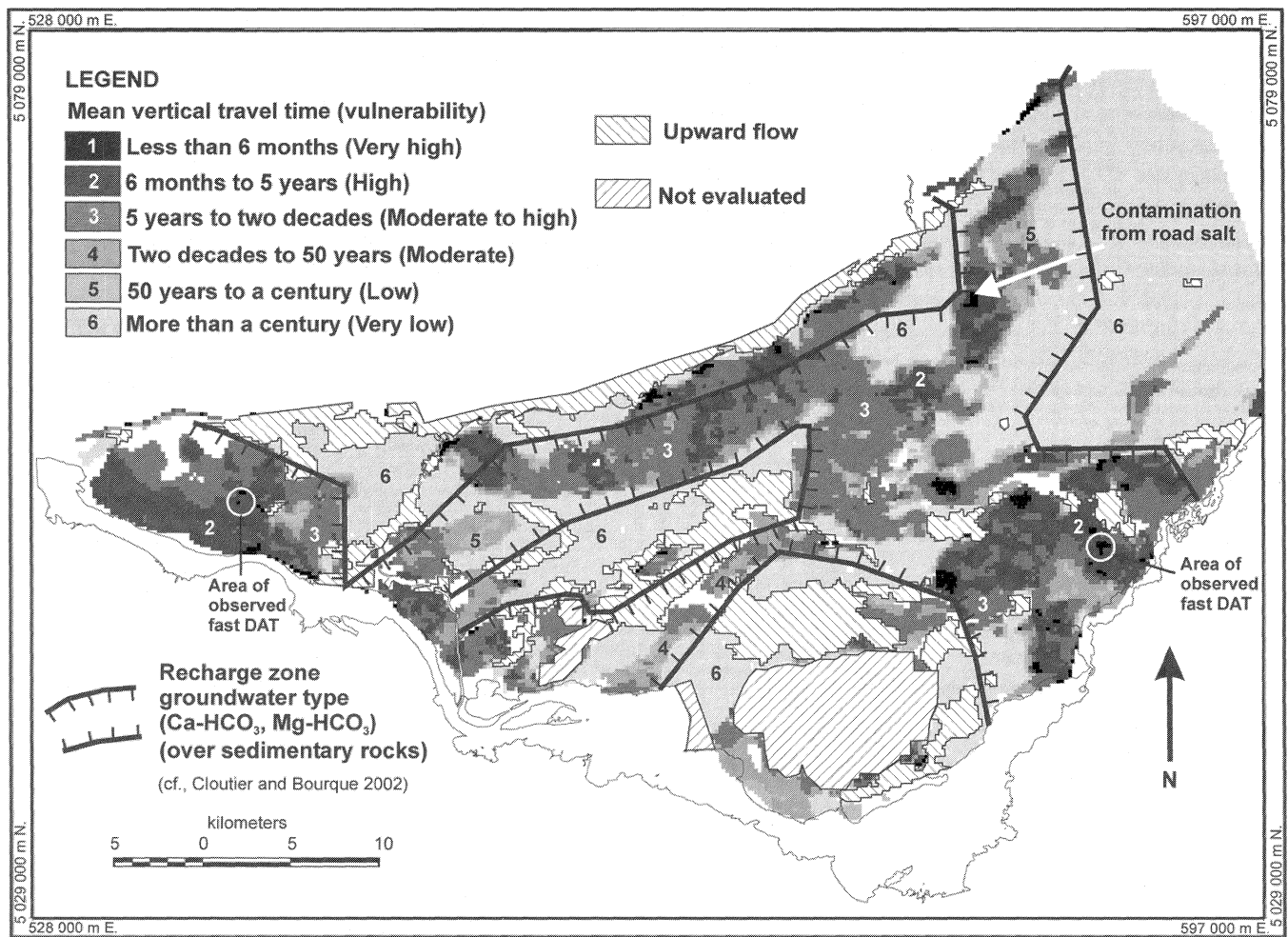


Fig. 5. Distribution of DAT classes over the study area. Results are in good agreement with groundwater type.

DRASTIC assessment such that there are differences in the input parameters used by both methods which could explain in part the discrepancies between both assessments. Nevertheless, there are some fundamental differences between DRASTIC and the method used in this study such that "true" differences are expected in the vulnerability maps.

DRASTIC uses a relative rating system (Aller *et al.*, 1987) which was developed especially for estimating the vulnerability of surficial aquifers. As pointed out by Kalinski *et al.* (1994), the hydrogeologic variables considered in the DRASTIC rating system that influence vadose DAT are assigned high weighting factors in the determination of relative DRASTIC indices such that DRASTIC scores can be expected to increase with decreasing vadose zone DAT. Yet, the DRASTIC scores are very low in some areas of thin overburden and where evidence of rapid recharge to the rock aquifer have been observed (Paradis *et al.*, 2004). In fact, DRASTIC seems to fail to appropriately assess the vulnerability of areas of shallow depth to bedrock characterized by fast DAT

through a thick unsaturated zone due to preferential flow paths (e.g., fractures) in till or fractured rocks. This has major implications which go beyond the vulnerability assessment itself because remediation is particularly difficult once contaminants have entered fractured rock units (Maxe and Johansson, 1998). Therefore, these zones must be considered highly vulnerable. In contrast with the DRASTIC map, the results of this assessment are in much better agreement with these observations of fast DAT. A conservative approach would thus be to consider the safer vulnerability estimate of this study. On the basis of the above observations, lower porosities could even be considered to reduce the DAT estimate, especially for the unsaturated portions of the fractured rock layer included in the travel distance D.

In addition, the current DAT map is in good agreement with hydrogeologic settings and groundwater type zones based on hydrogeochemical data. Cloutier *et al.* (2001) defined groundwater types on the basis of some specific hydrogeochemical signatures and grouped samples accord-

ingly. Samples characterized by Ca-HCO₃ and Mg-HCO₃ are typical of recharge areas over sedimentary rocks (Figure 5) whereas those characterized by Na-HCO₃ and Na-Cl are associated with confined conditions. Some samples have mixed compositions in confined areas due to nearby recharge and a few Na-Cl type samples are found in recharge areas along a highway. This was demonstrated to result from salt application for highway deicing during winter (Cloutier, 2004). It is interesting to note that the vulnerability map indeed suggests high vulnerability for this zone (Figure 5). Results are also generally in agreement with tritium unit (TU) data with the exception of well R-8, which is most likely due to a nearby recharge zone (Table 3). Although, the use of hydro-geochemical data to evaluate a vulnerability assessment method must be done with considerable caution for a number of reasons (NRC, 1993), the overall comparison suggests that the results are realistic and provide a good estimate of rock aquifer vulnerability to contamination at regional scale.

Uncertainty

Uncertainty is inherent to any assessment of aquifer vulnerability to contamination (NRC, 1993). Uncertainty depends on data quality, quantity and distribution as well as

on the adopted simplifying assumptions. Potential sources of uncertainty should at least be documented in a report and anyone using a vulnerability map should understand its limitations. For instance, constant soil properties have been used in this case study and are thus an important source of uncertainty. Therefore, although results are realistic according to the actual knowledge of the system, significant difference between DAT estimate and real DAT may exist in some parts of the study area due to spatial heterogeneity and preferential flow paths. Future development of the method will focus on these aspects to try to better take into account the uncertainty and to verify its impact on the vulnerability assessment (Ross *et al.*, in press, b).

CONCLUSION

Contamination of an aquifer usually affects large volumes of the subsurface and involves high social and economic costs such that one important goal in groundwater management is to first take appropriate measures to prevent contamination of aquifers. Regional aquifer vulnerability assessments constitute a key part of such preventive actions. The method used in this study relates aquifer vulnerability directly to Downward Advective Times (DAT) estimated

Table 3

Comparison of geometric mean downward TOT from a 1 km² area centered on wells with tritium data from groundwater samples taken under the upper limit of the fractured rock aquifer. Note the difference in TU data due to decay between 1977 and 2000

Well name	Tritium units (TU)	Ground water age (yrs)	Mean estimated downward TOT (yrs)
MT-2	^a 234 ± 11	^c Modern	4.9
R-1	^a 104 ± 4	^c Modern	4.1
R-7	^a 10.0 ± 0.5	^c 7990/3260	Upward flow
R-8	^a 97 ± 4	^c Modern	757.8
R-13	^a 15.4 ± 0.6	^c 7430/8170	2551.1
R-14	^a 156 ± 6	^c Modern	0.6
R-16	^a 10.6 ± 0.6	^c 3450	9557.4
R-17	^a 6.1 ± 0.5	^c 3585	444.3
LAV-F1	^b 16.2 ± 1.2	Modern	5.8
VIN-P1	^b 8.2 ± 0.8	Modern	8.5
VIN-P2*	^b 17.1 ± 1.3	Modern	8.5
STE-F1	^b 16.6 ± 1.2	Modern	1.2
AH-99-079	^b 10.4 ± 0.8	Modern	8.1
NF-99-067	^b <0.9 ± 0.5	Pre-modern	4115.6

^a From Simard (1977)

^c ¹⁴C age determination of groundwater samples (Simard, 1977)

^b From Cloutier (pers. comm. 2003)

* In till

from a regional 3D geologic model that integrates a few key input parameters. Such an approach can be applied in areas with different hydrogeologic characteristics. Here, it is used to estimate DAT between ground surface and saturated fractured rocks, which is the regional aquifer system, but other travel distances may also be used. Finally, once the system is set, this method can readily provide new estimates as new data become available without requiring any lithological attribute correspondence nor any weighing scheme.

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