COMPARING VULNERABILITY MAPPING METHODS IN TWO CANADIAN HYDROGEOLOGICAL SETTINGS.

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ABSTRACT
In order to preserve the quality of the resource, appropriate land management at local and regional scale has to be implemented. The evaluation of the aquifer vulnerability is one of the tools supporting decision making related to aquifer protection. Several vulnerability evaluation methods exist and our study aimed at comparing their relative performance. In the first study, DRASTIC, GOD, Minnesota and Evarisk were used at the 1/100 000 scale to test their relative performance in porous media aquifers west of Québec City. Another study compare DRASTIC and GOD, at the same scale, in a fractured rock aquifer system which is overlain by a complex system of quaternary surficial sediments, northwest of Montreal. Near Québec, three of the four methods gave quite consistent results compatible with the hydrogeological contexts based on the quaternary geology. These methods show that the deltaic sand aquifer is highly vulnerable. Evarisk produces a map quite different from the ones yielded by the other three methods. Near Montreal, DRASTIC provides a map matching the recharge areas identified through detailed mapping as the most vulnerable zones, whereas GOD fails to identify these areas. It is clear through this comparative study that vulnerability maps vary significantly with the selected vulnerability evaluation methods and the type of hydrogeological setting investigated. DRASTIC appears to be the method that provides the best results in both the surficial granular and confined/semi-confined fractured rock contexts studied.

RÉSUMÉ
Afin de préserver la qualité de l'eau souterraine, une gestion adéquate du territoire à l'échelle locale et régionale doit être adoptée. L'évaluation de la vulnérabilité des aquifères est un des outils qui aide à supporter les preneurs de décisions en relation avec la protection des aquifères. Plusieurs méthodes d'évaluation de la vulnérabilité existent et notre étude a comme objectif de comparer leur performance relative. Dans une première étude DRASTIC, GOD, Minnesota et Evarisk sont appliqués à l'échelle 1/100 000 afin de tester leur performance relative dans un contexte d'aquifères libres en milieu poreux à l'ouest de la ville de Québec. Une seconde étude, à la même échelle, compare l'application de DRASTIC et GOD dans un système aquifères confinés/semi-confinés dans le roc fracturé recouvert par des sédiments quaternaire de géométrie complexe au nord-ouest de Montréal. Près de Québec, trois des quatre méthodes ont produit des cartes compatibles avec le contexte hydrogéologique qui est dérivé de la géologie du quaternaire. Ces méthodes montrent que l'aquifère situé dans le sable deltaïque est très vulnérable. Evarisk a produit une carte différente des autres issues des trois autres méthodes. Près de Montréal, la carte DRASTIC montre les zones les plus vulnérables correspondant aux zones de recharge identifiées par une cartographie détaillée, alors que la carte GOD ne permet pas d'identifier ces zones. À partir de cette étude comparative, Il est clair que les cartes de vulnérabilité varient en fonction de la méthode d'évaluation de vulnérabilité sélectionnée et du type de contexte hydrogéologique investigué. DRASTIC nous apparaît comme la méthode d'évaluation qui fournit les meilleurs résultats pour les deux contextes étudiés : aquifères libres en milieu poreux et aquifères confinés/semi-confinés de roc fracturé.

1. INTRODUCTION

In Canada, 30% of the population depends on groundwater for its domestic use. The quality of groundwater is commonly threatened by increasing numbers of diffuse and point source pollutants. One approach to prevent groundwater pollution is by delineating the aquifer vulnerable zones and managing polluting activities in such zones. Aquifer vulnerability evaluation estimates the relative possibility that groundwater get contaminated by pollutants released from the surface. Vulnerability maps thus indicate the most vulnerable zones to contamination and therefore can serve for land use management. Following recent groundwater regulations (Gazette Officielle du Québec, 2002) and the initiation of a Canadian groundwater inventory (Rivera et al., 2001), vulnerability maps produced through the application of the DRASTIC method have become important. Our study aimed at verifying the validity of DRASTIC and its relative performance to Evarisk, GOD and Minnesota vulnerability evaluation methods.

2. CONTEXTS OF VULNERABILITY EVALUATION

The first area selected for vulnerability evaluation of granular aquifers is located in south-central Quebec, in the Laurentian foothills. The area covers approximately 900 km2. Its physiography is marked by the St.Lawrence Lowlands (Paleozoic sedimentary rocks) and the Laurentian mountains (Precambrian metamorphic rocks) (fig.1). Quaternary marine clays cover glacio-fluvial and glacial till sediments, but are located underneath sediments of either deltaic, coastal or alluvial origin. This uppermost unit forms large unconfined aquifers. The second area chosen for vulnerability evaluation of a fractured rock aquifer system, is located north-west of Montreal. The aquifer system belongs to the St.Lawrence Lowlands platform and is mainly composed of fractured sandstone, dolostone, limestone, and siltstone. The overlying Quaternary deposits include glacial tills and glacio-fluvial units which are covered by marine clays. The latter unit offers a natural protection to the fractured aquifer. The sedimentary rocks locally outcrop or are covered by thin layers of till.

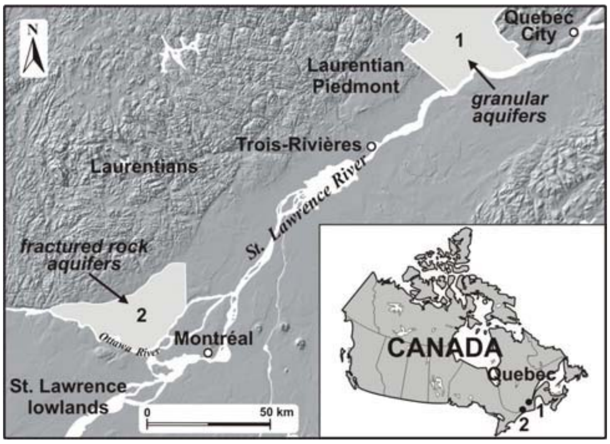

Figure 1. Location of study areas.

3. METHODOLOGY

The concept of aquifer vulnerability includes two types of approaches : 1) the intrinsic vulnerability exclusively considers physical properties, and 2) the specific vulnerability combines physical parameters with contaminant properties (Vrba and Zaporozec, 1994). In general, the choice of approach depends on the purpose of the evaluation. The evaluation of the intrinsic vulnerability at a scale of 1/100 000 is well adapted for regional land use management. Cartographic methods based on map superposition, parametric system methods using a numeric quotation system, and analytical methods referring to basic mathematical equations are the different types of intrinsic evaluation methods from which we retained 4 methods: 1 cartographic method (Minnesota (The geologic sensitivity project workgroup, 1991)), 2 numerical quotation methods (DRASTIC (Aller et al., 1987), GOD (Foster and Hirata,1991)) and 1 analytical method (EVARISK (Banton et al., 1997; AGEOS and INRS-EAU, 1997)).

The vulnerability evaluation by the cartographic method Minnesota was done at 2 levels. Level 1 requires few data (surficial deposits and water level above or equal to 1.83 m) and level 2 allows the improvement of the evaluation where data are available.

DRASTIC is a commonly used empirical method which is based on the evaluation of 7 parameters: depth of water table (D), recharge (R), type of aquifer (A), type of soil (S), topography (T), influence of the vadoze zone (I), and hydraulic conductivity (C). The vulnerability index is evaluated by adding the value of the 7 parameters (Dr, Rr, … Cr) balanced by a weight (Dw, Rw, … Cw), which depends on the importance of the parameter as shown in the following equation:

$$I_{DRASTIC} = D_w D_r + R_w R_r + A_w A_r + S_w S_r + T_w T_r + I_w I_r + C_w C_r$$

Where w and r are the weight and value of each parameter, respectively. DRASTIC requires an important dataset and the redondancy of the parameters allows a certain stability of the final results. However, the use of 7 parameters makes the method somewhat costly.

In the GOD method, the vulnerability of aquifer is based on the inaccessibility of the saturated zone in terms of the capacity of pollutants to reach groundwater and of the attenuation offered by the upper layer of the saturated zone. The methodology of this model implies the identification of the type of aquifer in terms of containment levels (Ci); depth of water table (Cp) and specification of the layers that cover the aquifer (relative porosity, permeability and water content)(Ca). The vulnerability index (IGOD) is obtained by multiplying the values of the previous characteristics:

$$\mathrm{I}_{\mathrm{GOD}} = Ci * Cp * Ca$$

The analytical method EVARISK is designed to evaluate the specific vulnerability, but it can be adapted for an intrinsic evaluation by giving a value of 0 to the pollutant and evaluating the parameters for the first meter of soil, the slope and vegetation. Other parameters integrated in the model are automatically chosen depending on the area studied. The value of the index is a measure of the vertical water flux. Evarisk integrates parameters on which the user does not have any control (Table 1).

Table 1. Parameters associated with the different vulnerability evaluation methods

PARAMETERS	Vegetation / soil occupation	Topography	thickness/soil texture	zone vadose caracteristics	depth to water tabl	hydrogeologics caractéristics	hydraulic conductivity	confined aquifers differenciation	others
DRASTIC (Aller & al., 1987)		X	X	X	X	X	X	X	
GOD (Foster & al, 1987)			X	X	X	X			
EVARISK (O. Banton & M. Larocque & al, 1997)	X	X	X						18
Minnesota method (geologic sensitivity project workgroup, 1991)			X	X	X			X	

Methods used for the two project: [grey box]

For the study of the aquifers in granular material, 4 methods were used. The 4 maps produced were visually compared with each other and with the Quaternary geology map. The maps were also compared between them using the Kappa statistical test (Bernard, 1993). This test shows the level of agreement (coincidence of vulnerability index classes) and the level of association (coincidence of spatial variability of the vulnerability index classes) between methods. To be able to do a statistical comparison based on the same scale, the vulnerability index were grouped in 4 classes for each method.

4. RESULTS

The maps done with either DRASTIC, GOD or Minnesota in granular media indicate that the aquifers located in sand or gravel are more vulnerable to a contamination than those in less permeable units. A high vulnerability index is linked with the type of soil, a permeable vadoze zone, and a slight slope. The deltaic sands and gravels associated with rivers are aquifers which cover the largest area. On the EVARISK map, sandy and gravely hydrogeological units, and confined units are not delineated because EVARISK does not use the information on the type of soil on the first meter from surface. Consequently, the data related to the geological map and to the surficial deposits are not used. EVARISK is a local method, and its application on a continuous area induces simplifications which hide the spatial variability of the vulnerability. This produces a uniform evaluation of the vulnerability which is underlined by the Kappa statistical test. Higher vulnerability zones can be identified on the map produced by the Minnesota method, but the vulnerability is overestimated for the whole area, however this favors safe decisions. GOD gives satisfactory results because the recharge zones, mostly those with high sand thickness, are identified as the most vulnerable. The comparison of results obtained with GOD with those from the other methods show good agreement. Even if GOD and Minnesota yield interesting results, the statistical comparison indicates that the evaluation of the vulnerability differs from the one found with DRASTIC. DRASTIC and GOD agree relatively well on the classification of high vulnerability zones with an identical index value of 43% (fig 2.). As for the zones in the medium and low vulnerability classes, GOD overestimates its quotation compared to DRASTIC with 37% of index values superior to 1 unit for GOD. The result is a spreading of the DRASTIC vs GOD curves. With the GOD method, the differentiation between high and medium vulnerability zones is less obvious than with DRASTIC. As for Minnesota, the spreading of the curve is important with a peak at 52% of the index overestimated by 1 compared to DRASTIC. The proportion of association between DRASTIC and Minnesota is good, but not the proportion of agreement. DRASTIC, GOD and Minnesota methods gave quite consistent results compatible with the quaternary geology map. These methods consistently show that the deltaic sand aquifer is the most vulnerable one. Evarisk gave a map quite different from the other three and was not used for the second part of the study in fractured rock aquifers. For the fractured-rock aquifer, on the DRASTIC map, 60% of the surface represents moderately vulnerable zones (fig.3). These zones are located where there is sand or sub-outcroping bedrock. The recharge zones are recognizable with a more important vulnerability.

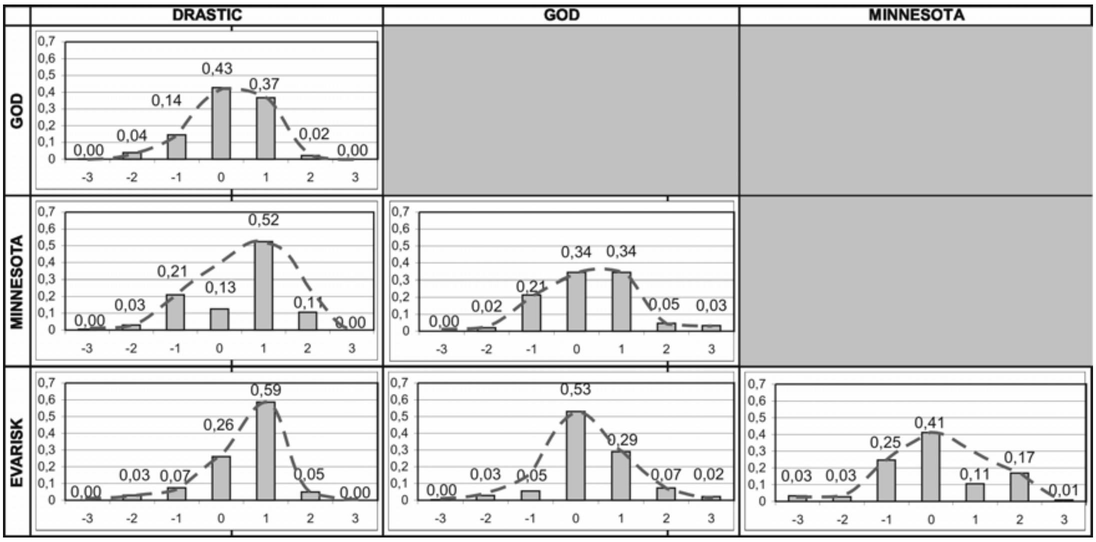

Figure 2. Statistical comparison of maps in granular media (modified from Murat et al., 2000).

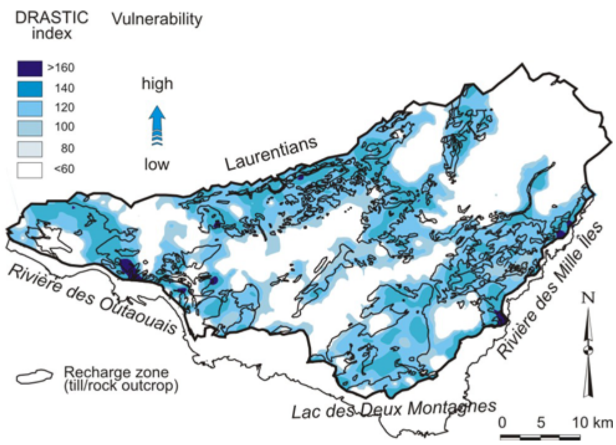

Figure 3. DRASTIC map for fractured rock aquifers (modified from Murat et al., 2003).

The GOD map for the same context is moderately vulnerable and more homogeneous than the DRASTIC map. GOD does not identify the recharge zones as more vulnerable than their surrounding sectors. GOD uses only 3 parameters compared to 7 for DRASTIC. The general appearance of the GOD map could have been improved if the information on fracturation level had been known. In short, GOD does not appear well adapted to evaluate the vulnerability for less documented aquifers, and for areas with complex characteristics. However, DRASTIC yields an evaluation that seems to meet the expectations. Given the results of the statistical analysis, the difference of evaluation between both methods in a more complex context than the granular media was foreseeable.

5. CONCLUSION

The evaluation of regional vulnerability to pollution by a method such as DRASTIC appears to yield good results in the two contexts studied. The systematic use of DRASTIC as a standardized vulnerability evaluation method appears to be a sound approach. However, rules for the proper application for this method have to be followed: (1) the raw data and the data resulting from any treatment (type of aquifer evaluated, quantity of data, data precision, scale) have to be documented; (2) maps drawn at a scale of 1/100 000 cannot be used at a smaller scale; (3) the resolution limit of the maps is related to the extent of the pixels that have been used to generate these maps. The Minesota method seems to overestimate the overall vulnerability of the studied area. The GOD method seems not well adapted for vulnerability evaluation of less documented aquifers, and for aquifers with complex characteristics. Finally, the EVARISK method is a local method and its application on a continuous area induces over-simplifications which tend to smooth out the spatial variability of the vulnerability.

ACKNOWLEDGMENTS

The study was financially supported by the Geological Survey of Canada, Economic Development Canada, Conseil Régional de Développement-Laurentides, Ministère de l'Environnement du Québec, the regional county municipalities of Argenteuil, Deux-Montagnes, Mirabel, Thérèse-de-Blainville and Portneuf. Part of the drilling was supported by the Ministère des Transports du Québec.

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