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AN ASSESSMENT OF AQUIFER VULNERABILITY MAPPING METHODS FOR THE OAK RIDGES MORAINE

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ABSTRACT
Groundwater vulnerability mapping was completed across the Oak Ridges Moraine in southern Ontario, as part of a comprehensive provincial planning exercise. The resulting maps identify areas where contamination of groundwater is more (or less) likely to occur as a result of the introduction of contaminants at the ground surface. Land use planners apply the maps to preserve groundwater quality by diverting potentially harmful land uses from areas of higher groundwater vulnerability to areas of lower groundwater vulnerability.

Three current, well-based methodologies (DRASTIC, Ontario Ministry of the Environment and Energy Aquifer Vulnerability Index, and Grand River Conservation Authority) were compared to assess their applicability on the Oak Ridges Moraine. Indices were calculated on a well by well basis and interpolated across the moraine. Borehole GIS analysis software (Viewlog) was used to analyze the methodologies. The study underlines the role of the water table, hydrostratigraphic modeling, and aquifer definition rules in the development of a groundwater vulnerability map. A comparison of results identifies respective strengths of the methods.

RÉSUMÉ
La cartographie de la vulnérabilité de l'eau souterraine a été completé à travers la Moraine d'Oak Ridges dans le sud de l'Ontario. Ceci faisait partie d'une démarche compréhensive de planification provinciale. Les cartes identifient les régions où la contamination de l’eau souterraine est plus (ou moins) probable dû à l'introduction de contaminants à la surface du sol. Les plannificateurs utilisent les cartes afin de préserver la qualité de l'eau souterraine en déviant les utilisations potentiellement nuisibles des endroits de plus grande vulnérabilité à ceux de moindre vulnérabilité.

Trois méthodes bien établies (DRASTIC, l'index de vulnerabilité d'aquifer du Ministère de l'environnement et de l'énergie, et la Grand River Conservation Authority) ont été comparées pour évaluer leur applicabilité sur la Moraine d'Oak Ridges. Les indices ont été calculés en se servant de chacun des puits et ont aussi été interpolés à travers la moraine. Le logiciel d'analyse GIS (Viewlog) a été utlisé pour évaluer les méthodes. L'étude souligne le rôle de la nappe d'eau, le modèle hydrostratigraphique, et les règles de définition d'aquifer dans le développement d'une carte du vulnerabilité d'eau souterraine. Une comparaison des résultats identifie les puissances respectivent des méthodes.

1. BACKGROUND

The Oak Ridges Moraine (ORM) is the most prominent moraine complex in southern Ontario extending from the Niagara Escarpment in the west to the Rice Lake area near Trenton in the east. The moraine forms the drainage divide between Lake Ontario and Lake Simcoe. Given the coarse grained nature of sediment comprising the moraine, and therefore the dynamic groundwater flow system that is correlated with its physical setting, the ORM is recognized for its important role in maintaining the quality and quantity of water resources for numerous major streams and countless groundwater systems covering an area of about 3,000 square kilometers.

The provincial government of Ontario, in May of 2001, introduced the Oak Ridges Moraine Act along with the Oak Ridges Moraine Conservation Plan. The goal of these documents was to provide for land use controls across the ORM. As part of this land use planning strategy the Ontario Ministry of the Environment and Energy (MOEE) was interested in developing a map of aquifer vulnerability across the ORM. The resulting groundwater vulnerability maps are intended to identify areas where contamination of groundwater is more (or less) likely to occur as a result of the introduction of contaminants at the ground surface. The mapping was to provide guidance to Municipalities and Conservation Authorities, who are ultimately responsible for implementing the act, so that they could ensure inappropriate land uses were kept away from more sensitive hydrogeological settings.

2. AQUIFER VULNERABILITY

Much has been written on aquifer vulnerability mapping over the past 20 to 30 years. Two documents in particular merit mention here as providing significant contributions to the area of aquifer vulnerability mapping. In 1993 the National Research Council in the U.S. undertook a review of aquifer vulnerability mapping across the U.S (National Research Council, 1993). Shortly thereafter, the International Association of Hydrogeologists completed a guidebook on mapping aquifer vulnerability (Vrba and Zoporozec, 1994). Both documents provide comprehensive analyses of aquifer vulnerability mapping techniques along with selected case studies.

Fundamentally, the concept of groundwater vulnerability relates to the fact that certain physiographic settings are inherently more vulnerable or sensitive to having contaminants migrate from surface to impact ground water quality. If these areas of higher vulnerability can be identified, then land use developments that pose a higher risk to the groundwater system can be redirected to less sensitive areas.

Factors that have been deemed to be of primary importance to a groundwater vulnerability assessment include the groundwater recharge rate, soil properties, characteristics of the saturated and unsaturated zone and topography.

Problems arise in vulnerability mapping for a variety of reasons:

- groundwater vulnerability is a relative, non-measurable, dimensionless property that cannot be verified even by normal scientific methods;
- vulnerability mapping methodologies cannot take into account all of the site specific heterogeneities that exist in the subsurface geological framework, therefore it is important to keep in the forefront that all groundwater is vulnerable, and that aquifer vulnerability maps are not intended to imply complacency in areas that have a lower vulnerability rating,
- given the variation in the data density as well as the data types that are used to determine aquifer vulnerability, it must be recognized that there is certainly a degree of uncertainty in any aquifer vulnerability assessment,
- depending on the aquifer of interest, different studies might focus on different parts of the subsurface, thereby producing different vulnerability maps – as an example the vulnerability of a particular municipal aquifer at depth might be very different than the vulnerability of a shallower aquifer that is providing drinking water to a shallow dug well or cold water to a local surface water system;
- vulnerability maps are not calibrated to individual contaminants, and therefore do not take into account that specific contaminants react differently, and therefore move at different speeds and different distances in the subsurface;
- although shallow unconfined aquifers are often considered more vulnerable to contamination, it must be kept in mind that there is also ample recharge in these areas so that the resulting concentration of a contaminant might end up being quite low in the aquifer itself. Therefore vulnerability mapping should have as a goal the reduction of a mass loading to the aquifer and not just the reduction of the final contaminant concentration within the aquifer itself. A long term mass loading to a shallow aquifer, might not significantly alter the concentration of a contaminant within an aquifer, however, depending on the contaminant of concern, it could result in a buildup of contaminants in stream bottom;
- because of the relative nature of vulnerability mapping, the extent of the investigation can have implications on the resulting mapping. Smaller more uniform settings could have vulnerable areas identified that would be mapped as lower vulnerability if a larger more heterogeneous area was taken as the study area.

As a result of these concerns, it is important to ensure that the purposes of the mapping are laid out clearly at the onset of the project. The mapping for the ORM project was initiated with a view to providing planners and other decision makers with an overall assessment of the moraine, identifying areas that might be less suitable for urban development, or areas where prioritized use of resources, say for development review, would be required.

It was also determined that the aquifer vulnerability mapping for the ORM would focus on the uppermost aquifer regardless of whether it was being used for a drinking water source or not. This strategy reflects the importance of surface water streams across the moraine, many of which are linked to the groundwater system and receive considerable water from groundwater discharge. In light of this focus on shallow aquifers, the maps can be viewed as partial ecosystem vulnerability maps as much as they are groundwater vulnerability maps.

3. DATA SOURCES

The MOEE water well database was the primary data source for geological and water table conditions. Maps included Digital Elevation Map (DEM, 30 m cell size and 10 m contour intervals, Kenny et al, 1999), Ontario Base Maps (MNR) and the Geological Survey of Canada Quaternary Geology map (Sharpe et al, 1997).

4. APPROACH

Three vulnerability mapping methods were selected that make effective use of a well record data source. All three methodologies are consistent in that all are based, at a minimum, on calculating vulnerability indices at each well based on the geological sequence and water table configuration. These methods are advantageous over more simple map based methods in that they make the best use of the water well record source data available. For example, the three methods avoid the exclusive use of existing surficial geological maps to determine aquifer vulnerability, and therefore they reflect changes in deeper subsurface geological conditions.

Because the methods do rely on water well records, they suffer from poor correlation of strata between adjacent wells (the cuttings returned to surface by a reverse circulation water well rig are often insufficient to provide the detailed geological sequence, particularly in complex geological settings like the ORM). This can be reflected in the final maps by significant fluctuations in vulnerability indices over short distances. Efforts to smooth these fluctuations through enhancements to the well logs are a key part of the process, and are discussed further in this document.

In addition, the level of effort required by the various vulnerability mapping methods varies considerably, from simple methods based on straightforward database queries, to complex methods requiring custom code development, GIS based analysis and a multitude of data sources. Striking a balance between the selected method, project scope and available data is therefore important.

The three methods were applied to a section of the ORM (Figure 1) to assess their respective strengths.

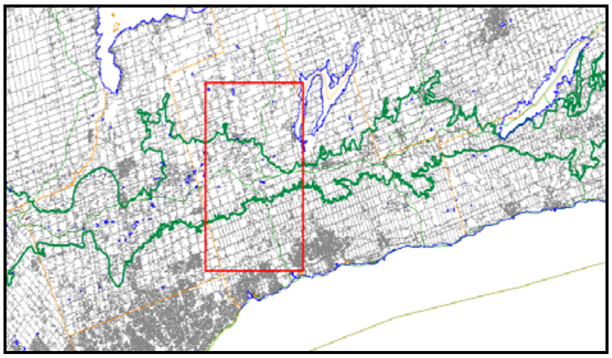

Figure 1: Study Area

4.1. VULNERABILITY METHODS CONSIDERED

4.1.1 Grand River Conservation Authority Method

The GRCA method is based on the depth to the first aquifer plus the depth to the water table, offering both simplicity and transparency (Holysh et al, 2001) developed as part of the groundwater mapping project carried out across the Grand River watershed. The method was applied at a map scale of 1:50,000. The method was originally applied by looking at an interpolated water table surface and an interpolated surface of the depth to the uppermost aquifer (bedrock or any sand/gravel layer greater than 3 m thick). Where the sum of these two depths measurements is less than 10, indicating that in general both the water table and the uppermost aquifer are within 5 m of ground surface, then the area was designated as being more vulnerable.

For this study, the method was modified by initially applying several updates to the well database (see Data Corrections) and treating confined and unconfined aquifers differently. Calculations were performed on a well by well basis, summing the depth to the aquifer, plus the depth to water table (if unconfined) or the depth to the aquifer (if confined).

4.1.2 MOEE Aquifer Vulnerability Index (AVI) Method

The MOEE AVI method is based on the method of Van Stempvoort et al (1993). The method examines the geology from ground surface to the aquifer of interest. The method requires that the thickness of each unit above the aquifer be multiplied by an estimate of the hydraulic conductivity. These values are then summed up to develop what Van Stempvoort et al (1993) refer to as hydraulic resistance measurements, which provide an indication of the resistance of overlying material to vertical groundwater flow. The values are interpolated to create a vulnerability map. The MOEE has slightly revised the method by substituting 'K Numbers' (loosely related to the exponent of the permeability, in cm/sec) for the actual hydraulic conductivity.

For this study, calculations were preformed on a well by well basis, summing the product of the thickness of each unit above the water table (if unconfined), or above the aquifer (if confined) and the corresponding K factor for the unit.

4.1.3 DRASTIC

DRASTIC (Aller et al, 1985) was developed as a cooperative agreement between the National Water Well Association and the United States Environmental Protection Agency (US EPA). The method is based on the Point Count System with values assigned to depth to water table (D), recharge (R), aquifer media (A), soil media (S), topography (T), impact of vadose zone (I) and conductivity of aquifer (C), each with a weighting factor between 1 and 5.

DRASTIC is the most comprehensive of the three methods, and the only method to account for recharge, however, the method is computationally complex, requires considerably more data then the other methods and relies on the subjective process of assigning arbitrary values from the look up tables provided.

For this study, the method is applied on a well by well basis, using a 'look up' table to provide the value for each of the above variables based on conditions at the well.

4.2. DATA ENHANCEMENTS

The following enhancements were applied to the well database in an effort to reduce variability in the geological logs.

1. Update the ground elevation of each well to an elevation obtained from a 30 m grid Digital Elevation Model, and cascade the revised elevations through the balance of the data (e.g. water table elevation, geological contact elevations).
2. Disregard wells with poor confidence codes for the well position.
3. Apply the Geological Survey of Canada (GSC) geo-material conversion to the MOEE geology codes (Russell et al, 1998). This process was designed to improve the quality of the geological descriptions in the MOEE data base.
4. Substitute the uppermost geological unit in the MOEE well logs with the surfical unit on the GSC quaternary geology map.

4.3. WATER TABLE SURFACE

Depth to water table is an important variable in the determination of groundwater vulnerability, especially when using well log based methods. When combined with the geologic log for a well, the target aquifer for the vulnerability mapping can be readily identified.

A water table surface was interpolated from the static water levels of shallow wells (<20 m deep) listed in the MOEE well log database (20 m was considered to represent water table conditions and not the potentiometric head conditions in a deeper and likely confined system). The interpolated surface was compared to the DEM of ground surface, and where water table exceeded ground surface, the water table was corrected by making it equal to ground surface. A derived water table elevation for each well was then assigned to each well from the corrected water table surface.

4.4. SELECTION OF TARGET AQUIFER

As mentioned above, deeper confined systems are thought to be less vulnerable then surficial sand/gravel systems. This is attributed to the fact that under unconfined conditions, a contaminant particle must only travel to the water table to cause impact to the target aquifer, whereas under confined conditions, the same particle must reach the upper boundary of the aquifer. The current study focussed on the uppermost aquifer, given the strong linkage between the ground and surface water systems on the ORM.

A sequential series of rules was prepared to identify the target aquifer in each well, and it's confined/unconfined condition. Target aquifers were identified by reviewing the well log at a given well and grouping consecutive aquifer units (based on a database reference table of all possible geological descriptions), then applying the rules to the simplified aquifer/aquitard geological column.

This was carried out by a computer code generated to run against the well database. The code takes each individual well, starts at ground surface and then steps through the sequence of geological layers. Consecutive aquifer units were merged and then assessed using the following rules.

Starting at ground surface, for the each geologic layer in well the following questions are asked:

- Is the unit an aquifer greater then 2 m thick?, and
- Is the unit an aquifer containing the water table or is water table is less then 3 m below unit (allowing for seasonal fluctuations)?

If the preceding are true, then this unit is designated as the target aquifer and flagged as unconfined. If not, the code proceeds down through the sequence of geological layers units in the well, until a unit that meets the above criteria is selected. If a unit is identified, then it is designated as the target aquifer and flagged as unconfined. If no units meet the above criteria then the code proceeds down through the sequence of aquifer units in the well and tests for the following

- Is the unit an aquifer greater then 2 m thick? and
- Is the water table above the top of the aquifer?

If the preceding are true, then this unit is designated as the target aquifer and flagged as confined.

If no target aquifers were identified in running through the above process, then the thickness criteria on the aquifer was removed so that the uppermost aquifer, regardless of thickness was targeted. After having gone through this second iteration and still no aquifer was identified, then the base of the well was designated to be the top of the aquifer (confined) on the premise that the driller terminated the well in the upper part of an aquifer.

Once the target aquifer was identified, the vulnerability score for the well was calculated using each of the three methods investigated.

5. RESULTS

Figure 2 compares the vulnerability maps generated using DRASTIC, MOEE AVI and GRCA. For all maps, red and pink represent areas considered more vulnerable, and blue and green are considered less vulnerable. Examination of Figure 2 reveals that similar areas are identified by all three methods as being vulnerable, although the boundaries of the areas vary. Reflections of the depth to water table map occur in all maps, underlining the role of this parameter in all three methods.

Figure 3 profiles the vulnerability components of the three methods along a north-south cross section running up the middle of the study area.

The profiles, which also display the water table, piezometric head and confining layer presence and thickness, effectively display how the methods respond to varying hydrogeological conditions. Key points include:

- The downward gradients that dominate the core of the ORM are not reflected in the vulnerability profiles.
- Vulnerability indices on the south flank of the ORM (right side of profile), are more variable then elsewhere. This is likely attributed to a more variable water table coupled with the presence of surficial till in this area that serves to confine many of the wells.
- The DRASTIC profile suggests that aquifer permeability, surface soil type and surface slope are negligible in comparison to the recharge, depth to water table, aquifer media and vadose zone elements. This is evidenced by the fact that the values for these first three components are all quite consistently low while the other factors are much more variable with higher scores.

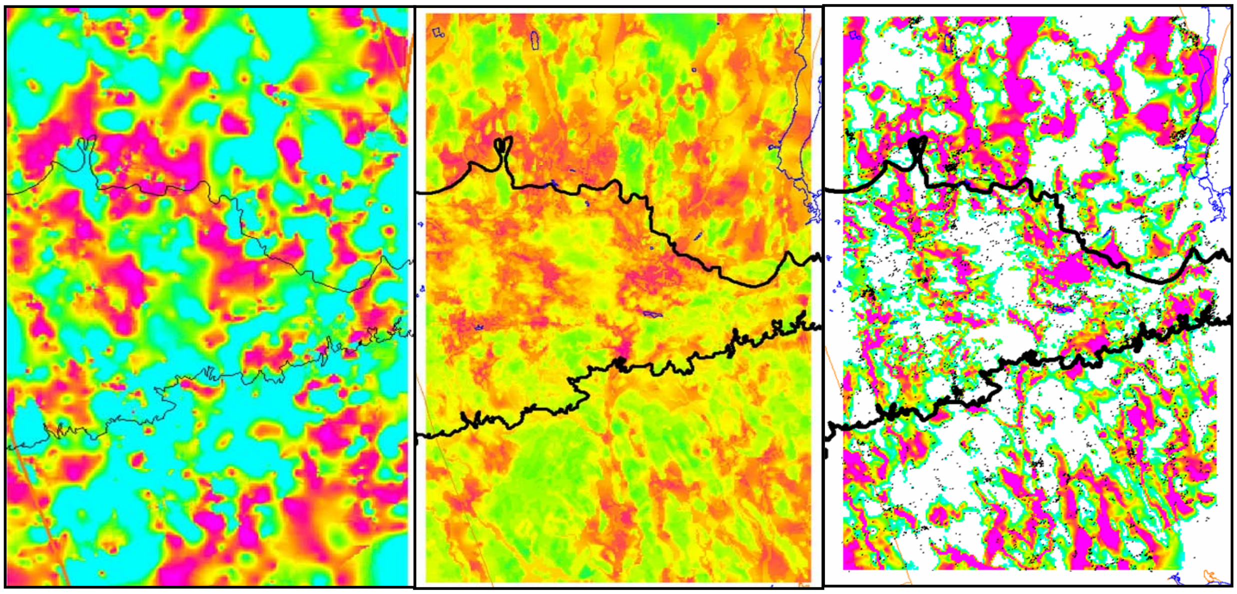

Figure 2: Vulnerability Maps from Study Area, MOEE AVI (left), DRASTIC (centre), GRCA (right, colour clipped to highlight vulnerable areas))

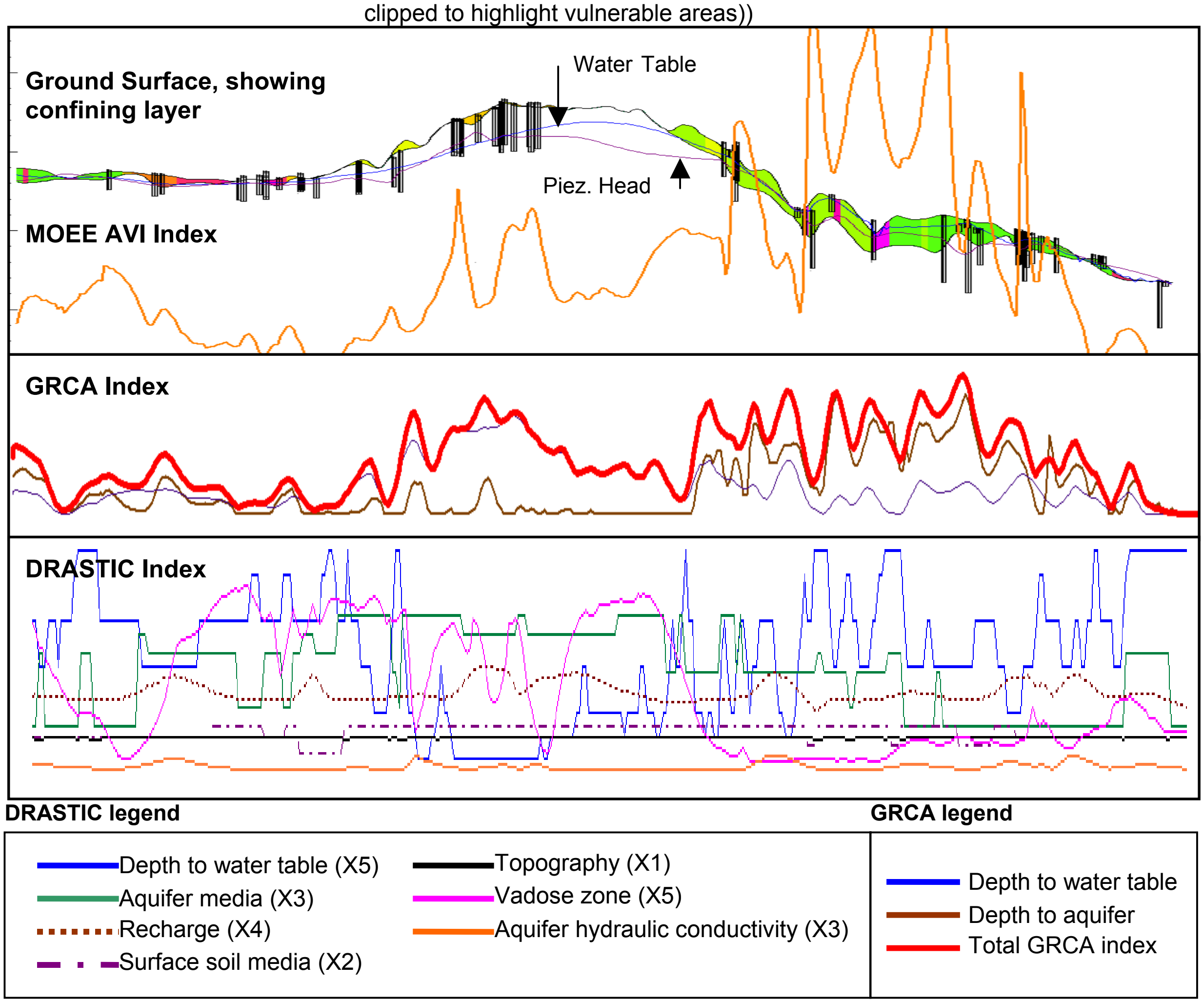

Figure 3: North – south section showing vulnerability components (North on left)

5.1. VERTICAL GRADIENTS

In light of the hummocky terrain and coarse-grained composition, the ORM has important groundwater recharge functions. Intuitively, recharge areas are thought to be more vulnerable than discharge areas. It was therefore anticipated that by adding a recharge component to the vulnerability scoring, an increase in relative vulnerability of the moraine core would be observed. It was hoped that this would assist in highlighting some those core areas of the moraine where, despite the coarse-grained nature of the soils, the depth to water can exceed 20 m resulting in lower vulnerability scores for the GRCA method in particular.

To this end, a recharge function was added to the GRCA method. Recharge was calculated as the difference, in metres, between the water table and the potentiometric surface (interpolated from the static level in wells greater then 40 m deep). The recharge function is positive for discharge areas and negative for recharge areas. The red (square) data points in Figure 4 illustrate the effect of the vertical gradient function on the GRCA method.

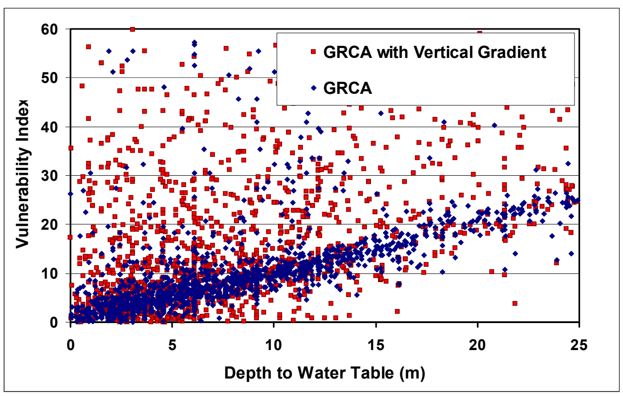

Figure 4: GRCA Index Comparison

Figure 4 illustrates the variability in the vulnerability indices calculated by the two variants of the GRCA methodology. In Figure 4, the depth to water table has been used as a horizontal axis as it is a primary component of both mapping methods, and effectively illustrates patterns in the resulting vulnerability scores.

The blue diamonds show the GRCA method without the vertical gradient, whereas the red squares show the GRCA methodology when the vertical gradient is incorporated into the process. The increased scatter in the data is attributed inaccuracies in the calculation of the gradient based on the inherent variability in the static levels of the well logs. No methodology was established for effectively reducing this variability and therefore, for this current study, vertical gradients were not used in the final vulnerability mapping.

5.2. SELECTED MAPPING METHOD

A combination of the GRCA and MOEE AVI method was recommended for the final vulnerability mapping of the ORM, however in the end, due to consistency with other Provincial mapping, the AVI method was ultimately chosen by the MOE. Two factors underpinned the initial recommendation. First, from a production perspective, DRASTIC ranked poorly in light of the large data requirements and the sequence of steps required to generate the final vulnerability map. It is estimated that the DRASTIC method required between five and eight times the level of effort as the MOEE AVI method. Under the circumstances, this became an important consideration as the method selected and applied to the ORM was expected to serve as a bench mark for more widespread mapping across Ontario. Furthermore, the parameter assignment process of DRASTIC was subjective, and threatened the repeatability of the mapping process.

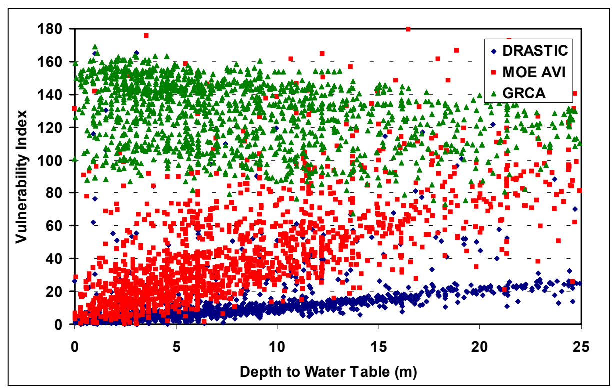

Figure 5: Index Comparison - all methods

The DRASTIC profile in Figure 3 suggests that aquifer permeability, surface soil type and surface slope components are negligible in comparison to the recharge, depth to water table, aquifer media and vadose zone components. Recharge was the main advantage in the DRASTIC methodology, however given the complex geology and hummocky nature of the ORM it was recognized the recharge component of the vulnerability rating could likely not be accurately assessed for the DRASTIC methodolgy. The DRASTIC method was discounted from being pursued further.

A combination of MOEE AVI and GRCA was recommended so as to benefit from the strong water table component of the GRCA method, and the travel time component in the MOEE AVI method. In Figure 5, the dependence of the depth to water table on the vulnerability index is shown for each of the three methods. A strong correlation was observed for the GRCA methodology. Because the MOE AVI methodology was also adjusted to take into account the depth to the water table, there is also a reasonably strong association between the depth to the water table and the resulting MOE AVI scores. The correlation is not so strong for the DRASTIC methodology.

5.3 THRESHOLDS

Groundwater sensitivity to contamination is a relative index, often largely based on empirical relationships between variables with non-consistent units. As a result, the final vulnerability map uses a relative scale to indicate areas of higher or lower sensitivity. To facilitate the land use planning process, maps showing two or three categories of vulnerability (e.g., low, medium and high, or simply low and high) are preferred. Established procedures for selecting the thresholds between these categories do not exist, resulting in a committee or community based approach that reflects local interests at the time of mapping.

For the ORM work, the project adopted the thresholds used by the Grand River Conservation Authority Study, where wells with an index value of 10 or less (sum of depth to aquifer and depth to water table) were considered vulnerable. Stempvoort (1993) offers an elegant solution based on travel times from surface to the target aquifer, suggesting five categories ranging from a travel time of less then 10 years (extremely high vulnerability) to greater then 10,000 years (extremely low).

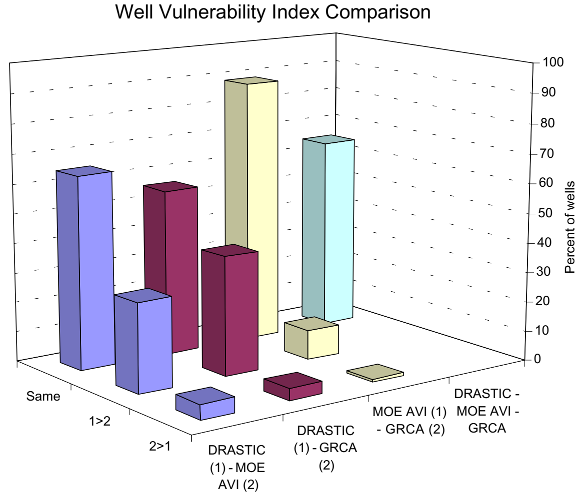

Figure 6: Comparison of methods

Referring to some of the concerns with vulnerability mapping that were brought up earlier, the basic problem is that vulnerability mapping is not refined sufficiently to permit grouping of vulnerability indices into more than at most, three categories. To illustrate this concern over threshold selection, generic thresholds were calculated and applied to the data on a well by well basis. The thresholds were arbitrarily assigned as the mean of the normalized vulnerability index for each method. Wells with a normalized index below the mean were deemed vulnerable, wells with indexes above the mean were deemed not vulnerable.

Figure 6 illustrates the vulnerability classification of the wells (as a percentage of all wells in the study area) by comparing each method against the other two methods, and counting the wells where the vulnerability classification is the same, where method 2 is more vulnerable then method 1, and where method 2 is less vulnerable then method 1.

As shown by the light blue bar, approximately 65 percent of the wells displayed the same vulnerability classification regardless of which of the three vulnerability mapping methods were used. This is consistent with Figure 2 that shows the similarity in the mapped vulnerability data from the three methods. Note that a 90 percent commonality occurs between MOEE AVI and GRCA, as shown by the yellow bar. The 1>2 column counts wells where method 1 is not vulnerable and method 2 is vulnerable, the 2>1 column is the reciprocal.

To assess spatial patterns in these comparisons, Figure 7a displays the bars from Figure 6 in map view. Orange circles represent wells where GRCA method classifies the well as vulnerable, yet MOEE AVI does not (the 1>2 column in Figure 6), and blue triangles the reciprocal. For comparison, Figure 7b displays the blue bars from Figure 6. Orange circles represent wells where the MOEE AVI method classifies the well as vulnerable, yet DRASTIC does not, and blue triangles the reciprocal. On both Figure 7a and 7b, the grey crosses represent wells where the vulnerability indexes are consistent.

Several patterns are noteworthy. First, north of the ORM (outlined by the black line), the proportion of wells with conflicting indexes is reduced. This is attributed to fewer wells in general, shallower water table, and simpler geology. Second, Figure 7a suggests that MOEE AVI under-estimates vulnerabilities compared to GRCA in areas of more complex geology and deeper water tables.

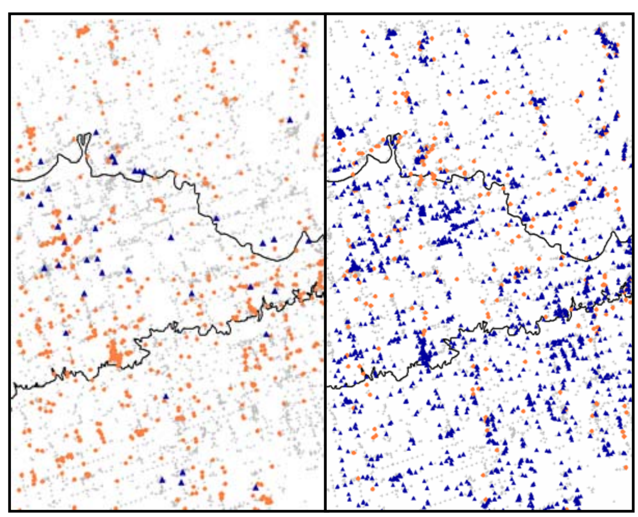

Figure 7: Spatial comparison of conflicting vulnerability indexes. 7a (left) compares GRCA to MOEE AVI, 7b compares DRASTIC to MOEE AVI. See text for details.

6. CONCLUSIONS

Three methodologies for characterizing the vulnerability to groundwater contamination were assessed for an area on the Oak Ridges moraine. Of the three methodologies both the MOE-AVI and the GRCA methodology were found to be more conservative than the DRASTIC methodology, that is they identified more area of the ORM as being more vulnerable. Of these two methodologies, the GRCA methodology was found to be the most conservative. Nearly 90% of the wells were classified as being similarly vulnerable or not vulnerable by the GRCA and the MOE-AVI methodologies.

In producing the maps, it was found that there were many opportunities for the practitioners to incorporate information that would alter the final vulnerability map produced. As examples, the thickness of the target aquifer could be adjusted which would change the vulnerability rating up or down. Similarly the criteria for interpolating a water table surface could also change the final vulnerability scores. Finally once the vulnerability scores were identified, there remains the question as to what threshold value constitutes vulnerable from not vulnerable.

Given these opportunities to adjust the resulting vulnerability mapping, it is recommended that the overall uncertainty in the mapping be conveyed to the final decision makers who will use the map; most likely planning staff from municipalities and conservation authorities. It is recommended that the maps be used more for guidance in the planning process, and that any vulnerability map issued should take care to reflect the inherent uncertainty in the map. An example of the application of vulnerability mapping could be as simple as using the maps to determine which development applications receive more scrutiny in the development review process. In a similar vein, the maps could be used to request the implementation of more rigorous best management practices when development proceeds in identified vulnerable areas. The maps could also be used to guide or prioritize the spending of limited financial resources. In summary, where the maps are going to be used to aggressively limit or prohibit specific land uses, it is strongly recommended that site specific work be undertaken to support the vulnerability map.

Although groundwater vulnerability itself remains relatively static, the mapping products produced are only as accurate as the data provided. As new wells are drilled and further hydrogeological studies undertaken, there will be a need to incorporate the new work and revise and re-issue the maps.

Methods for aquifer vulnerability mapping are project and data specific. It is doubtful a single method can be adequately applied to all hydrogeological environments of southern Ontario, or any other large area. It should be noted that with improvements to the data sets and pre and post processor software for numerical groundwater flow models, the gap between vulnerability mapping and groundwater modelling is closing. In areas of rich data sets, it is likely to be more appropriate to investigate vulnerability through a fully calibrated numerical model.

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