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Evaluating Methods of Aquifer Vulnerability Mapping for the Prevention of Groundwater Contamination in British Columbia

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Executive Summary

Two documented methods of aquifer vulnerability mapping, AVI and DRASTIC, were evaluated as to their suitability for use in unconsolidated, glaciated, shallow aquifer terrains in southern British Columbia. Both methods were applied, at a 1:20,000 mapping scale, in a pilot project area 50 km southeast of the city of Vancouver. The study area is 85 km^2 in size and is underlain by two adjacent unconsolidated aquifers. Both aquifers comprise glaciofluvial sand and gravel. The Abbotsford-Sumas aquifer is an unconfined aquifer with the water table ranging from 0 to 40 m below the land surface. The Aldergrove aquifer is confined mainly by glaciomarine stony clays and tills up to 30 m thick.

Results of applying the two vulnerability mapping methods show the area above the unconfined Abbotsford-Sumas aquifer is highly vulnerable to contamination while the vulnerability of the area above the confined Aldergrove aquifer is very low. Areas of high and low vulnerability correspond with areas underlain by glaciofluvial sand and gravel, and glaciomarine stony clay and till, respectively.

AVI and DRASTIC vulnerability areas were compared to water quality data to see how the two methods correspond with reported nitrate concentrations in the aquifers. In the study area, elevated Nitrate - Nitrogen (NO_3-N) occurrences reflect non-point source water quality degradation from human activities. As expected, areas of water quality degradation coincided with higher vulnerability areas. Low NO_3-N concentrations were associated with low vulnerability areas and the low NO_3-N concentrations reported in high vulnerability areas reflect the absence of any NO_3-N contamination source and water quality degradation at these locations.

Both AVI and DRASTIC appear suitable for application in shallow, unconsolidated, glaciated aquifer terrains where there is sufficient coverage of well record data. Where sufficient well record data are available, the AVI method, in conjunction with available surficial geology information to assist in defining vulnerability boundaries, is recommended. Ease of use, data availability and more objective vulnerability values were the main reasons the AVI method is preferred over DRASTIC.

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Acknowledgments

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Evaluating Methods of Aquifer Vulnerability Mapping for the Prevention of Groundwater Contamination in British Columbia

1 Introduction

British Columbia has an abundance of good quality groundwater (B.C. Environment, 1994; B.C. Environment, 1993). A significant portion of the Province's groundwater supply comes from shallow, unconfined aquifers which receive recharge directly from infiltration of precipitation or from surface water bodies such as rivers and lakes. These unconfined aquifers are prone to impacts from human activities that have resulted in incidences of water quality degradation (Carmichael et al., 1995; Wei et al., 1993; Liebscher et al., 1992; Kwong, 1986).

One cost–effective approach to protecting water quality is to map the vulnerability of aquifers to assist in planning development and guiding human activities to minimize water quality impacts. In a recent report Sacre and Patrick (1994) cited vulnerability mapping as the "most suited to the protection of groundwater on a regional scale such as the Fraser Basin where numerous wells, rather than a single wellfield, are present". Piteau Associates and Turner Groundwater Consultants (1993), in their report on groundwater assessment for British Columbia, also recommend vulnerability mapping as an initial phase in a two-phase groundwater assessment program.

Aquifer vulnerability is defined here as the intrinsic susceptibility of an aquifer to contamination solely as a function of the physical characteristics of the aquifer itself and the overlying soil and geological sediments (Vrba and Zaporozec, 1994). The type and intensity of human activities above an aquifer are not criteria in determining aquifer vulnerability but rather in the overall assessment of an aquifer's actual risk to contamination.

Two aquifer vulnerability mapping methods were evaluated for use in British Columbia: AVI (Aquifer Vulnerability Index), developed by the Prairie Provinces Water Board (Van Stempvoort et al., 1992), and DRASTIC, developed by US Environmental Protection Agency (Aller et al., 1987). This report presents the results of applying and evaluating AVI and DRASTIC to a shallow unconsolidated, glaciated aquifer terrain in southwestern British Columbia.

1.1 AVI

In the AVI method, an aquifer's vulnerability is quantified by the hydraulic resistance (c) to the vertical flow of water through the geologic sediments lying above the top of the aquifer. The hydraulic resistance is calculated (Equation 1) from two variables: the thickness (d) of each sediment layer above the top of the uppermost aquifer and the hydraulic conductivity (K) of each of the layers.

$$c = \sum d_i / K_i \text{, for layers 1 to i} \qquad (1)$$

Hydraulic resistance (c) has the dimension of time (e.g. years) and indicates the approximate flux–time per unit head gradient for water traveling downward through the various sediment layers to the top of the uppermost aquifer. The lower the hydraulic resistance (c), the greater the vulnerability. The vulnerability map is constructed by calculating the logarithm of the hydraulic resistance (log c) for each well location and contouring these values. The resultant contour map identifies areas of varying resistance that is grouped into vulnerability categories (Table 1).

Hydraulic Resistance 'c'	Log 'c'	Vulnerability Category
< 10 years	< 1	extremely high vulnerability
10 - 100 years	1 - 2	high vulnerability
100 - 1000 years	2 - 3	moderate vulnerability
1000 - 10,000 years	3 - 4	low vulnerability
> 10,000 years	> 4	extremely low vulnerability

Table 1. AVI vulnerability categories.

AVI defines an aquifer as any water–bearing zone of > 0.6 m thickness with at least one well tapping it. AVI considers all aquifers to be of equal value, ignoring water quality and water use of aquifers. The contouring aspect of AVI implies a gradation of vulnerability which, in reality, may not exist as geological conditions can change abruptly across contact boundaries.

1.2 DRASTIC

DRASTIC identifies and maps vulnerability areas that are composite representations of: the **D**epth to water table or top of aquifer, net aquifer **R**echarge, **A**quifer media, **S**oil media, **T**opography, **I**mpact of the vadose zone and the hydraulic **C**onductivity of the aquifer. Each vulnerability area, depicted by a polygon, represents similar hydrogeological conditions, and consequently, similar vulnerability. DRASTIC incorporates a relative ranking scheme that uses a combination of weights and ratings to produce a numerical value called the DRASTIC Index (Equation 2).

$$D_RD_5 + R_RR_4 + A_RA_3 + S_RS_2 + T_RT_1 + I_RI_5 + C_RC_3 = \text{DRASTIC Index (pollution potential)} \quad (2)$$

E.g. $D_R D_5$ where D_R = the DRASTIC rating for Depth to water table; and D_5 = the weight assigned to the Depth to water table (each DRASTIC factor has an assigned weight)

Hydrogeologic settings combine with DRASTIC indexes to create polygon areas graphically on a map. The higher the DRASTIC index score, the greater the vulnerability. Although DRASTIC is physically based, the final DRASTIC index, unlike the AVI, has no physical meaning, but rather, is a numerical ranking value. Adjacent vulnerability areas are not related but only serve as a means of comparison. Vulnerability polygon areas in DRASTIC can depict discreet breaks along geological or topographical boundaries.

1.3 Assumptions

AVI and DRASTIC have common assumptions which include: potential contaminant source is at or near the land surface, the contaminant has the same behaviour as water, recharge to the aquifer is from infiltration of precipitation, and flow in the vadose (and saturated) zone above the aquifer is vertically downward. The assumption that the contaminant has the same behaviour as water is justifiable because AVI and DRASTIC are designed to be used as a screening tool. Assessment of aquifer vulnerability, for specific contaminants, would be more appropriately done at specific sites using other contaminant transport models. For a more comprehensive description of AVI and DRASTIC, refer to Van Stempvoort et al. (1992) and Aller et al. (1987), respectively.

2 Study Area

The study area is situated in the Lower Fraser River Valley, 50 km southeast of Vancouver, British Columbia (Figure 1) and covers 85 km^2. The area was selected for the following reasons:

- it is underlain by two regional sand and gravel aquifers, one confined (the Aldergrove aquifer), located at the west and north portion of the study area, and the other unconfined (the Abbotsford–Sumas aquifer), located at the south and southeast portion of the study area, to provide vulnerability contrast,
- the hydrogeology of both aquifers has been reasonably well described (Kreye and Wei, 1994; Liebscher et al., 1992; Dakin and Tiplady, 1991; Kohut, 1987; Halstead, 1986),
- there are adequate geologic, soil, and topographic mapping and well record information to apply both methods,
- there are water chemistry data available to compare vulnerability mapping results to actual water quality, and
- the unconsolidated hydrogeologic setting is representative of similar glaciated terrains of the Province.

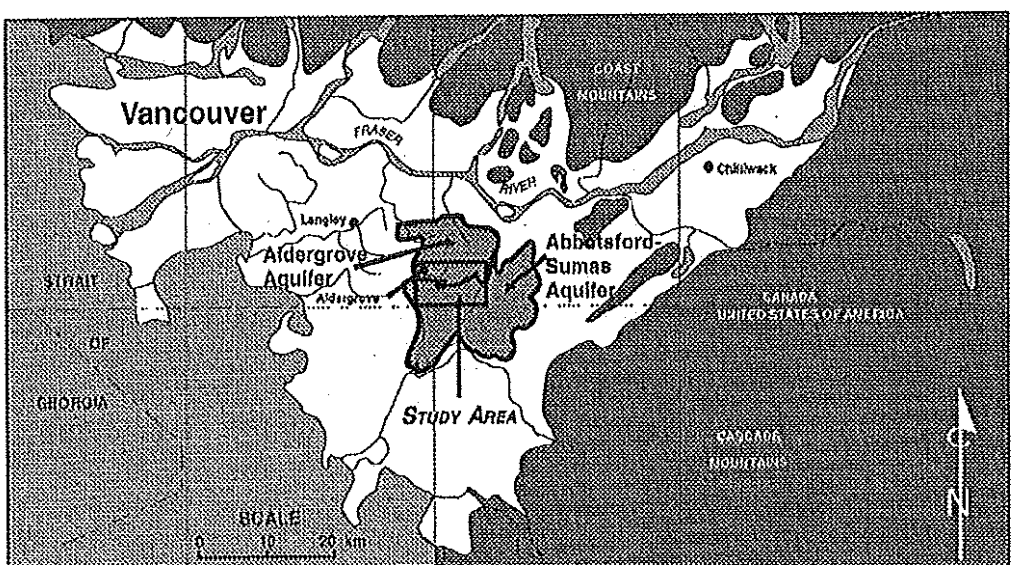

Figure 1. Map of the study area.

The hydrogeology of the Abbotsford–Sumas aquifer and Aldergrove aquifer has been described by Kreye and Wei (1994), Liebscher et al. (1992), Dakin and Tiplady (1991), Kohut (1987), and Halstead (1986). Both aquifers comprise predominantly glaciofluvial sand and gravel associated with the last glacial period. The Abbotsford–Sumas aquifer is unconfined, with the water table ranging from 0 – 40 m below the land surface. The Aldergrove aquifer is confined by up to 30 m of likely low permeability glaciomarine stony clay and till.

Locally perched water–bearing zones occur in the confining layer above the Aldergrove aquifer. Recharge to both aquifers and the perched water–bearing zones are believed to be from infiltration of precipitation (Dakin and Tiplady, 1991; Kohut, 1987). Kreye and Wei (1994) have subjectively classified the entire Abbotsford–Sumas aquifer as highly vulnerable and the Aldergrove aquifer as having low vulnerability to contamination from surface sources.

Both aquifers supply groundwater for domestic, municipal, irrigation, industrial, and commercial uses. Six hundred of the 990 well records available from the Provincial water well database for the study area have the requisite information (well location, water level, lithology and well construction) necessary for mapping vulnerability using either the AVI or DRASTIC methodologies. The remaining wells were wells with no information on lithology and/or water levels and were not used.

3 Methodology

In this study, the AVI and DRASTIC methodologies were generally followed. The UTM coordinates of water wells were digitized from well locations plotted on 1:5000 and 1:2000 scale maps. In our study with the AVI method, saturated hydraulic conductivity values (K) were assigned to lithologic descriptions in the well records (Table 2). These values generally followed those K-values used by Van Stempvoort et al. (1992) which are based on typical values found in Freeze and Cherry (1979). The use of saturated hydraulic conductivity for unsaturated sediments was considered a reasonable first approximation and should give more conservative hydraulic resistance values (i.e. higher vulnerability). The thickness of individual sedimentary layers was taken directly from the lithologic descriptions reported in the water well records. The AVI vulnerability map was constructed by contouring the logarithm of the hydraulic resistance values (log c) using the SURFER contouring package (Golden Software, 1994).

With DRASTIC, ratings and total DRASTIC index scores were assigned for each well location. The depth to the top of the uppermost water bearing zone or aquifer was determined directly from water well records. Average net recharge for the Abbotsford-Sumas (unconfined) aquifer was obtained from existing studies (B.C. Environment, 1994; Kohut, 1987; Callan, 1971). Recharge for the Aldergrove (confined) aquifer was available from Dakin and Tiplady (1991). Ratings for aquifer media and aquifer hydraulic conductivity were assigned based on lithology from well records. Ratings for soil media and topographic slope for each well location were determined from 1:25,000 scale soil mapping (Luttmerding, 1981) and 1:5000 and 1:2000 scale topographic mapping, respectively.

Table 2. Hydraulic conductivity 'K' estimates for various sediments.

Hydraulic Conductivity * (K) Estimates for Various Sediments	
**Sediment Type ** **	**(K) metres/day**
gravel	1.00E+03
sand	1.00E+01
silty sand	1.00E+00
silt	1.00E-01
sandy gravely till	1.00E-04
clayey till	1.00E-05
clay	1.00E-06

* Saturated hydraulic conductivity values. ** In reality, each of these sediment types has a range of values over several orders of magnitude; the values here are considered to be representative values.

Equivalent saturated vertical hydraulic conductivity for each well was calculated by dividing the total depth to top of uppermost aquifer by the sum of the hydraulic resistance of the individual sediment layers. The assigned rating for the impact of the vadose zone was determined from linking the equivalent vertical hydraulic conductivity to the equivalent lithologic descriptions (Table 2) at each well location. To incorporate geologic and geomorphic boundaries, surficial geology (Armstrong, 1976), soils (Luttmerding, 1981) and topographic maps were used to guide delineation of the polygon boundaries for the individual DRASTIC factors and for the total DRASTIC index score.

4 Results and Discussion

Preliminary AVI and DRASTIC maps generated for the study area are shown in Figures 2 and 3, respectively. For comparison, the surficial geology of the study area (adapted from Armstrong, 1976) is shown in Figure 4.

4.1 AVI

Vulnerability in the study area ranges from extremely low to extremely high (Figure 2). High vulnerability areas occur predominately in the southeast portion of the study area above the unconfined Abbotsford–Sumas aquifer and as isolated zones in the western portion of the study area. The majority of the area designated extremely high vulnerability actually has an estimated hydraulic resistance of less than 0.1 year. Low vulnerability areas are found in the west and northern portions of the study area above the Aldergrove aquifer. Narrow areas of moderate vulnerability separating high and low vulnerability areas may be an artifact of the contouring rather than the existence of actual moderately vulnerable areas. The areal extent of the moderate vulnerability areas along a surficial geologic boundary may be governed by well density which affects the contouring.

The high and extremely high vulnerability areas correlate (compare Figures 2 and 4) with the uppermost, glaciofluvial recessional sand and gravel deposits while low vulnerability areas correspond with the areas underlain by glaciomarine stony clay and minor till. The close resemblance of the boundary of the high vulnerability area to the boundary of the glaciofluvial recessional sand and gravel deposits is due to 2 factors:

- the unconfined sand and gravel deposits directly underlie the land surface and
- the high well density (7 wells/km^2) allowed high resolution in the contouring.

Perched water-bearing zones and low permeability lenses significantly affected the AVI vulnerability rating. The high well density and the two AVI variables (K and d) also allowed local perched water-bearing zones within the low vulnerability glaciomarine stony clay and till in the study area to be delineated. Presence of shallow perched water-bearing zones in the confining stony clay and till layer near the UTM 541000 east; 5434000 north coordinate area, for example, decreases the total thickness of the sedimentary layers above the uppermost aquifer (d) in equation (1) which decreases the hydraulic resistance. However, the resulting c-value is a measure of the resistance to the perched water-bearing zone and not the deeper confined Aldergrove aquifer.

The presence of thin low permeability till and clay lenses in the recessional glaciofluvial sand and gravel above the unconfined Abbotsford-Sumas Aquifer can decrease the aquifer vulnerability locally because the low permeability layer is dominant in calculating the resistance. This phenomenon, for example is apparent near the UTM 545250 east; 5430500 north coordinate area.

4.2 DRASTIC

Within the study area, there are 7 classes of vulnerability, each defining a (20-point) range of DRASTIC indexes, from <100 for the least vulnerable to 200-219 for the most vulnerable (Figure 3). Ranges of higher DRASTIC indexes (160-200+) are mostly found in the southeast above the Abbotsford–Sumas aquifer and in pockets in the mid-west portions of the study area. Ranges of lower DRASTIC indexes (<100-139) are found in the west and north half portions of the study area above the Aldergrove aquifer.

The DRASTIC map also appears physically consistent with the surficial geology map (compare Figures 3 and 4); the areas covered by the higher DRASTIC index ranges correspond with the recessional glaciofluvial sand and gravel deposits and areas of lower DRASTIC index ranges correspond with the areas underlain by the glaciomarine stony clay and till confining layer. Where possible, DRASTIC polygon boundaries are aligned with soil and surficial geology boundaries (compare Figures 3 and 4). Unlike AVI which has a sequential progression between high and low vulnerability areas, DRASTIC high and low vulnerability polygon areas may share the same border.

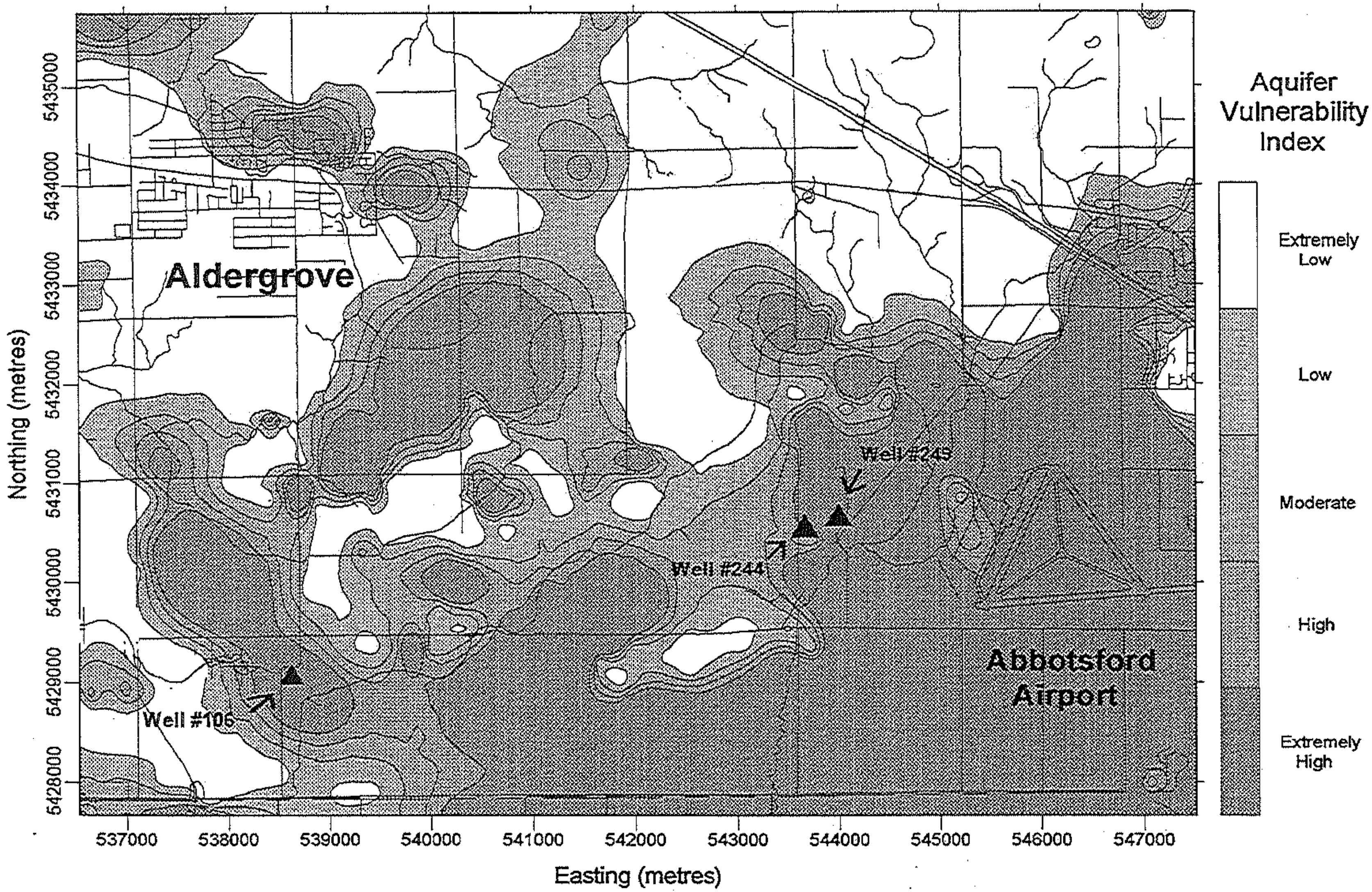

Figure 2. AVI aquifer vulnerability map.

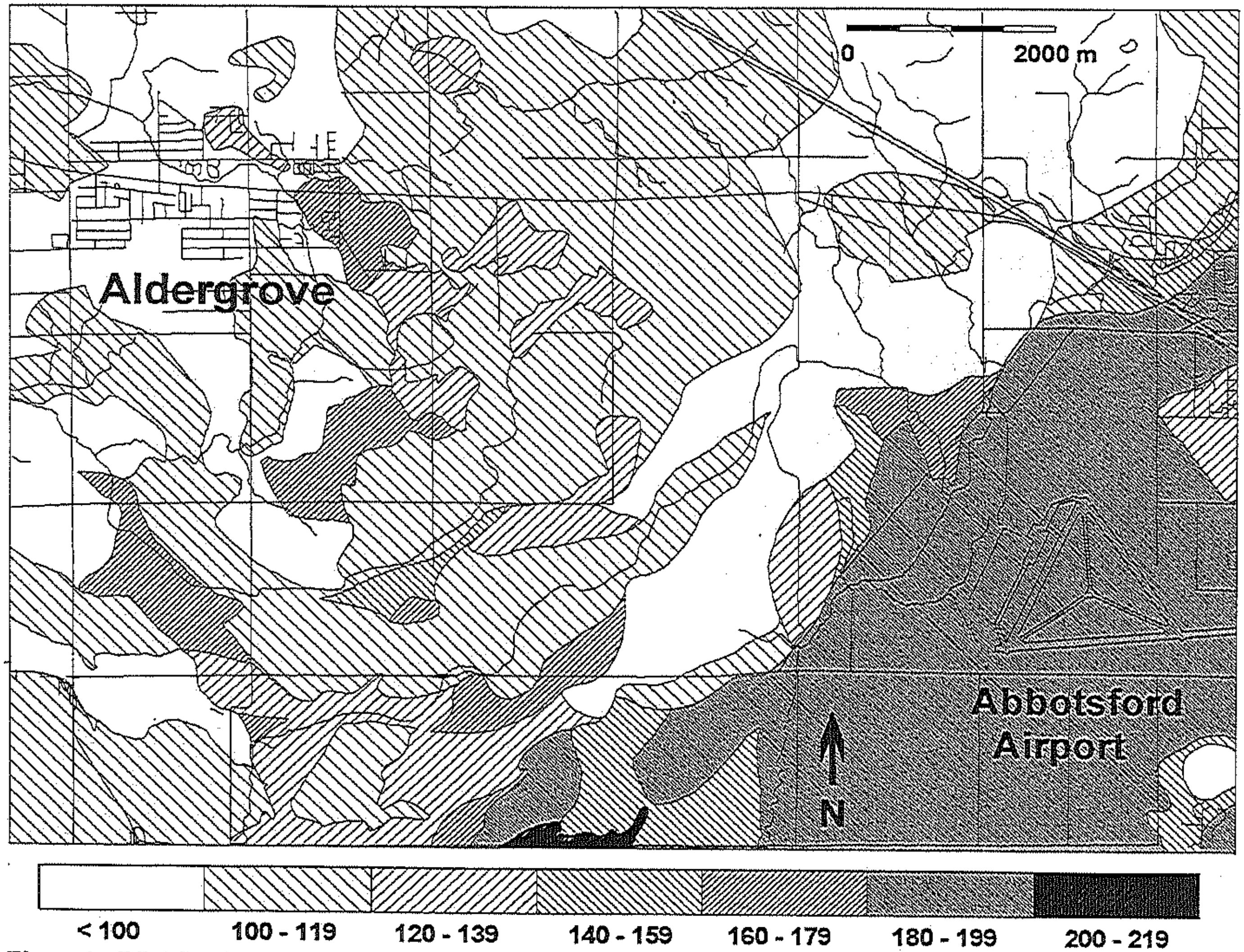

Figure 3. DRASTIC aquifer vulnerability map showing seven DRASTIC index ranges.

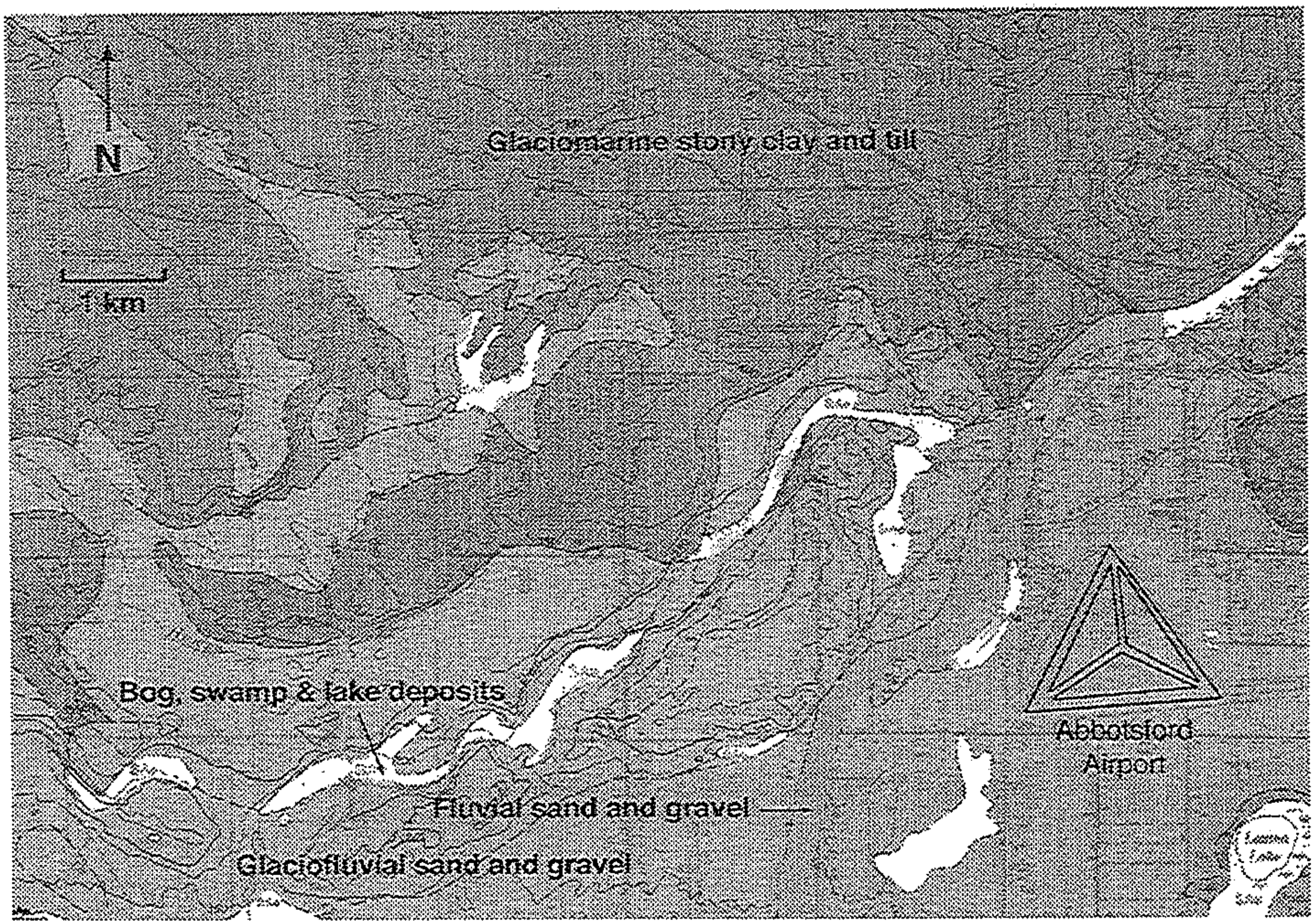

Figure 4. A generalized surficial geology map of the study area (after Armstrong, 1976).

4.3 Comparing AVI and DRASTIC

AVI and DRASTIC vulnerability areas follow the same regional pattern which is consistent with the surficial geology. This suggests that, in the study area, and possibly in other areas of similar hydrogeology, the surficial geology is a main controlling factor in aquifer vulnerability. The results from both methods are also consistent with the subjective classifications of vulnerability designated for both aquifers by Kreye and Wei (1994). Areas delineated extremely high and extremely low vulnerability by the AVI method compare favourably with the delineated areas of high and low DRASTIC indexes respectively. In part, this similarity is due to the fact that, the two factors included in the AVI approach are essentially the two DRASTIC factors with the greatest weights (i.e. Depth to water table and Impact of the vadose zone)

Locally, AVI and DRASTIC vulnerability areas, were not readily comparable. Local differences included: low permeability lenses and perched water bearing zones were not evident in the DRASTIC map (the result of lumping the 7 factors) and boundaries between vulnerability areas varied considerably (because the boundaries were delineated by different methods). The AVI hydraulic resistance was plotted against total DRASTIC indexes for each well to investigate any obvious relationships (Figure 5)

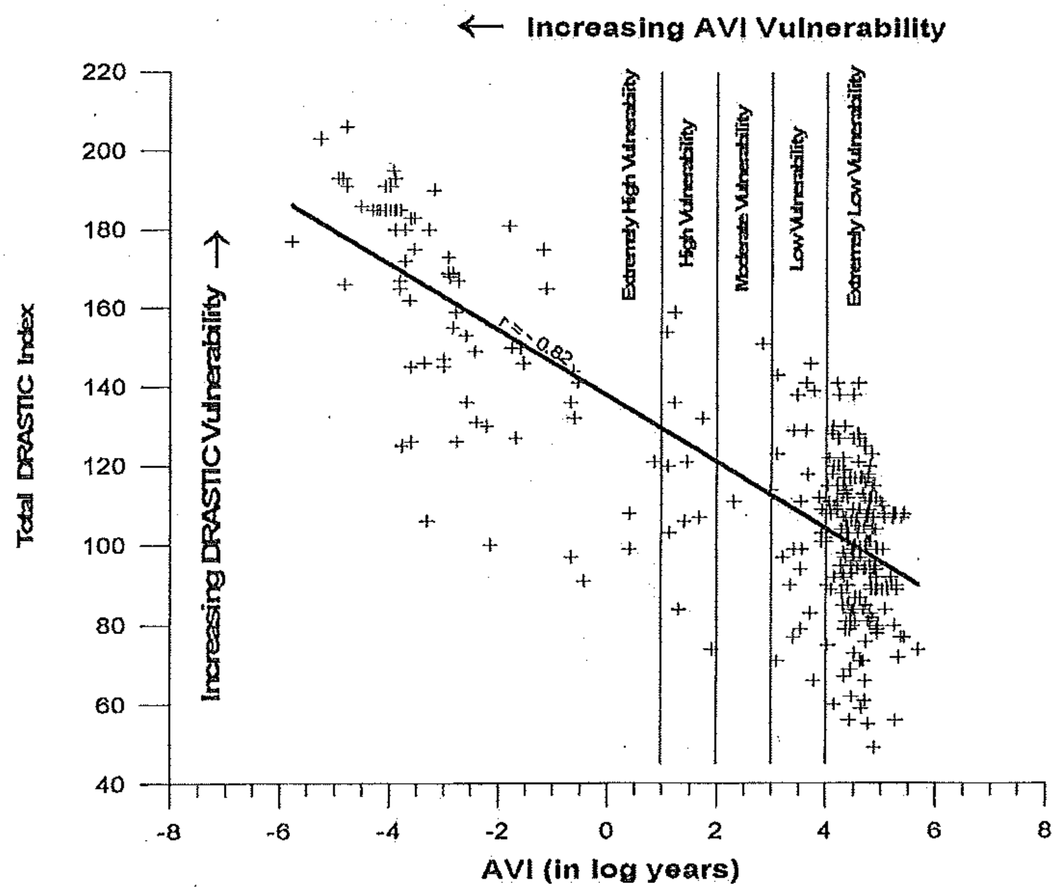

Figure 5. AVI versus total DRASTIC index.

Generally, AVI and DRASTIC appear consistent; the lower the hydraulic resistance, the higher the DRASTIC index score (and the greater the vulnerability). However, for a given AVI vulnerability category, up to 7 DRASTIC ranges are covered. Similarly, a given DRASTIC range (20 points) can span all five AVI vulnerability categories. There are very few data points in the low, moderate or high vulnerable AVI zones (log c of 3-4, 2-3 and 1-2 respectively). This probably reflects the geology rather than the sensitivity of the AVI methodology. In the study area, the aquifers tend to be either extremely vulnerable to contamination or they are not.

The AVI method is more objective, while the DRASTIC method appears better able to take into account discreet geologic boundaries. The AVI is directly based on physical property – the hydraulic resistance – while the DRASTIC index is a composite of a number of physical factors and is subjected to greater interpretation. More information and preparation time was required for DRASTIC than for AVI. Table 3 summarizes the advantages and difficulties encountered when the AVI and DRASTIC methodologies were applied.

AVI

Advantages

- Objective - consistent reproducibility of results
- Physically based directly on physical properties of overlying sediments
- Relatively easy to apply
- Requires only well log information (well locations, water level, lithology and well construction) which are readily available from the Provincial water well database
- Is sensitive to perched water bearing zones in low permeability areas and low permeability lenses in high permeability areas
- Ability to provide finer intervals of hydraulic resistance (c)
- Is scale independent

Difficulties

- Does not consider hydrogeologic settings like DRASTIC does
- May indicate a sequential progression between high and low vulnerability areas which may not exist
- Does not consider the effect of the soil layer on contaminant transport

DRASTIC

Advantages

- Maps hydrogeologic settings, that is, a specific area with common hydrogeologic characteristics
- Will identify where high and low vulnerability areas may share the same border
- Where insufficient well record data are available, there is usually some information available to estimate nominal differences in vulnerability between areas

Difficulties

- Subjective - results can vary when different people delineate polygon boundaries.
- Based directly on physical properties but weighting of each DRASTIC factor based on Delphi method rather than physical theory
- Cumbersome to apply (e.g. mapping scales between the 7 variable data sources are often different)
- Information on the 7 DRASTIC factors are not always readily available
- Overlap or redundancy between factors (e.g. soil media is a subset of the vadose zone)
- Does not consider travel time of contaminant
- Local low permeability lenses and perched water bearing zones were not readily evident

Table 3. A summary of the advantages and difficulties encountered when the AVI and DRASTIC methodologies were applied.

4.4 Comparing AVI and DRASTIC to Actual Water Quality Degradation

AVI and DRASTIC vulnerability areas were compared to actual water quality data to see how the two methods correspond with nitrate concentrations from recent sampling (Carmichael et al, 1995). In the study area, elevated Nitrate-Nitrogen (NO_3-N) occurrence reflects non-point source water quality degradation from human activities. It would be expected that areas of water quality degradation would coincide with higher vulnerability areas (Figure 6). As was expected, high NO_3-N concentrations were associated with high vulnerability areas and low NO_3-N concentrations were associated with low vulnerability areas. The low NO_3-N concentrations reported in high vulnerability areas reflect the absence of NO_3-N contamination and water quality degradation at these locations.

Wells 249 and 244 (well numbers in Carmichael et al., 1995) appear to be anomalous (see Figure 6a). Well 249 would be expected to have a lower AVI because of the elevated NO_3-N. The reported lithology for this well log indicates some likely low permeability sediments which are not found at adjacent well sites. The likely low-K sediments resulted in a higher AVI for well 249. However, the low-K sediments do not appear to extend much beyond the well site and the elevated NO_3-N measured in well 249 reflects water quality degradation in the up-gradient area which is highly vulnerable. Well 244 is similar to well 249 in that the lithology indicates some low permeability sediments at the well site but is underlain and surrounded by much higher permeability sediments. Well 106 is an example of a well sited in an extremely high vulnerability area with NO_3-N concentrations very low because the well, located in the Aldergrove Lake Regional Park, is not subject to adverse human activities.

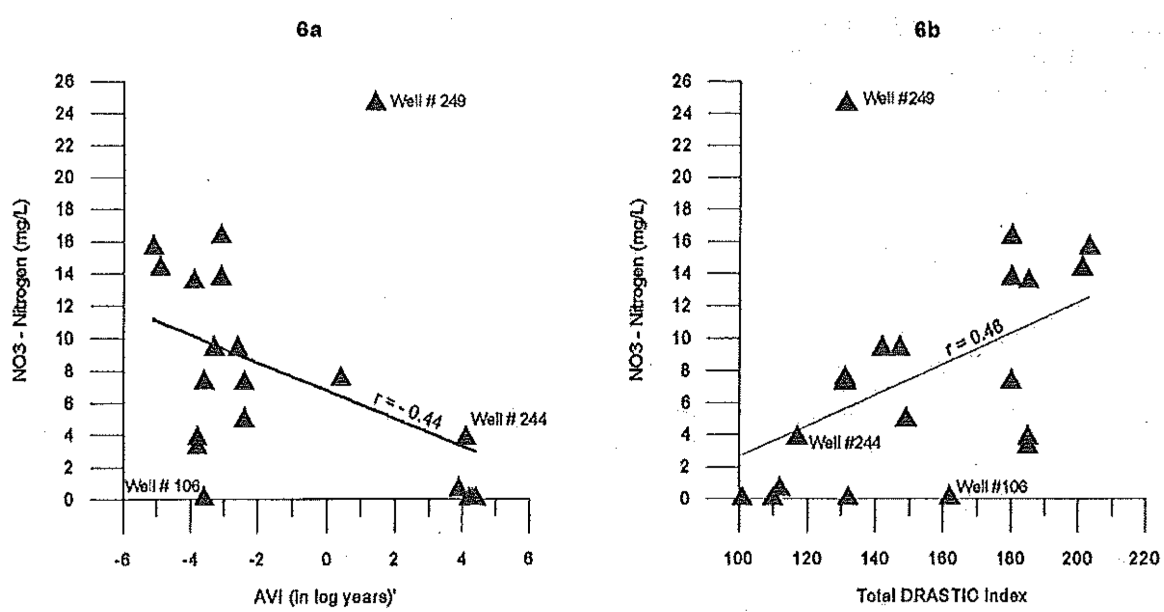

Figure 6. Comparison of AVI and total DRASTIC index to nitrate-nitrogen concentrations.

Figure 6b shows a similar trend of increasing NO_3-N concentrations with increasing DRASTIC aquifer vulnerability. There appears to be less clustering than that found in the AVI graph (Figure 6a) indicating the smoothing effect of combining the 7 factors used in the DRASTIC methodology.

In their study of non-point source nitrate contamination of groundwater in Grand Forks, British Columbia, Wei et. al. (1993) found that the ratios of total alkalinity/Total Dissolved Solids (alkalinity/TDS) and Chloride/NO_3-N (Cl/NO_3-N) are related to NO_3-N occurrence. These ratios may serve as indicators of water quality degradation by nitrate. Ratio of alkalinity/TDS and NO_3-N/Cl were plotted against NO_3-N (Figure 7). Figures 7a and 7d show that the total alkalinity/TDS and NO_3-N/Cl indicators follow the same general trend with what Wei et al (1993) found in Grand Forks. Figure 7a shows that generally, as the NO_3-N concentrations increase the alkalinity/TDS ratio decreases because nitrification results in an increase of H^+ concentration and subsequent decrease in HCO_3^- concentration. Accordingly, in Figures 7b and 7c as the vulnerability increases the alkalinity/TDS ratio generally decreases. The NO_3-N/Cl ratio for wells with background concentrations of NO_3-N (< 0.1 mg/L NO_3-N) are generally < 0.1. Low NO_3-N/Cl ratios at low NO_3-N concentrations may be due to the difference in background concentrations of Cl^- (1-2 mg/L) and NO_3-N (<0.1 mg/L). As similar amounts of Cl^- and NO_3-N from anthropogenic sources are leached into the aquifer, the NO_3-N/Cl ratio (Figure 7d) increases. The NO_3-N/Cl ratio tends to increase as the vulnerability increases (Figures 7e and 7f). The shaded area of Figures 7e and 7f is interpreted to be a measure of the impact of nitrogen contamination for a given vulnerability. The outer border of the shaded area delineates the probable uppermost NO_3-N/Cl ratio expected for a given vulnerability in the study area. Points (e.g. 249 and 244) found above this line could be considered outliers.

4.5 Additional Work Required

Although both AVI and DRASTIC appear suitable for use in shallow, unconsolidated, glaciated aquifer terrains in British Columbia, further work needs to be done. As aquifers are a natural management unit, vulnerability mapping may need to be applied specifically to individual aquifers. Vulnerability mapping should be extended to cover the entire Abbotsford-Sumas aquifer. This should include mapping the Abbotsford-Sumas aquifer south of the Canada/USA border. In the AVI methodology, surficial geology boundaries or aquifer boundaries should be used to assist in delineation of vulnerability areas instead of solely relying on boundaries delineated by contouring.

Measured K–values, required for the DRASTIC method, are almost never available from the Provincial water well database because aquifer productivity is usually measured in terms of transmissivity or inferred from specific capacity from pumping tests. The potential for use of transmissivity and/or specific capacity, instead of aquifer hydraulic conductivity, should be investigated for DRASTIC.

Since hydraulic conductivity values are not normally available, assigning K-values to well lithologic descriptions for calculating the hydraulic resistance or AVI involves a level of uncertainity. The potential exists for adopting a probabilistic component to the current AVI method to quantify the uncertainty of the vulnerability index.

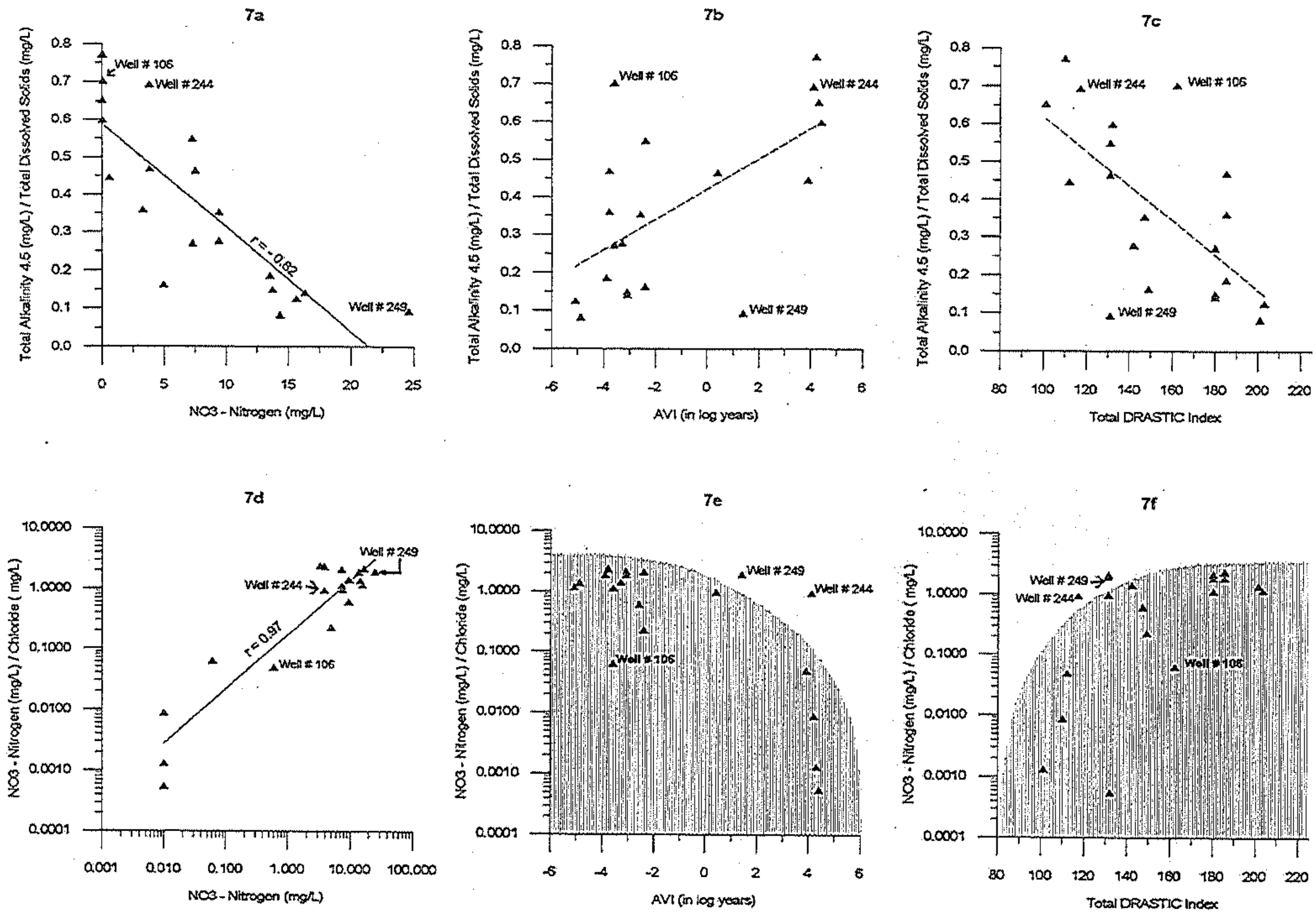

Figure 7. Comparison of AVI and total DRASTIC index to actual water quality data. Dashed lines are used as a visual guide. Shaded areas are a measure of the impact of nitrogen contamination for a given vulnerability.

The suitability of applying AVI and DRASTIC to fractured bedrock terrains and areas of limited data needs to be evaluated. An area with a variety of rock types, varied overburden and sufficient data needs to be tested. In conjunction with hydraulic conductivity as an important factor governing flow and transport in bedrock aquifers in British Columbia, the need to consider fracture porosity in vulnerability mapping, may be appropriate, for both site specific and regional, in bedrock terrrains.

4.6 Uses of Aquifer Vulnerability Maps

Aquifer vulnerability maps are valuable derivative maps that should reveal, relatively easily, the vulnerability of groundwater for a given location. They need to be scientifically robust, yet the methodology to construct them, simple enough to be cost-effective. The vulnerability maps, one of the many tools to be used in environmental management, should be used only to the limits of their accuracy. For example, the vulnerability areas within a mapsheet should be compared on a relative rather than an absolute sense because some of the variables for calculating the vulnerability index were estimated (eg. hydraulic conductivity). Although the AVI methodology is conceptually scale independent, the variable distribution of data points and the use of contouring to delineate vulnerability areas mean that use of AVI maps alone for making site-specific decisions on groundwater protection is insufficient. The main value of vulnerability maps is their use as a screening tool for the management and protection of groundwater which includes: guiding land use activities and land use planning, growth management and identifying areas that need protection. Vulnerability maps are also valuable as an educational tool to inform the public and policy makers about the vulnerability of the groundwater resource in specific areas and the need to minimize human impacts in these areas. In British Columbia, aquifer vulnerability mapping would be of benefit to Protected Areas Strategies, Ground Water Management Areas (pending), regional and municipal planning and for local health units in their mandate to protect public drinking water supplies.

5 Conclusions

This study reviewed two methods of aquifer vulnerability mapping: AVI (Van Stempvoort et al, 1992), and DRASTIC (Aller et al, 1987). There were merits and drawbacks for both methodologies (Table 3). The strongest merits in favour of the AVI method were its ease of use and objectivity. DRASTIC was better able to delineate a boundary between two different hydrogeologic environments and may be more valuable where there was a paucity of well lithology and aquifer data. Where sufficient well log data are available in unconsolidated, glaciated aquifer terrains in British Columbia, the AVI method, in conjunction with the more readily available surficial geology and aquifer boundaries for fine tuning vulnerability boundaries, is recommended. To successfully apply any vulnerability mapping method, it is imperative to have: good, accurate, large scale surficial geological mapping; maps showing delineated aquifer boundaries; and, the most current, and widest possible coverage of accurately located water wells with accompanying lithologic and water level information. The applied use of this information in the development of derivative products, such as aquifer vulnerability maps, will help insure a sustained and healthy groundwater resource in British Columbia.

6 References

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Appendix IV. Summary of Aquifer Vulnerability Mapping Methods in Select Jurisdictions

Method / Reference	Description	Advantages/Disadvantages
Bengtsson and Rosen (1995)	Calculate (using a probabilistic approach) and map (on separate maps) the retention times in the unsaturated ($t=d*\theta/R$) and saturated ($t=L*n*i/K$) zones. The shorter the retention time (t), the higher the vulnerability.	Advantages: • probabilistic approach • retention time is a physical parameter • considers fractured bedrock aquifers • objective Disadvantages: • some required data (eg. hydraulic gradient (i), hydraulic conductivity (K), effective porosity (n), recharge (R), and field capacity (θ) not readily available and often are estimated
Aquifer Classification System for BC (Kreye and Wei, 1994)	Subjectively categorize aquifer vulnerability based on a preliminary assessment of depth to water table, permeability of aquifer, degree of confinement, and fracture porosity. Vulnerability is categorized as: high, moderate, and low.	Advantages: • required data available from water well records • considers fractured bedrock aquifers Disadvantages: • vulnerability categorized for aquifer as a whole, does not reflect variability within the aquifer • subjective • developed for a specific area and need to be evaluated for applicability to other geologic terrains
Aquifer Vulnerability Index (AVI) (Van Stempvoort et al, 1993)	Calculate the hydraulic resistence ($c=\Sigma(d/K)$ above the aquifer, from well records, and delineate areas of equal resistence. Vulnerability is indicated by the hydraulic resistence (c); the lower the resistence, the higher the vulnerability.	Advantages: • based on actual well records • hydraulic resistence is a physical parameter • objective, easy to apply, and results are reproducible Disadvantages: • hydraulic conductivity values (K) needed to calculate hydraulic resistence not readily available and often are estimated
Adams and Foster (1992)	Categorize vulnerability based on permeability of aquifer (high, variable, and low) and depth to aquifer (<5m and >5m). The possible combinations of permeability and depth to aquifer results in 3 main categories of vulnerability: A (high), B (moderate), and C (low).	Advantages: • easy to apply • considers vulnerability of fractured bedrock Disadvantages: • permeability ranges not quantitatively defined • developed for a specific area and need to be evaluated for applicability to other geologic terrains

Appendix IV. Summary of Aquifer Vulnerability Mapping Methods in Select Jurisdictions (continued)

Method / Reference	Description	Advantages/Disadvantages
Mapping areas vulnerable to groundwater contamination by pesticides (McRae, 1991)	Map areas vulnerable to leaching of pesticides using the following 4 physical criteria: soil texture, topographic slope, depth to water table, and surface landform expression. Polygons for each criteria are constructed, overlayed, and compared against areas of actual groundwater contamination to outline vulnerable areas. Vulnerable areas are characterized by sandy or sandy loam soils, 0-9% slope gradient, and hummocky, level, kettled, and undulating terrains.	Advantages: • vulnerability areas delineated based on knowledge of actual groundwater contamination Disadvantages: • considers primarily soils and landforms only • developed for a specific area and specifically for pesticides and need to be evaluated for applicability to other geologic terrains and other contaminants
Regina Aquifers Sensitivity Mapping (Roeper, 1990)	Vulnerability areas are delineated based on the presence, type, and thickness of the overlying geologic materials (determined from existing geologic mapping) above the aquifer. Vulnerability categories are specified based on given thickness range for clays, tills, and other unconsolidated materials.	Advantages: • easy to appply Disadvantages: • developed for a specific area and need to be evaluated for applicability to other geologic terrains
Contamination Vulnerability Index (Lemme et al, 1990)	Calculate the aquifer vulnerability index at each well site using an empirical equation that includes 3 physical parameters: soil organic matter, soil profile thickness, and effective hydraulic conductivity of the vadose zone above the aquifer. Construct the vulnerability map by contouring the index values. Vulnerability is indicated by the index value, VI, which ranges from 0-10; the higher the index value, the higher the vulnerability.	Advantages: • there is a corresponding vulnerability index for surface water to provide a basis of comparison between surface and groundwater Disadvantages: • data on soil organic matter and hydraulic conductivity are not readily available and would need to be estimated • the units in the empirical equation are not consistent
GOD (Foster,1987)	Calculate aquifer pollution vulnerability index (varies from 0 to 1) by multiplying indices for 3 physical factors: degree of aquifer confinement (G-varies from 0-1), aquifer material and degree of fracturing and/or consolidation (O-varies from 0-1), and depth to water table (D-varies from 0-1). Vulnerability is indicated by index value (GxOxD); the higher the index, the higher the vulnerability.	Advantages: • easy to apply • all required data available from water well records • considers vulnerability of fractured bedrock aquifers Disadvantages: • aquifer pollution vulnerability index is physically dimensionless • developed for a specific area and need to be evaluated for applicability to other geologic terrains

Appendix IV. Summary of Aquifer Vulnerability Mapping Methods in Select Jurisdictions (continued)

Method / Reference	Description	Advantages/Disadvantages
DRASTIC (Aller et al, 1986)	Designate mappable units and calculate the pollution index by summing weighted point scores for 7 factors: depth to aquifer, recharge, aquifer media, soil media, topography, impact of vadose zone, and aquifer hydraulic conductivity. Delineate areas with similar pollution index and common hydrogeologic characteristics. Vulnerability is indicated by the pollution index; the higher the index, the higher the vulnerability.	Advantages: • considers a comprehensive suite of physical factors • method is widely used in North America • can be applied to evaluate vulnerability to pesticides • applicable for all geologic terrains in North America Disadvantages: • the pollution index is physically dimensionless • subjective • information for some of the factors such as recharge and hydraulic conductivity are not readily available and often are estimated
Haertle (1983)	Categorize vulnerability based on depth to water table (01m, >1-5m, >5-10m, and >10m) and permeability of materials overlying the aquifer (low permeable, fine grain permeable, and coarse grain permeable). The possible combinations of depth ot water table and permeability result in 3 categories of vulnerability: high, medium, and low.	Advantages: • takes into account multi-layered geology • required data available from well records Disadvantages: • does not consider bedrock • developed for a specific area and need to be evaluated for applicability to other geologic terrains
Vierhuff (1981)	Categorize vulnerability based on kind of aquifer, materials overlying the aquifer, and thickness of unsaturated zone. A flow chart guides assessment of vulnerability to 5 vulnerability categories: high, high-medium, medium-low, low, and very low.	Advantages: • easy to apply • required data available from water well records • considers fractured bedrock Disadvantages: • developed for a specific area and need to be evaluated for applicability to other geologic terrains
Groundwater Pollution Vulnerability Mapping for Cranbrook, BC (Le Breton, 1979)	Examine lithology in the well records to delineate 3 categories of vulnerability areas (high, moderate, and low). Contour the thickness of geologic materials above the aquifer within each of these 3 categories of areas. Vulnerability is indicated by the type of area and thickness of the overlying geologic materials.	Adavntages: • based on actual well records • easy to apply Disadvantages: • vulnerability areas delineated based on driller's lithologic description in the well records which is subjective • developed for a specific area and need to be evaluated for applicability to other geologic terrains

BC Environment

FACT SHEET

Aquifer Vulnerability Mapping for the Prevention of Groundwater Contamination in British Columbia

Background

British Columbia has an abundance of good quality groundwater. However, a major portion of the Province's groundwater supply comes from shallow, unconfined aquifers that are prone to impacts from human activities. Past unregulated human activities have already resulted in incidences of water quality degradation in some areas.

A key to protecting water quality is to prevent further degradation. This requires considering vulnerability of the groundwater resources in planning land use activities. As part of its mandate to manage groundwater quality, Water Management Program is evaluating methods for mapping aquifer vulnerability.

Benefits of Aquifer Vulnerability Mapping

The benefits of aquifer vulnerability maps include:

- assisting regional governments in planning development and guiding local land use activities to minimize water quality impacts,
- being used as a screening tool for siting waste disposal activities,
- identifying sensitive areas that need protection,
- enhancing awareness about the vulnerability of the groundwater resource, and
- avoiding expensive clean-up costs associated with contaminated aquifers.

Aquifer Vulnerability Mapping in the Abbotsford Area

The Water Management Program has evaluated a number of vulnerability mapping methods and is currently applying the Aquifer Vulnerability Index method, developed by the National Hydrology Research Institute, to the Abbotsford area. This work is being done in partnership with Environment Canada through funding from the Green Plan. To date, two-thirds of the Abbotsford-Sumas Aquifer have been mapped (see map below). Mapping is scheduled to be completed by 1996/97, subject to continued funding. The estimated cost for mapping the entire aquifer is $60K.

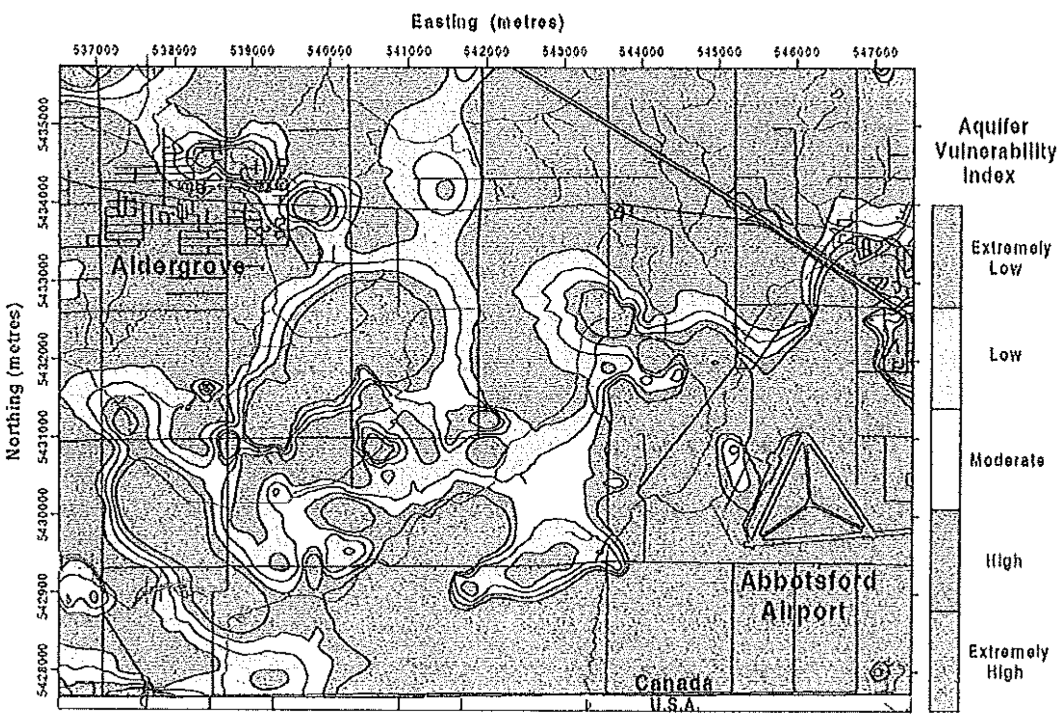
Future Directions: Vulnerability Mapping Applied to Bedrock Aquifers

Bedrock aquifers are an important source of water supply for many individuals and communities in the Province. To better manage water quality in these aquifers, the application of vulnerability mapping to bedrock aquifers in the Province also needs to be evaluated.

Further Information

For more information on the aquifer vulnerability mapping project, please contact M. Wei (604-356-5062), Groundwater Section, Hydrology Branch.

Aquifer Vulnerability Index Map of the Aldergrove - Abbotsford Area



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