Evaluating AVI and DRASTIC for Assessing Pollution Potential in the Lower Fraser Valley, British Columbia: Aquifer Vulnerability and Nitrate Occurrence

by

M. Wei, P. Eng.
Aquifer Assessment and Monitoring Unit
Groundwater Section

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by M. Wei, Groundwater Section, Water Management Branch, Ministry of Environment, Lands and Parks

Executive Summary

AVI and DRASTIC indexes calculated for 169 wells in the Lower Fraser Valley, British Columbia (BC) show generally consistent results. Low AVI and high DRASTIC indexes correspond with high vulnerability while high AVI and low DRASTIC indexes correspond with low vulnerability. AVI and DRASTIC indexes show a bimodal distribution with data points clustered around either high vulnerability or low vulnerability with very few in the moderate vulnerability range. High vulnerability is associated with unconfined conditions and low vulnerability is generally associated with confined conditions. The bimodal distribution likely reflects the confined and unconfined nature of aquifers in the Lower Fraser Valley. The AVI and DRASTIC indexes are also consistent with the vulnerability of the aquifers as designated under the BC Aquifer Classification System.

AVI and DRASTIC appear to correlate with occurrence of water quality degradation by nitrate in the Lower Fraser Valley. Most of the elevated nitrates (NO_3-N > 3 mg/L) occur in wells where AVI values are <-1 and DRASTIC indexes are >160. Elevated nitrates are not expected in areas where the DRASTIC index is <100. Nitrate exceeding the drinking water guideline (NO_3-N > 10 mg/L) could occur in the Lower Fraser Valley (depending on land use activities) where AVI values are <-1 and DRASTIC indexes are greater than 120, based on water quality data in the study area.

Presence of fine-grained lenses at a particular well can cause anomalously high AVI results to be calculated. Interpretation of pollution potential in a local area should, therefore, not be made based on the AVI index calculated for a single well but should also include AVI indexes from other wells nearby. A key to properly assessing pollution potential is to have good quality well records.

Both AVI and DRASTIC appear suitable for predicting pollution potential for unconsolidated aquifers in southwestern BC. The choice of which method to use for aquifer vulnerability mapping may depend, in the end, on additional factors such as ease of use (AVI is less subjective than DRASTIC) and on the information available (e.g., soils mapping, recharge estimates, etc.). The suitability of AVI and DRASTIC for predicting pollution potential in fractured bedrock aquifers in BC needs to be further evaluated.

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1 Introduction

British Columbia (BC) has an abundance of good quality groundwater (BC Environment, 1994). A significant portion of the Province's groundwater supply comes from shallow, unconfined aquifers that 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 which have resulted in incidences of water quality degradation (BC Environment, 1997; BC Environment, 1996; Carmichael et al, 1995; Wei et al, 1993; Liebscher et al, 1992). A cost–effective way to protect water quality is to map and assess the vulnerability[1] of aquifers to assist in planning land use activities and, thereby, minimizing water quality impacts (Sacre and Patrick, 1994; Piteau Associates and Turner Groundwater Consultants, 1993).

There is a surprising number of methods for characterizing aquifer vulnerability (see Vrba and Zaporozec, 1994). Many of the methods were developed empirically, based on the local hydrogeologic settings, data sets, and intended objectives of the mapping project. Some of these methods are summarized in Appendix A. However, few comparisons of these methods have been done. Two methods currently being used by other Provinces and States and which are being considered for use in BC are: AVI (Aquifer Vulnerability Index), developed by the Prairie Provinces Water Board (Van Stempvoort et al, 1992), and DRASTIC, developed by US EPA (Aller et al, 1987). Rosen (1994) did a conceptual evaluation of DRASTIC and concluded that DRASTIC had some advantages and is relevant for assessing groundwater pollution potential in southwest Sweden. Ronneseth et al (1995) did a mapping evaluation of both AVI and DRASTIC in the Abbotsford-Aldergrove area, east of Vancouver, BC and concluded that both methods appear suitable for use in shallow, unconsolidated, glaciated terrains in southwestern BC.

However, few studies have been done to evaluate how aquifer vulnerability determined from of AVI and DRASTIC correlate with actual water quality impacts from human activities; the suitability of these methods for predicting the pollution potential of aquifers has not been thoroughly validated. Kalinski et al (1994) found that DRASTIC indexes correlated with frequency of volatile organic compound (VOC) detections in municipal wells in Nebraska. Garrett et al (1989) concluded, on the other hand, that DRASTIC was a poor indicator of hydrocarbon and road salt contamination in Maine, probably because DRASTIC does not deal very well with fate and transport of contaminants in Maine's fractured bedrock aquifers. Ronneseth et al (1995) compared AVI and DRASTIC against nitrate-nitrogen concentrations for a limited number of wells in the Abbotsford-Aldergrove area. This report evaluates how well AVI and DRASTIC correlate with actual water quality (specifically nitrate) impacts from human activities in the Lower Fraser Valley.

1.1 AVI

AVI quantifies an aquifer's vulnerability at any given location by the hydraulic resistance (c) to the vertical flow of water through the geologic sediments above the aquifer. The hydraulic resistance is calculated from two variables: the thickness (d) of each sedimentary layer above the uppermost aquifer and the hydraulic conductivity (K) of each of the layers (Equation 1).

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

[1] Aquifer vulnerability is defined here as the intrinsic vulnerability of an aquifer to contamination strictly as a function of the physical characteristics of the aquifer and the overlying soil and geological sediments (see 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.

Hydraulic resistance (c) has the dimension of time (e.g. years) and represents the flux–time per unit head gradient for water travelling downward through the various sediment layers to the aquifer. The lower the hydraulic resistance (c), the greater the vulnerability. A vulnerability map can be constructed by calculating the logarithm of the hydraulic resistance (log c) for each well and delineating areas of similar log c (AVI) values. The resultant areas represent areas of different resistance which are grouped into the vulnerability categories in Table 1. AVI defines an aquifer as any water–bearing zone of > 0.6 m thickness with at least one well tapping it.

Table 1. AVI categories.

Hydraulic resistance, c (years)	Log (c)	Vulnerability category
< 10 years	<1	extremely high vulnerability
10 -100 years	1 to 2	high vulnerability
100 -1000 years	2 to 3	moderate vulnerability
1000 -10000 years	3 to 4	low vulnerability
>10,000 years	>4	extremely low vulnerability

1.2 DRASTIC

DRASTIC is a composite rating of the **D**epth to water, net **R**echarge, **A**quifer media, **S**oil media, **T**opography, **I**mpact of the vadose zone and the hydraulic **C**onductivity of the aquifer (Equation 2).

$$\text{DRASTIC Index} = 5D + 4R + 3A + 2S + 1T + 5I + 3C \qquad (2)$$

In equation (2), the numbers represent the relative weights and the letters correspond to each of the seven physical parameters. DRASTIC incorporates a relative ranking scheme that uses a combination of weights and ratings to produce a numerical value called the DRASTIC index. Hydrogeologic settings combine with DRASTIC indexes to form polygon areas on a map. Each polygon area represents similar hydrogeological conditions and consequently similar vulnerability. The DRASTIC index ranges from 23 to 230; the higher the DRASTIC index, the greater the vulnerability. Although DRASTIC is physically based, the final DRASTIC index, unlike AVI, has no physical units, but rather is a numerical index.

1.3 Assumptions

Both AVI and DRASTIC assume that the potential contaminant source is at or near the land surface, the contaminant has the same behaviour as water, recharge to the aquifer is from vertical infiltration of precipitation, and flow in the vadose (and saturated) zone above the aquifer is vertically downward. For a more detailed description of AVI and DRASTIC, refer to van Stempvoort et al (1992) and Aller et al (1987), respectively.

1.4 Study Objectives

The objectives of this study are to:

- determine AVI and DRASTIC indexes for all community wells and select private wells in the Lower Fraser Valley (Figure 1) to quantify the aquifer's vulnerability to contamination at those specific well locations and
- evaluate how water quality impacts from human activities relate to the aquifer vulnerability indexes calculated.

1.5 Study Area

The study area is situated in the Lower Fraser Valley, east of Vancouver (Figure 1). Unconsolidated deposits, up to 300 m thick, underlie the area; most of the sediments were deposited within the last

62,000 years, during alternating glacial and non-glacial periods. Consequently, surficial geology strongly influences the occurrence of aquifers in the Lower Fraser Valley. Fluvial and glaciofluvial deposits comprise the principle unconfined aquifers in the study area while deeper glaciofluvial and marine deposits comprise confined aquifers, particularly in the western portion of the study area. Many communities, including Langley, Abbotsford, and Chilliwack, rely on groundwater as a source of drinking water supply. Groundwater is also used for irrigation, commercial bottling, and aquaculture. There are 193 community wells and thousands of domestic wells in the study area; most of the wells are completed into unconsolidated sediments. Some wells are completed into bedrock in the mountainous areas north of the Fraser River and in the Chilliwack area.

The 193 community wells and 75 domestic wells were part of a network of wells in a groundwater monitoring program conducted by the Province between 1992 and 1994 (Carmichael et al, 1995). The study wells are completed into 31 of 54 aquifers identified in the study area (17 unconfined, 12 confined, and 2 bedrock aquifers); the unconfined and bedrock aquifers are shown in Figure 1 (the confined aquifers are not shown to minimize clutter).

Land use in the study area is varied. There is a mixture of suburban and agricultural areas and some local industrial areas. Agricultural and rural residential areas dominate in the eastern part of the study area. Some of these activities have caused groundwater quality degradation locally (Carmichael et al, 1995; Liebscher et al, 1992).

2 Methods

The AVI and DRASTIC methods outlined in van Stempvoort et al (1992) and Aller et al (1987), respectively, were generally followed. In the AVI method, saturated hydraulic conductivity values (K_{sat}) were assigned to lithologic descriptions (Table 2) in the well records, even for unsaturated sediments above the aquifer or above the water table. These values are generally consistent with K-values used by Van Stempvoort et al (1992) which were based on typical values found in Freeze and Cherry (1979). The use of K_{sat} for unsaturated sediments should give more conservative hydraulic resistance values (higher vulnerability) and is considered a reasonable first approximation. Thickness of individual sedimentary layers was taken directly from the lithologic descriptions in well records.

AVI and DRASTIC indexes were calculated for wells completed into unconsolidated as well as bedrock aquifers. For unconsolidated aquifers, the AVI and DRASTIC indexes were calculated to the top of the aquifer tapped by the well, not necessarily the uppermost aquifer, as is normally the case. This is done so that the vulnerability indexes are calculated for the aquifers tapped by the sampled wells to allow comparison with water quality results. For bedrock aquifers, the AVI and DRASTIC indexes are calculated to the top of the bedrock surface or top of the water table, depending on the hydraulic condition at the well.

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

Hydraulic Conductivity * (K) Estimates for Various Sediments

Sediment Type **	(K) metres/day (approx.)
gravel	1000
sand and gravel, gravelly sand, sandy gravel, coarse sand	100
gravel, sand, and silt, medium sand, sand	10
fine sand, silty sand and gravel, very fine sand, silty sand	1
gravelly silt, sandy silt, silt, clayey gravel, clayey sand	0.1
clayey silt, gravel till, sandy till, fractured bedrock	0.001
clayey till, till, hardpan	0.00001
clay, gravelly clay, sandy clay, silty clay	0.000001

* (K) Saturated ** In reality, each of these sediment types has a range of values over several orders of magnitude; the values here are representative values.

With DRASTIC, individual ratings and total DRASTIC indexes were determined for each well location. The depth to water table (or top of aquifer) was determined directly from well records. Average net recharge was estimated for specific aquifers using recharge information in Table 9.2 of the *Groundwater Resources of British Columbia* (BC Environment, 1994). Recharge estimates for other aquifers were inferred from aquifers comprising similar deposits and in similar physical settings. Table 3 shows the estimated recharge values for all the aquifers tapped by the study wells. Aquifer recharge is assumed to be uniform for the whole aquifer. For wells not completed in any identified aquifers in Table 3, a rating for recharge of 9 was given for unconfined water-bearing zones and 6 for confined water-bearing zones for wells < 30m and 3 for confined water-bearing zones in wells > 30 m deep.

Table 3. Summary of recharge for aquifers in the study area and ratings for the DRASTIC method.

Aquifers	Assigned Recharge/Area (in/yr)	R, Recharge Rating	Rationale
Chilliwack-Rosedale	14	9	from BC Environment (1993)
Vedder River Fan	24	9	from BC Environment (1993)
Chilliwack River	26	9	from BC Environment (1993)
Lake Erroch/Derroche Creek	>10	9	
Nicomen Slough	>10	9	R/Area should be similar to Chawuthen, Chehalis and Chilliwack-Rosedale
Norrish Creek	>10	9	from BC Environment (1993)
Hatzic Prairie	>10	9	R/Area should be similar to Norrish Creek
Abbotsford-Sumas	22	9	from BC Environment (1993)
Mt. Lehman	>10	6	
Mission Floodplain	>10	9	R/Area should be similar to Chawuthen, Chehalis and Chilliwack-Rosedale
Mission		8?	
Grant Hill		8?	
Columbia Valley	>10	9	R/Area should be similar to Abbotsford-Sumas
Glen Valley	~10	~9	
Miracle Valley	3	3	R/Area should be similar to White Rock (very low)
Kanaka/Whonnock Creek	3?	3?	
Aldergrove	11	6	from BC Environment (1993) but averaged for a larger aquifer area
Beaver River	3	3	R/Area should be similar to White Rock (very low)
West of Aldergrove	3?	3?	
Hopington	8	8	from BC Environment (1993)
Fort Langley	12	9	from BC Environment (1993)
East Pitt River	>10	9	R/Area should be similar to Chawuthen, Chehalis and Chilliwack-Rosedale
Langley/Brookswood	22	9	from BC Environment (1993)
South of Hopington	3?	3?	
South of Murrayville	3	3	R/Area should be similar to White Rock (very low)
Langley Upland Inter-till	3?	3?	
Grandview	3	3	R/Area should be similar to White Rock (very low)
Nicomekl-Serpentine	3	3	R/Area should be similar to White Rock (very low)
Clayton Upland (Upper)	3?	3?	
Clayton Upland (Lower)	3	3	R/Area should be similar to White Rock (very low)
McMillan Island	>10	9	R/Area should be similar to Chawuthen, Chehalis and Chilliwack-Rosedale

Ratings for aquifer media and aquifer K-values were assigned based on lithologic descriptions from well records (Table 4). Where lithology is layered, an arithmetic average K-value was estimated. 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 (2 metre contours) mapping, respectively. In the 092H area, where soils mapping were not available, Armstrong's (1980) surficial geology map was used to infer the soils in that area (Table 5). For impact of the vadose zone, the equivalent saturated vertical K-value for each well was calculated (total depth to water table or top of aquifer divided by the sum of the hydraulic resistance of the individual sedimentary layers) instead of relying strictly on the lithologic description of sediments above the aquifer or above the water table. Ratings for impact of the vadose zone were then determined by relating the equivalent vertical K-value of the vadose zone to the equivalent lithologic descriptions in Table 6. Ratings for aquifer K-values were assigned using Table 7. Where the lithology is layered, the arithmetic average K-value was estimated.

Table 4. Aquifer media descriptions and ratings for the DRASTIC method.

Lithologic description	A Rating
Karstic limestone	10
Gravel	9
Sand and gravel, sandy gravel, sand, sand with clay balls/clay stringers	8
Silty sand and gravel, silty gravel, silty sand	7
Fine sand, limestone, sandstone	6
Clayey sand, sandy silt, loam	5
Silt, silty loam, silt and sand with clay	4
Clay loam, granite	3
Shale	2
Clay	1

Table 5. Soil descriptions and ratings for the DRASTIC method.

Soil name (and surficial geologic deposit)	Perviousness	S Rating
Coghlan, Harrison, Lehman, Sardis, (slope wash deposits, stream deposits, Abbotsford Outwash, Huntingdon Gravel and other Pre-Sumas Till fluvial deposits, exposed bedrock)	rapidly pervious	10
Columbia, Chehalis, Roach, (Fraser floodplain sand deposits, lacustrine sand deposits)	rapidly pervious	9
Buntzen, Bose, Cannel, Capilano, Defehr, Elk, Errock, Eunice, Grevell, Glen Valley, Heron, Isar, Judson, Lumbum, Lynden, Stave, Sunshine	rapidly pervious, rapidly to moderately pervious (Elk, Sunshine), moderately pervious (Glen Valley, Judson, Lumbum)	8
Keystone, Laxton	rapidly pervious	7
Monroe, Matsqui	rapidly to moderately pervious and moderately pervious (Monroe)	6
Abbotsford, Durieu, Hopedale, Lonzo Creek, McElvee, Marble Hill, Neaves, Peardonville, Page, Steelhead	moderately pervious, rapidly to moderately pervious (Hopedale), moderately pervious but slow in subsoil (Steelhead)	5
Bates, Fairfield, Nicholson, Milner, Ryder, (Fraser floodplain silt and clay deposits, lacustrine silt and clay deposits)	moderately pervious, moderately to slowly pervious (Milner)	4
Albion, Banford, Beharrel, Berry, Calkins, Carvolth, Ross, Scat, Whatcom, (Sumas Till)	moderately to slowly pervious, moderately pervious (Banford, Calkins), slowly pervious (Carvolth, Scat)	3

Table 6. Impact of vadose zone categories and ratings for the DRASTIC method.

Equivalent lithological description	log (K_z) (m/day)	I Rating
till, hardpan, clay	<-5	1
	-4	2
sandy till, clayey silt, bedrock	-3	3
	-2	4
silt, sandy silt	-1	5
fine sand, silty sand	0	6
medium sand, sand	1	7
sand and gravel, coarse sand	2	8
gravel	>3	9
no vadose zone		10

Table 7. Aquifer hydraulic conductivity categories and ratings for the DRASTIC method.

Typical lithological descriptions	K (m/day)	C Rating
Gravel, sand and gravel, gravelly sand, coarse sand	28->80	10
Packed sand and gravel, medium sand, sand	12-28	4
Fine sand, very fine sand	4-12	2
Silty sand, sandy silt, silt, bedrock	<4	1

3 Results and Discussions

AVI and DRASTIC indexes were calculated for 169 of the 253 study wells (103 community wells and 66 private wells). Vulnerability indexes could not be calculated for the other 84 wells (77 community wells and 7 private wells) due to lack of lithology in the well records. Vulnerability indexes for the 169 study wells are tabulated in Appendix B.

AVI values range from a low of -6[2] (extremely high vulnerability) to a high of 5.56 (extremely low vulnerability). DRASTIC indexes range from a high of 220 (highly vulnerable) to a low of 50 (low vulnerability). Histograms of AVI and DRASTIC indexes (Figures 2 and 3) show a bimodal distribution. Both AVI and DRASTIC indexes group into very high and high vulnerability (AVI values of <0 and DRASTIC indexes of >160) and low vulnerability (AVI values greater than 3 and DRASTIC indexes of <120) categories with very few indexes in the moderate vulnerability range. The bimodal nature of the DRASTIC histogram is less pronounced, because the combination of seven DRASTIC factors help dampen this. Rosen (1994) concluded that the fairly large number of parameters in DRASTIC tends to limit variability of the results. Both histograms show that high vulnerability is associated with unconfined conditions while low vulnerability is associated with mostly confined conditions[3]. The few wells associated with unconfined conditions having high AVI and low DRASTIC indexes are wells that encountered clay or till lenses <3 m thick. The presence of localized clay or till lenses significantly impacts on the vulnerability index calculation, causing the vulnerability to be under-estimated. AVI and DRASTIC indexes for most of the 11 bedrock wells in the study reflect mostly low to moderate vulnerability.

[2] AVI values of -6 were assigned where the hydraulic resistance, c, was zero (e.g., where depth to water was zero).

[3] Wells that have >3 m of likely low permeability sediments (e.g. clay, till) are designated as confined (even though they may be completed into an essentially unconfined aquifer). Wells that have <3 m of likely low permeability sediments are designated as unconfined; the likely low permeability sediments are interpreted as lenses and are assumed to be not areally extensive.

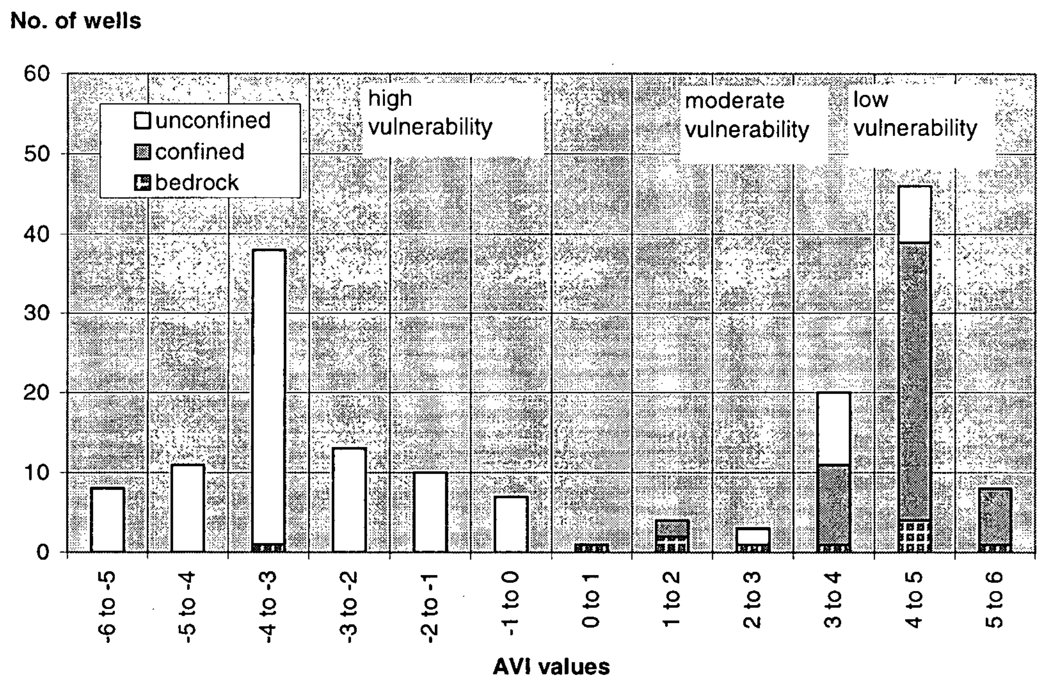

Figure 2. Histogram of AVI values for the study wells.

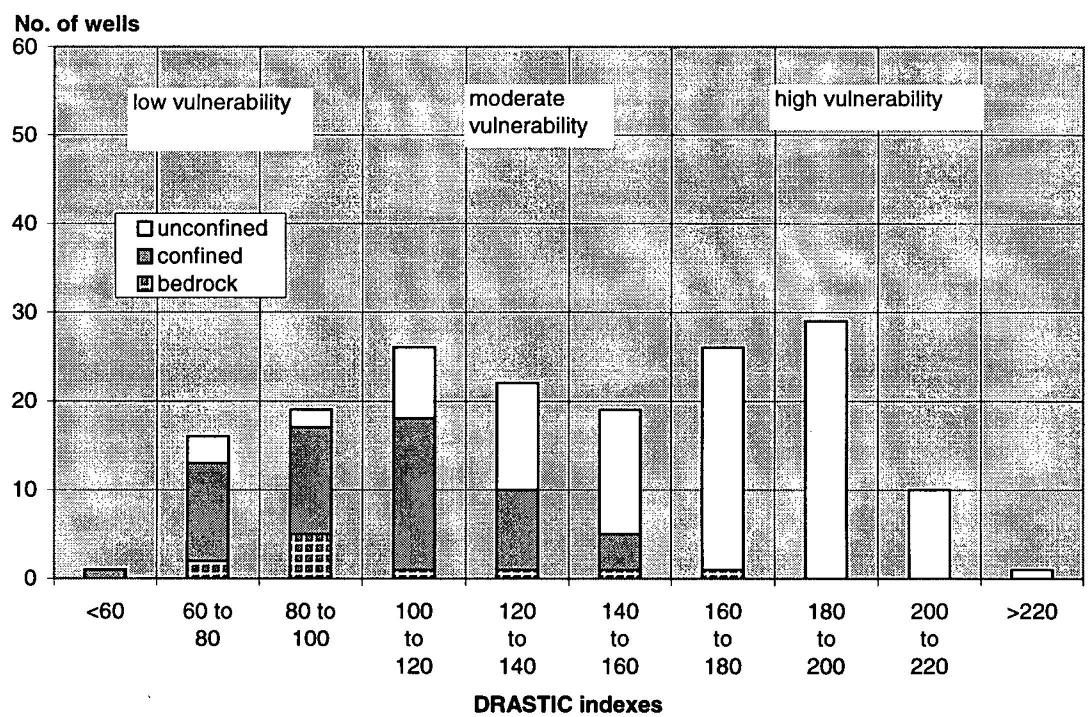

Figure 3. Histogram of DRASTIC indexes for the study wells.

A correlation analysis of the DRASTIC factors shows that there are six correlation coefficients of >0.4 (interpreted as fairly significant): Conductivity of the aquifer and Aquifer media, Conductivity and Topography, Aquifer media and Topography, Depth to water and Impact of vadose zone, Depth to water and recharge, and Impact of vadose zone and recharge (Figure 4). Conductivity of the aquifer and Aquifer media are essentially duplicate parameters. Conductivity is rated according to the estimated hydraulic conductivity of the aquifer and Aquifer media is rated according to the lithologic description of the aquifer, with the higher permeability sediments given higher ratings. Both Conductivity and Aquifer media correlate with topography because the highly productive aquifers in the Lower Fraser Valley generally occur in floodplains and outwash plains (e.g. Chilliwack River and Abbotsford-Sumas aquifers) while the generally less productive aquifers are located on steeper terrains associated with bedrock and glacial deposits (e.g. aquifers at Grant Hill, Mission, and Kanaka/Whonnock Creeks).

Depth to water table or aquifer correlate with Impact of vadose zone because, in the study area, many of the unconfined aquifers in the floodplain and outwash plains have shallow water tables and a correspondingly low hydraulic resistance. Depth to water and Impact of vadose zone are also correlated with recharge because unconfined aquifers are assumed to receive greater precipitation recharge than confined aquifers that have higher hydraulic resistance and generally greater depth to the aquifer.

Figure 4. Correlation analysis of the DRASTIC factors for the study wells.

	D	R	A	S	T	I	C
D	X						
R	+ **(r=0.45)**	X					
A	+ (r=0.14)	+ (r=0.12)	X				
S	+ (r=0.23)	+ (r=0.26)	- (r=-0.01)	X			
T	- (r=-0.23)	+ (r=0.10)	+ **(r=0.50)**	- (r=-0.004)	X		
I	+ **(r=0.48)**	+ **(r=0.49)**	+ (r=0.20)	+ (r=0.35)	+ (r=0.18)	X	
C	+ (r=0.26)	+ (r=0.25)	+ **(r=0.63)**	+ (r=0.11)	+ **(r=0.40)**	+ (0.31)	X

3.1 Comparing AVI and DRASTIC Indexes

Figure 5 shows a scatter plot of AVI versus DRASTIC indexes for the study wells. AVI and DRASTIC indexes appear consistent. In general, low AVI values correspond with high DRASTIC indexes (high vulnerability) while high AVI values correspond with low DRASTIC indexes (low vulnerability). DRASTIC indexes of >160 (high vulnerability) and <80 (low vulnerability) fall under the extremely high and extremely low to low vulnerability AVI categories, respectively. Despite the general consistency, however, DRASTIC indexes between 100 and 160 can span all five AVI vulnerability categories, suggesting that DRASTIC may not be as sensitive as AVI for indicating the pollution potential of aquifers in the moderate vulnerability range. Another possible explanation is that the hydraulic conductivity values assigned to the fine-textured sediments (e.g. clay, silt, till) may be too low (the assigned K_{sat} values for these sediments are typical textbook values), resulting in artificially high AVI values for confined conditions. Actual hydraulic conductivity measurements of fine-textured sediments from the Lower Fraser Valley are required to assess this. However, since K_{sat} values are lower than K_{unsat} values, the use of K_{sat} values for calculating resistance in the vadose zone may offset, at least partly, any effect caused by assignment of excessively low K-values.

Figure 5 also shows the bimodal distribution of the AVI and DRASTIC values. The lack of data points with AVI values of 0 to 3 may reflect the geology of the study area and the high permeability contrast of coarse and fine textured sediments in calculating the hydraulic resistance. The dashed lines in Figure 5 bound the region where AVI and DRASTIC values for the study area are likely to plot. AVI and DRASTIC values plotting outside of this region are likely not physically plausible and may be anomalous.

There are several wells drilled through unconfined materials that have anomalously high AVI and/or low DRASTIC indexes (low vulnerability). High AVI and/or low DRASTIC indexes for wells drilled through essentially unconfined sediments can largely be explained by the occurrence of till or clay lenses. For example, the high AVI value for well 80 is a due to the presence of a thin clay layer from 0 m to 2.4 m depth. This clay layer is likely not extensive because it is not encountered in wells 78 nor 79 nearby. The presence of a thin clay or till layer significantly raises the hydraulic resistance because of the low K-value assigned to these sediments. For example, a 0.3 m thick clay layer with a K-value of 10^{-6} m/day has a hydraulic resistance of 835 years (log c = 2.92). The presence of 0.3 m lens of clay in an otherwise clean sand and gravel aquifer would cause the AVI value at the well to increase from a negative value to 2.9, giving a false impression of low vulnerability. AVI values calculated from individual wells should, therefore, be interpreted with caution; AVI values from neighbouring wells should be considered in assessing the vulnerability in a local area. No wells drilled through confining sediments have AVI values of <1 or DRASTIC indexes of >160. This illustrates the effect of low-K lenses in increasing hydraulic resistance.

Two wells (48 and 49) are completed into sandstone bedrock of the Grant Hill aquifer. Their high AVI and low DRASTIC values are due to the low K-value assigned to the bedrock. In fractured bedrock aquifers in many parts of BC where the hydraulic conductivity of the bulk bedrock is relatively low, both the AVI and DRASTIC methods would calculate indexes that indicate relatively low vulnerability. However, groundwater in fractured bedrock aquifers may be easily contaminated because the lower effective fracture porosity in bedrock promotes greater advective transport velocities (v=Ki/n). Neither DRASTIC nor AVI directly considers the role of effective porosity on advective transport in assessing pollution potential of aquifers.

Both Rosen (1994) and Garrett et al (1989) believe that advective transport, in addition to hydraulic conductivity, is a major factor in determining aquifer vulnerability, especially for fractured bedrock aquifers. Since both AVI and DRASTIC do not directly consider this, the AVI and DRASTIC indexes calculated for bedrock wells that have little or no overburden protection (e.g. wells 4, 48, 49, and 189) is likely underestimating the vulnerability of the bedrock aquifer. AVI or DRASTIC values for fractured bedrock aquifers in BC should be interpreted with caution.

Eleven of the 169 wells in the study are completed into bedrock aquifers. AVI for seven of these wells (2, 18, 36, 37, 61, 70, and 186) were estimated simply by calculating the hydraulic resistance of the overburden sediments above bedrock because the static water levels in these wells were above the bedrock surface. This approach is the same as for surficial aquifers. If the overburden sediments above bedrock were permeable, a low AVI value would be calculated (e.g. well 18). If the overburden sediments were not permeable, a high AVI value would be calculated (e.g. wells 2, 36, 37, 61, 70, and 186). AVI for the remaining four wells (4, 48, 49, and 189) were estimated by calculating the hydraulic resistance to the water table in the bedrock because overburden thickness at these wells are non-existent. This involved estimating a K-value for fractured bedrock, which is not well known and likely highly variable. DRASTIC indexes for the bedrock wells were calculated in the usual way. Ratings for various bedrock types are defined in Aquifer media, Impact of vadose zone, Aquifer hydraulic conductivity. Although the bedrock wells plot within reasonable ranges of AVI and DRASTIC indexes in Figure 5, there are not enough bedrock wells in this study to adequately evaluate the suitability of AVI and DRASTIC for mapping vulnerability of fractured bedrock aquifers in BC.

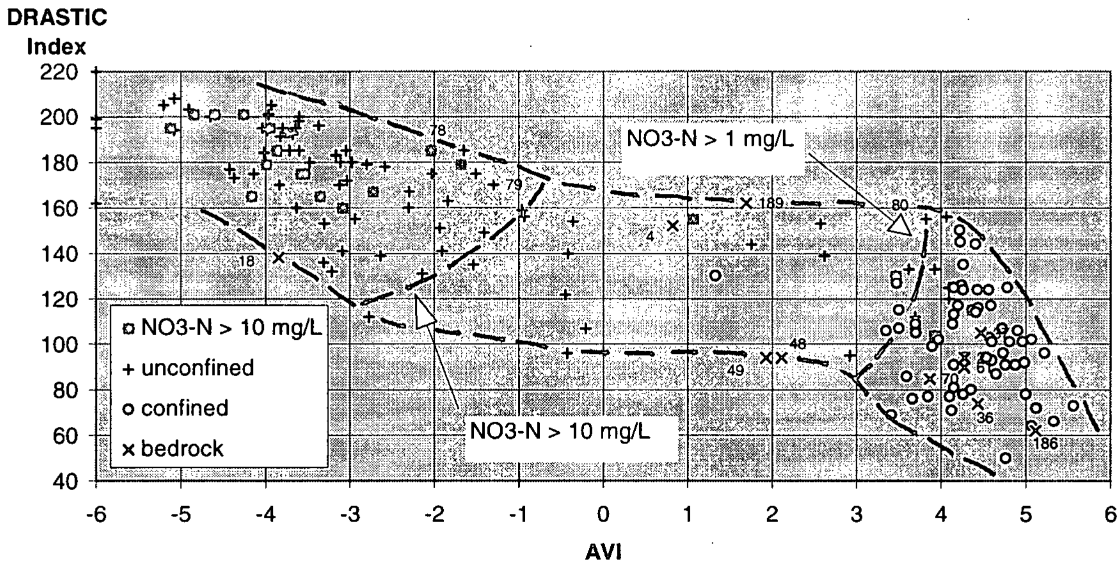

Figure 5. Scatter plot of AVI versus DRASTIC values for the study wells.

3.2 Comparing AVI and DRASTIC Indexes to Aquifer Classification

Carmichael et al (1995) correlated all the study wells to aquifers identified and classified by Kreye and Wei (1994)[4]. Box plots were constructed to compare AVI and DRASTIC indexes with Kreye and Wei (1994)'s aquifer vulnerability designation (Figures 6 and 7). The box plots show that there is a wide spread of AVI and DRASTIC indexes for each of the three vulnerability categories. The large spread may be explained by differences in vulnerability within a given aquifer and effects of local geology (presence of clay and till lenses in an unconfined aquifer and windows in a confined aquifer).

The median and average AVI and DRASTIC indexes show that vulnerability categories A and B are not very distinguishable but that there is a significant difference between categories A (and B) and C. The median AVI and DRASTIC indexes are -2.98 and 170, respectively for category A and 4.25 and 97.5, respectively for category C. The variability for category C seems to be less than for category A. The range of AVI and DRASTIC indexes between the 25th and 75th percentiles is 6.18 and 56.5, respectively for category A and only 1.5 and 29, respectively for category C. The greater variability for category A may, in part, reflect the dominant effect that low permeability lenses have on determining aquifer vulnerability.

[4] Aquifers were identified, delineated and subjectively classified according to level of use and vulnerability to contamination. Vulnerability is classified into three categories: A (high vulnerability), B (moderate vulnerability, and C (low vulnerability). For more information on the BC Aquifer Classification System, refer to Kreye et al (1996).

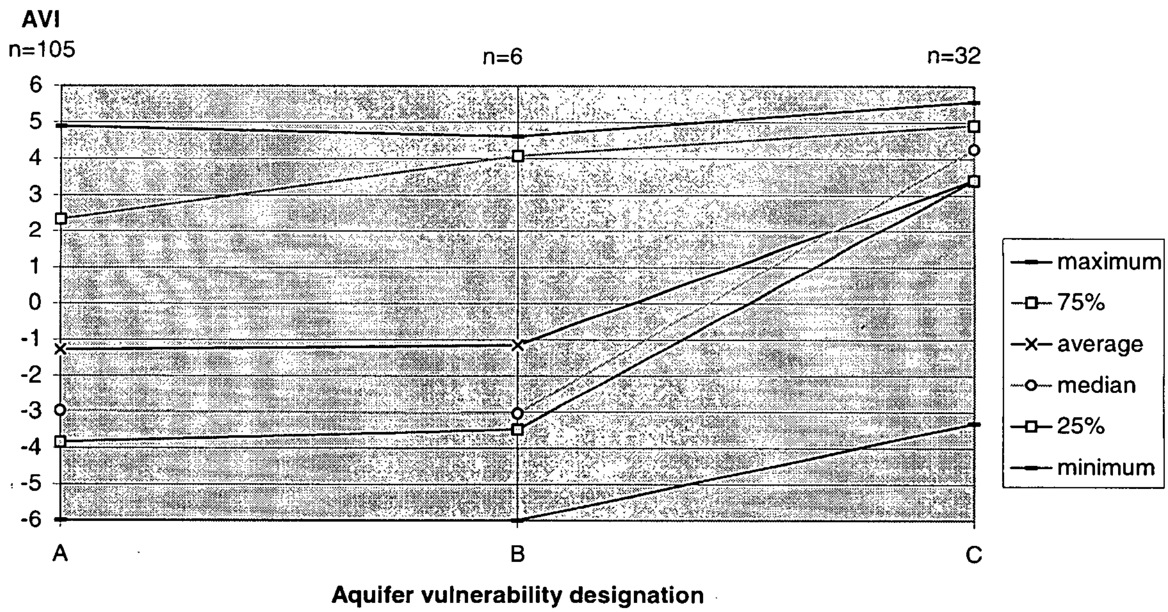

Figure 6. Box plot of AVI values for each aquifer vulnerability classification designation.

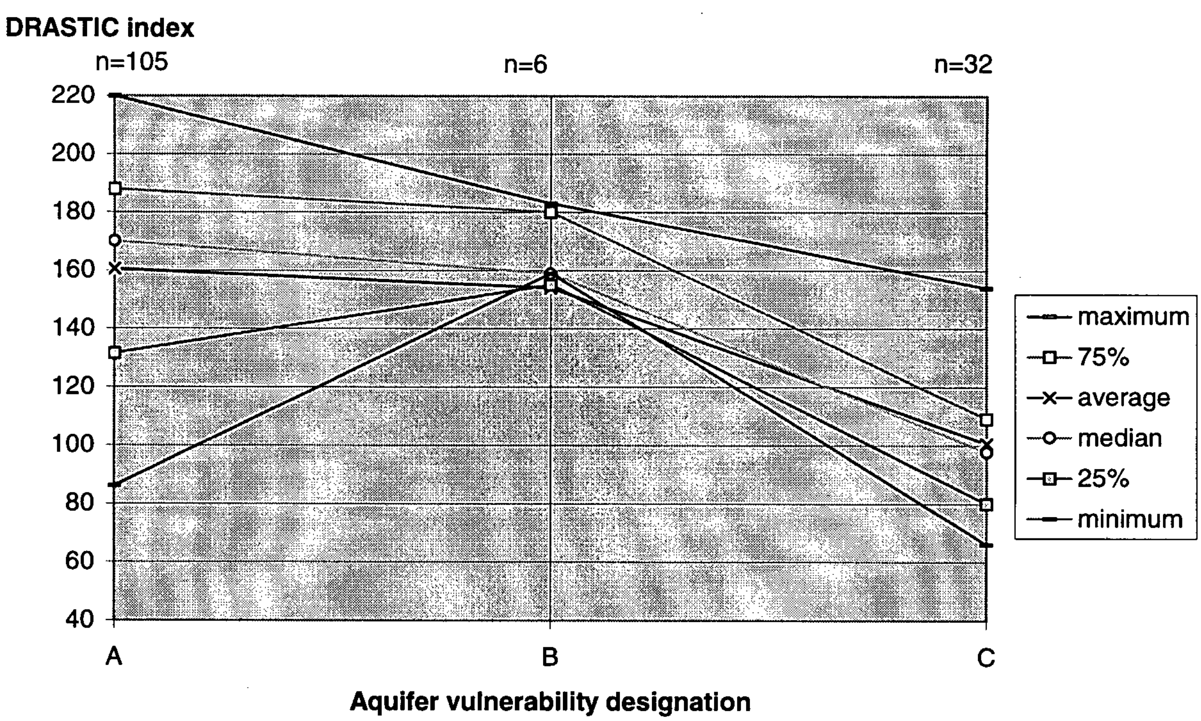

Figure 7. Box plot of DRASTIC indexes for each aquifer vulnerability classification designation.

3.3 Comparing AVI and DRASTIC Indexes to Water Quality

While DRASTIC and AVI have been applied to map the aquifer vulnerability elsewhere in North America and Europe, few studies have been done to validate how well these methods predict pollution potential and correlate with actual water quality impacts from human activities. Results of these few studies (e.g., Kalinski et al (1994) and Garrett et al (1989)) appear contradictory.

Garrett et al (1989) compared the number of contaminated sites for gasoline, other hydrocarbons, and salt piles with the DRASTIC index for the sites in Maine and found that contaminated sites occurred in wide ranging areas of DRASTIC indexes. Possible reasons for why the correlation was so poor include: 1) in Maine, deep water tables are associated with permeable soils and a high Aquifer media and Conductivity rating assigned for aquifers is countered by a low Depth to water table rating, resulting in a somewhat lower DRASTIC index, 2) the vulnerability of fractured bedrock aquifers as a result of high velocity advective flow through fractures which is not directly considered in DRASTIC, and 3) location of a site with respect to the aquifer's recharge and discharge areas is also not directly considered in DRASTIC. Kalinski et al (1994) compared the frequency of VOC in municipal wells in Nebraska with the DRASTIC index at each well site and found that the frequency of VOC detection in municipal wells increases with increasing DRASTIC index.

A comprehensive water quality survey of community wells and selected private wells in the Lower Fraser Valley between 1992 and 1994 (Carmichael et al, 1995) shows that the main groundwater contamination concern is nitrate and isolated detections of organic compounds[5] in unconfined aquifers. Other water quality exceedences, such as arsenic, fluoride, sodium, iron, and manganese appear to be naturally occurring. Nitrate, in particular, may be useful in assessing DRASTIC and AVI's suitability for predicting pollution potential because elevated concentrations of nitrate are typically caused by human activities in the study area. Nitrate is also relatively common compared to the frequency of detection of other constituents such as pesticides and VOCs and was sampled for in all the study wells.

Figures 8 and 9 show that a significant percentage of wells (>40%) with AVI values <-2 and DRASTIC indexes >160 (high vulnerability) have elevated nitrate values (NO_3-N > 3 mg/L). These results are consistent with Kalinski et al (1994). Most of the wells that had elevated nitrate are wells completed into aquifers with no confining layers; none were completed into bedrock. Elevated nitrates occur in some wells with AVI values >1 and DRASTIC indexes <160 (moderate to low vulnerability). However, these wells (77, 112, 208, 241, 249, and 255) are all completed into essentially unconfined aquifers (the Abbotsford-Sumas and Hopington aquifers) but encountered clay or till lenses or a deep water table (wells 112 and 255). The clay or till lenses at wells 77, 241, and 249 are local in extent because they are not reported in the logs of other study wells nearby. All elevated nitrates occur in aquifers designated as highly vulnerable "A" aquifers by Kreye and Wei (1994); no elevated nitrate levels occur in aquifers designated as moderate "B" or low "C" vulnerability.

[5] Organic compounds include pesticides, VOCs, and other organic compounds such as trichloroethane, xylene and carbon tetrachloride.

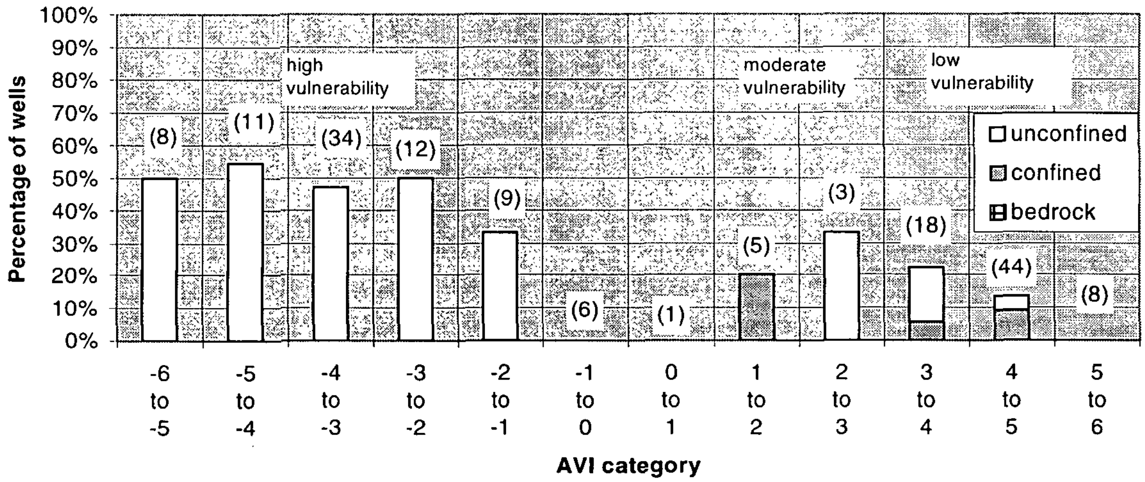

Figure 8. Percentage of study wells with NO3-N >3 mg/L per AVI category (number of wells in brackets).

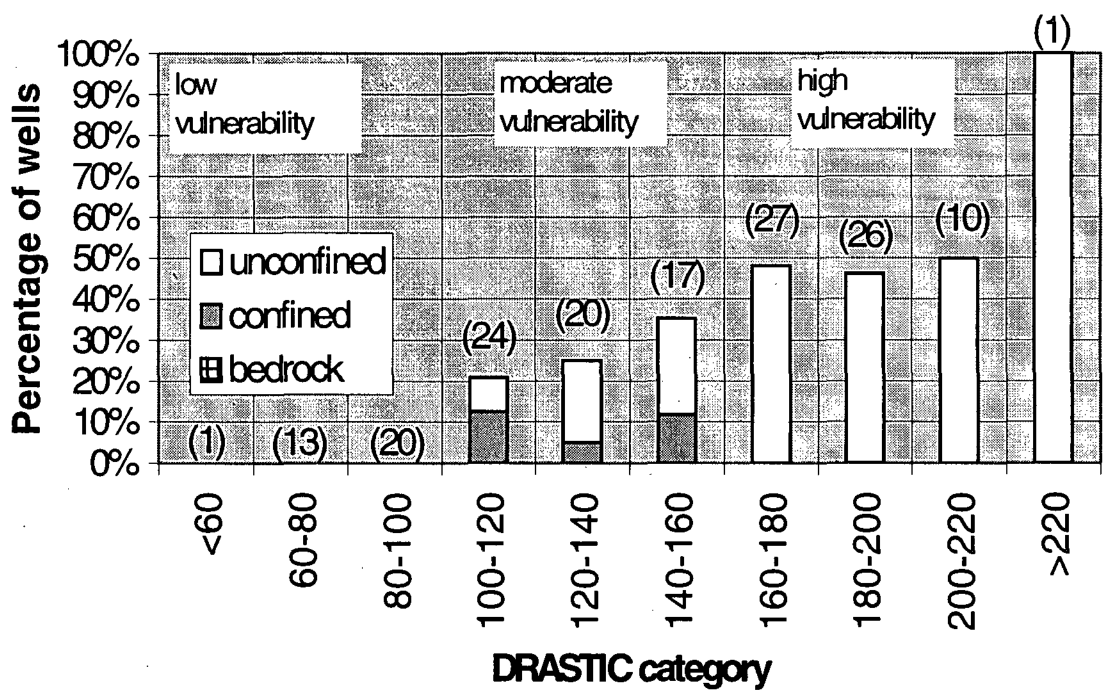

Figure 9. Percentage of study wells with NO3-N > 3 mg/L per DRASTIC category (number of wells in brackets).

One notable difference between AVI and DRASTIC results is that no elevated nitrates occur in wells with very low DRASTIC values (Figure 9) but elevated nitrates do occur in some wells with high AVI values (Figure 8). Again, the high AVI for wells with elevated nitrates is due mainly to the presence of fine-grained lenses, which causes anomalously high AVI values to be calculated. On the other hand, the DRASTIC index for the same wells is calculated based not only on well-specific information (e.g., Depth to water, Aquifer media, Impact of vadose zone, and aquifer hydraulic Conductivity) but also on other information that are taken from larger areas (e.g., Recharge, Soil media, and Topography). In DRASTIC, well-specific information has relatively less weight than in AVI and the combination of well-specific and local information for calculating DRASTIC may have resulted in fewer anomalous results.

Figure 10 shows nitrate-nitrogen concentrations plotted against AVI values. In general, higher nitrate concentrations appear to occur at AVI values of <-1. The empirical dashed line bounds the range of expected nitrate concentrations for any given AVI value in the study area. For example, where the AVI value is -2, the nitrate-nitrogen concentration may be expected to range up to 25-30 mg/L, depending on the specific land use activity. Where the AVI value is 2, the nitrate-nitrogen is expected to range up to no more than about 1-2 mg/L. The dashed lines suggest that nitrate exceedences would occur only in areas where AVI values are <-1. Figure 10 also shows that wells drilled through confined conditions have high AVI values and low nitrate-nitrogen concentrations.

The regions outside of the dashed lines represent the regions where nitrate-nitrogen concentrations are not expected. Nitrate-nitrogen concentrations for the study wells plotting in these regions may be explained by the presence of clay and till lenses reported in the well log. For example well 77, 80, 241, and 249 all encountered a clay or till lens which would result in a higher AVI value being calculated. Misidentification in logging the lithology during drilling can also lead to anomalous results. For example if a "silt" was described as a "clay" by the driller, a hydraulic conductivity of 0.000001 m/d instead of 0.1 m/d would be assigned for calculating the AVI value. This difference amounts to increasing the overall AVI value by 3.44 for 1 metre of silt.

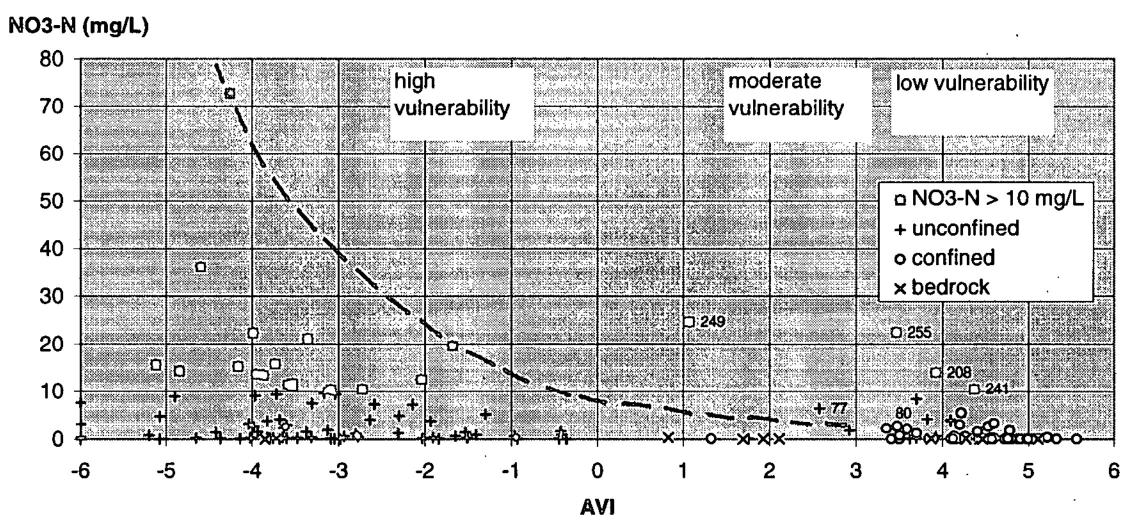

Figure 10. Plot of NO3-N versus AVI values.

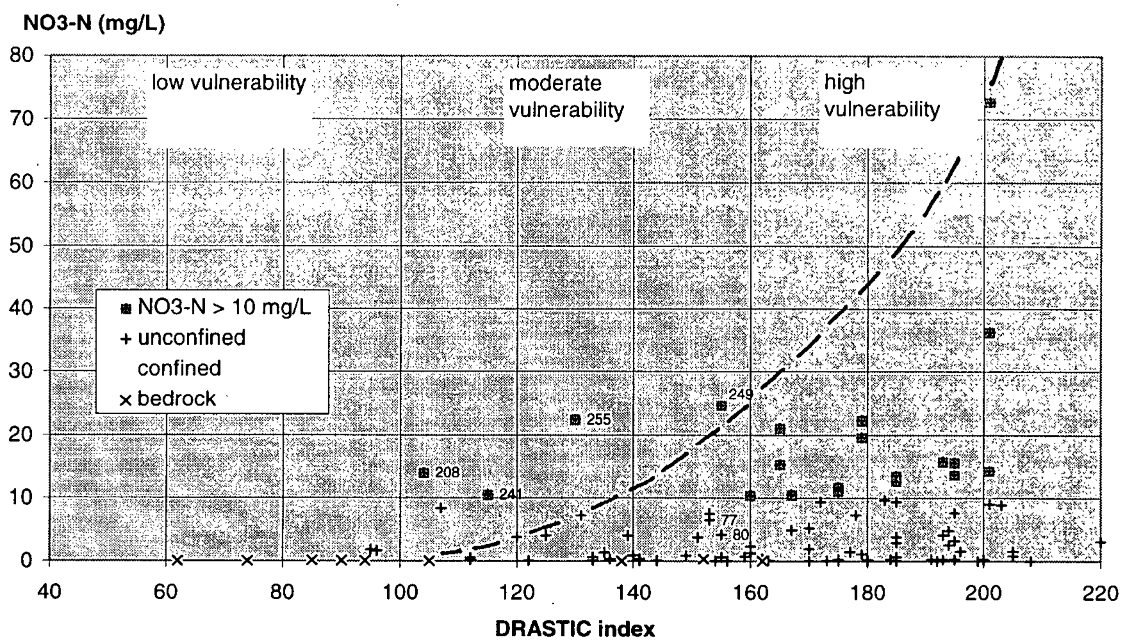

Figure 11. Plot of NO3-N versus DRASTIC indexes.

Nitrate-nitrogen concentrations were also plotted against DRASTIC indexes (Figure 11) which show a similar pattern. The higher the DRASTIC index, the higher the range of nitrate concentration can be expected. The dashed line also suggests that nitrate exceedences would occur only in areas where DRASTIC indexes exceed about 130. Wells drilled through confined conditions are generally associated with lower DRASTIC indexes and low nitrate-nitrogen concentrations. The data points above the empirical dashed line can be explained as for the anomalies in Figure 10.

Figures 10 and 11 suggest that regions of maximum expected nitrate-nitrogen concentrations can be outlined empirically for the study area in Figure 5. The upper range of nitrate-nitrogen concentrations is expected to increase from high AVI and low DRASTIC indexes (from the lower right hand side of Figure 5) to low AVI and high DRASTIC indexes (to the upper left hand corner of Figure 5). The dashed lines mark regions of expected upper limits of nitrate-nitrogen concentrations in the study area. For example, nitrate-nitrogen concentrations of greater than about 1 mg/L is not expected for the region on the right side of the graph where AVI values are greater than 3 or 4. Finally, it is important to stress that Figures 5, 10, and 11 are based on results specific to the Lower Fraser Valley. Data in other areas need to be assessed to see if the trends observed here can be used in other areas.

3.4 Uses of AVI and DRASTIC Indexes for Community Well Protection

AVI and DRASTIC indexes for the community wells in the study (wells 1 to 192b and well 266) can be used in a variety of ways for protecting the community well supply. Firstly, AVI and DRASTIC indexes provide an indication of the vulnerability of the source aquifer to pollution from human activities in the local area around the well. This information can be used, along with other information such as the well construction, local geology, water use, knowledge of historic water quality concerns, and land-use activities, in assessing the likelihood of pollution at the well and immediate area. This type of well assessment can assist in developing a groundwater protection plan for a local area.

The AVI and DRASTIC indexes can also be used by the local health authority to assist in setting operational priorities in managing and monitoring these community well systems. For example, the frequency of water quality sampling and suite of chemical analysis need not be the same for all community wells in the Lower Fraser Valley. AVI and DRASTIC indexes can be used as a factor to prioritize community wells and identify those wells in high vulnerability areas for more comprehensive sampling and monitoring.

The concept of aquifer vulnerability, as reflected in the AVI and DRASTIC indexes, can be communicated to water purveyors and customers to raise awareness about the relative vulnerability of their aquifer and the need to protect their well supply. Both AVI and DRASTIC have a simple numerical rating scheme which the public can readily understand.

Finally, the AVI and DRASTIC indexes for the wells can be compiled, along with indexes for private wells, to construct an aquifer vulnerability map for the area. Such a map can be used for planning land use and raising public awareness about the vulnerability of the various aquifers in the Lower Fraser Valley.

4 Conclusions and Recommendations

AVI and DRASTIC indexes were calculated for 169 wells in the study area of the Lower Fraser Valley. Results show that vulnerability indexes are clustered around low vulnerability and high vulnerability with very few in the moderate vulnerability range. Both AVI and DRASTIC gave consistent results. Generally, the higher the DRASTIC index, the lower the AVI value and the higher the vulnerability.

Both AVI and DRASTIC appear adequate for correlating vulnerability of surficial aquifers to nitrate contamination in the Lower Fraser Valley. The majority of elevated nitrates occur in study wells that have low AVI and high DRASTIC indexes (high vulnerability). Examination of nitrate results in the study indicate that nitrate-nitrogen concentrations are not expected to reach beyond about 1 mg/L in the Lower Fraser Valley where AVI values are 3 to 4. Nitrate exceeding the drinking water guidelines could occur in the Lower Fraser Valley (depending on land use activities) where AVI values are <-1 and DRASTIC values are greater than 130.

Presence of fine-grained lenses at a particular well can cause anomalously high AVI results to be calculated. Interpretation on pollution potential should, therefore, not be made based on the AVI index calculated for a single well but together with other wells in the local area. A key to using aquifer vulnerability to assess pollution potential is having good quality well records. Accurate locations and proper lithologic descriptions allow well records to be more effectively used in estimating pollution potential and in aquifer assessments.

Both AVI and DRASTIC appear suitable for predicting pollution potential for unconsolidated aquifers in southwestern BC. The choice of which method to use for aquifer vulnerability mapping may depend, in the end, on additional factors such as ease of use (AVI is less subjective than DRASTIC) and on the information available (e.g., soils mapping, recharge estimates, etc.).

The suitability of AVI and DRASTIC for mapping vulnerability of fractured bedrock aquifers needs to be further evaluated. Areas of contrasting bedrock types and overburden thicknesses need to be examined. The suitability of AVI and DRASTIC for fractured bedrock terrains may be significantly enhanced if advective velocity was considered in the methods. One possibility may be to modify the hydraulic resistance in AVI and incorporate an effective porosity term to account for flow velocity (Equation 3).

$$\text{effective resistance, } c_v = \sum d_i * n_i / K_i \text{, for layers 1 to i} \qquad (3)$$

However, fractured bedrock presents unique challenges. Hydraulic conductivity values for fractured bedrock are not well defined nor widely available. Furthermore, effective porosity is also very hard to estimate. Until this data becomes widely available, it may be necessary to rely on the subjective vulnerability designation of bedrock aquifers through the BC Aquifer Classification System (Kreye et al, 1996) or use other methods that rely on more easily measurable parameters as surrogates.

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

Method / Reference	Description	Advantages / Disadvantages
Tesoriero and Voss (1997)	Use logistic regression to relate the occurrence of nitrate concentrations to natural and land use variables to determine the probability of occurrence of elevated nitrates at any given location.	Advantages: • probabilistic approach • based on actual nitrate occurrence and land use Disadvantages: • requires a large number of water quality data which is not always available • suitability for use at larger scale needs to be evaluated
Bengtsson and Rosen (1995)	Calculate (using a probabilistic approach) and map (on separate maps) the retention times in the unsaturated (t=d*q/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 (e.g. hydraulic gradient (i), hydraulic conductivity (K), effective porosity (n), recharge (R), and field capacity (q) not readily available and often need to be estimated
BC Aquifer Classification System (Kreye et al, 1996)	Subjectively categorize aquifer vulnerability based on an assessment of depth to water table, aquifer permeability, 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
Aquifer Vulnerability Index (AVI) (Van Stempvoort et al, 1993)	Calculate the hydraulic resistance ($c=\Sigma(d/K)$ above the aquifer, from well records, and delineate areas of equal resistance. Vulnerability is indicated by the hydraulic resistance (c); the lower the resistance, the higher the vulnerability.	Advantages: • based on actual well records • hydraulic resistance is a physical parameter • objective, easy to apply, and results are reproducible Disadvantages: • hydraulic conductivity values (K) needed to calculate hydraulic resistance not readily available and often need to be estimated
Adams and Foster (1992)	Categorize vulnerability based on aquifer permeability (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 use in other geologic terrains

Appendix A. 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 pesticides leaching using four 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 use in other geologic terrains and for other contaminants
Regina Aquifers Sensitivity Mapping (Roeper, 1990)	Delineate vulnerability areas 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 apply Disadvantages: • developed for a specific area and need to be evaluated for use in 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, need to be evaluated for use in other geologic terrains

Appendix A. 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: o considers a comprehensive suite of physical factors o method is widely used in North America o can be applied to evaluate vulnerability to pesticides o applicable for all geologic terrains in North America Disadvantages: o the pollution index is physically dimensionless o subjective o information for some of the factors such as recharge and hydraulic conductivity are not readily available and often need to be estimated
Haertle (1983)	Categorize vulnerability based on depth to water table (0-1m, >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 to water table and permeability result in 3 categories of vulnerability: high, medium, and low.	Advantages: o takes into account multi-layered geology o required data available from well records Disadvantages: o does not consider bedrock o developed for a specific area and need to be evaluated for use in 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: o easy to apply o required data available from water well records o considers fractured bedrock Disadvantages: o developed for a specific area and need to be evaluated for use in 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.	Advantages: o based on actual well records o easy to apply Disadvantages: o developed for a specific area and need to be evaluated for use in other geologic terrains

Appendix B. AVI and DRASTIC Values for the Study Wells.

Well No.	Aquifer No.	Aquifer Vulnerability Classification	Confined / Unconfined	AVI	Comments	D	R	A	S	T	I	C	DRASTIC
1	11	A	Unconfined	-3.601	WT near GL but well screened @ 82-92'	10	9	8	10	5	7	10	200
2	18	A	Confined	4.276	AVI calculated for OB only; assume swl @ top of bedrock	7	8	2	4	5	1	1	94
3	11	A	Unconfined	3.697	Aquifer interpreted to be sand @ 78-80'; top 19' of sand assumed to be dry at well site	2	9	8	8	9	1	4	112
4	N/A		Unconfined	0.825	Assume no resistance in 10' overburden above bedrock	7	8	3	10	3	10	1	152
18	N/A		Unconfined	-3.848	AVI calculated for overburden above bedrock	7	8	3	9	1	8	1	138
20	N/A		Confined	3.503		3	3	8	8	5	1	10	107
21	14	A	Unconfined	-5.203		9	9	8	8	9	9	10	205
25	N/A, 18?		Confined	3.846	AVI calculated for till to 84'	2	8	3	9	5		1	77
26	25	C	Confined	5.221		1	3	8	5	10	1	10	96
29	N/A		Confined	4.767		1	3	6	3	1	1	1	50
33	N/A		Confined	3.502		5	3	6	8	9	1	10	115
36	N/A		Confined	4.435	AVI calculated for overburden above bedrock	1	8	6	3	5	1	1	74
37	18	A	Confined	4.468	AVI calculated for overburden above bedrock	1	8	4	7	9	6	1	105
42	26	C	Confined	4.264	Well completed opposite thin sand layer at 107'-110'	5	3	5	3	9	1	2	78
45	26	C	Confined	4.102		5	3	6	3	5	1	2	77
48	19	A	Unconfined	2.109		1	8	6	8	5	3	1	94
49	19	A	Unconfined	1.926		1	8	6	8	5	3	1	94
54	19	A			Can't calculate AVI nor DRASTIC due to lack of lithology		8	2	7	9		1	
57	N/A		Confined	4.651		1	3	8	3	5	1	10	87
58	26	C	Confined	3.899	Well completed at 110'-120'	5	3	8	3	9	1	6	99
59	26	C	Confined	1.326	Confining layers from 0'-61' interpreted to be gravelly till	3	3	6	8	9	6	10	130
61	19	A	Confined	4.274	AVI calculated for overburden above bedrock; AVI higher than for wells 48 & 49 due to 55' of overburden	3	8	6	8	1	1	1	90
66	N/A		Confined	4.535		3	3	8	8	10	1	4	94
67	N/A		Unconfined	-0.932	Well screened from 95'-99'	7	9	7	3	3	5	10	156
68	26	C	Confined	4.152		5	3	7	3	9	1	1	81
70	N/A		Confined	3.869	Top of bedrock aquifer assumed to be depth to bedrock	3	8	3	8	5	1	1	85
71	N/A		Confined	5.067		1	3	5	8	5	1	2	64
76	15	A	Unconfined	-5.078		9	9	9	5	1	9	10	194
77	15	A	Unconfined	2.575	Well logs for wells 76 & 77 (adjacent wells) are similar; higher AVI for well 77 due to till layer @ 0'-4.5'	9	9	8	5	3	1	10	153

Appendix B. AVI and DRASTIC Values for the Study Wells (continued).

Well No.	Aquifer No.	Aquifer Vulnerability Classification	Confined / Unconfined	AVI	Comments	D	R	A	S	T	I	C	DRASTIC
78	15	A	Unconfined	-2.041		9	9	8	5	10	6	10	185
79	15	A	Unconfined	-1.299		7	9	8	5	10	5	10	170
80	15	A	Unconfined	3.825	High AVI but completed in hghly vulnerable aquifer with NO3-N=4.19 mg/L; clay layer not likely extensive as wells 78 & 79 have low AVI numbers	9	9	8	5	5	1	10	155
81	15	A	Unconfined	-4.018	Although AVI number is low, well screen is at 99-109', below silt layer (60-70.5')	7	9	8	5	9	8	10	184
82	15	A	Unconfined	-2.8		7	9	8	5	9	7	10	179
83	15	A	Unconfined	2.621	High AVI due to clay @ 44'-49'	3	9	8	7	10	2	10	139
84b	N/A		Unconfined		Can't calculate AVI nor DRASTIC, can't assume overburden lithology		8	2	5	1		1	
87	15	A	Unconfined	3.621	High AVI due to clay @ 33'-38'	3	9	9	5	10	1	10	133
88	15	A	Unconfined	-2.307	Note that the duplicate log would give a much higher AVI number because of the description of "till" @ 15-42.5'	3	9	8	5	10	7	10	160
89	15	A		3.478	High AVI due to till @ 29'-water table	3	9	7	5	10	1	10	127
90	15	A	Unconfined	-3.717		7	9	8	5	10	8	10	185
91	15	A	Unconfined	-3.948		9	9	8	5	10	8	10	195
92	15	A	Unconfined	-4.425		5	9	7	5	10	9	10	177
93	15	A	Unconfined	-4.371		3	9	9	5	10	9	10	173
94	15	A	Unconfined	-0.415		3	9	8	5	10	3	10	140
95	15	A	Confined	4.785	Completed below Abbotsford-Sumas Aquifer (in Aldergrove Aquifer?)? Located @ NW edge of A-S aquifer	2	9	8	5	10	1	10	125
96	27	C	Confined	4.907	AVI calculated to likely uppermost WB zone; well screen @ depth	1	6	8	4	10	1	10	106
98	27	C			Can't calculate AVI nor DRASTIC due to lack of lithology & can't assume sand & gravel here as geology is heterogeneous		6		3	10			
99	N/A		Confined	4.413		5	6	8	3	9	1	7	114
100	52	C	Unconfined	3.971	Well completed into Langley Upland/Intertill aquifer (aq. no. 52)	9	9	8	8	10	8	10	102
102	35	A	Unconfined	-1.41		1	8	8	9	10	6	10	149
103	33	C	Unconfined	-3.315	Well completed into underlying West of Aldergrove aquifer	3	8	7	5	9	8	3	136

Appendix B. AVI and DRASTIC Values for the Study Wells (continued).

Well No.	Aquifer No.	Aquifer Vulnerability Classification	Confined / Unconfined	AVI	Comments	D	R	A	S	T	I	C	DRASTIC
104	N/A		Confined	5.287		1	3	7	4	10	1	4	73
105	33	C	Unconfined	4.407	AVI & DRASTIC for this well location is for the West of Aldergrove aquifer	2	8	8	9	10	8	10	144
106	15	A	Unconfined	-1.841	Check KRonneseth's AVI number for this well; AVI & DRASTIC calculated to uppermost aquifer, well tapping sand & gravel beneath blue clay @ 48-79', hence low NO3-N (0.06 mg/L)	5	9	7	9	3	6	10	163
107	41	A	Unconfined	-6	AVI undefined; zero resistance	10	9	8	9	9	10	4	199
108a	55	C	Unconfined	3.662	Well completed into Grandview aquifer (aq. no. 55)	9	9	8	9	9	8	10	76
108b	55	C	Unconfined	-0.427	Well completed into Grandview aquifer (aq. no. 55)	7	9	8	9	9	8	10	96
110	41	A	Unconfined	-3.981		9	9	8	9	10	8	7	194
111b	35	A	Unconfined	-1.909		2	8	8	9	10	7	4	141
112	35	A	Unconfined	-3.216		2	8	8	5	10	8	2	132
113	33	C	Unconfined	-3.087		2	3	7	9	10	8	10	141
115	35	A	Unconfined	-0.446		1	8	7	9	9	5	4	122
119	35	A	Confined	4.139	Well is completed into the southern, confined part of the Hopington aquifer	2	8	8	8	10	1	4	109
120	35	A	Confined	3.702	Well completed in the southern, confined part of the Hopington aquifer	2	8	6	9	10	1	4	105
122	50	C	Confined	4.244		3	6	8	9	10	1	10	126
123	72	A	Unconfined	-3.835		7	9	7	8	10	8	4	170
124	N/A		Unconfined	4.098	Completed into the Abbotsford-Sumas aquifer?	5	9	8	9	5	1	4	125
127	35	A	Unconfined	-3.631		7	8	8	4	9	8	4	160
129	32	C			Can't calculate AVI nor DRASTIC due to lack of lithology; AVI likely high & DRASTIC likely low		3	8	9	9			
132	33	C	Unconfined	4.961	AVI & DRASTIC calculated for the deeper, confined West of Aldergrove aquifer	9	8	8	8	9	6	4	101
134	35	A	Confined	4.879	Well completed in the southern confined part of the Hopington aquifer	1	8	7	3	10	1	4	91

Appendix B. AVI and DRASTIC Values for the Study Wells (continued).

Well No.	Aquifer No.	Aquifer Vulnerability Classification	Confined / Unconfined	AVI	Comments	D	R	A	S	T	I	C	DRASTIC
135	58	C	Confined	5.563		1	3	7	4	10	1	4	73
136	N/A		Confined	4.264	High AVI due to clay at 0'-22'	7	9	7	4	10	1	3	124
138	35	A	Confined	4.565	Located in the confined western part of the Hopington aquifer	5	8	7	3	5	1	10	124
139	59	C	Confined	4.575		1	3	8	3	5	9	2	103
140	58	C	Confined	5.121	AVI & DRASTIC are calculated for the deeper, confined Nicomekl-Serpentine aquifer	7	9	7	5	10	1	10	72
141	36	A	Confined	4.223	The high AVI value is due to the clay from 0'-20'	7	9	8	5	10	1	10	150
142	41	A	Unconfined	-3.608	Well screen at 52'-72.3'	9	9	8	9	10	7	10	198
146	41	A	Unconfined	-3.794	Well is completed deep into Langley/Brookswood aquifer at 153'-190'	7	9	8	10	10	8	10	195
147	41	A	Unconfined	-1.647	Well is completed deep into Langley/Brookswood aquifer at 122'-139'	7	9	8	10	10	6	10	185
148	33	C	Confined	4.808	Hopington aquifer seems absent at this site	2	3	8	5	10	1	10	101
150	33	C	Confined	3.411	Assume top of medium sand at 172' is top of aquifer; sand and gravel at 0'-44' assumed dry (SWL=60'-may need to check records in area to verify)	3	3	5	9	1	1	1	69
151	N/A		Confined	4.999	Assume sand from 0'-69' is dry (SWL=150'-may need to check records in area to verify)	1	3	8	5	10	1	4	78
153	32	C	Unconfined	4.353	Well is completed into the Beaver River aquifer	7	8	8	9	10	8	10	80
155	27	C	Confined	4.283		5	6	7	3	10	1	1	94
156	27	C	Confined	4.428		5	6	8	3	10	1	10	124
157	27	C	Unconfined	-0.361	Well record needs to be revised; top of aquifer is 72', not 40'	5	6	8	8	10	5	10	154
158	58	C	Confined	5.331	Well completed into Nicomekl-Serpentine aquifer	2	3	7	3	5	1	4	66
159	51	C	Confined	4.986	AVI calculated for uppermost WB zone; well screened @ 326-380'	1	3	8	3	10	1	10	92
160	35	A	Confined	4.59	Aquifer at 153', not 91' where sand is 2' thick. Completed in western confined part of Hopington aquifer	2	8	8	3	10	1	10	117
161	8	A	Unconfined	-4.652		7	9	8	10	10	9	10	200
162	8	A	Unconfined	-3.647		7	9	8	10	10	8	10	195

Appendix B. AVI and DRASTIC Values for the Study Wells (continued).

Well No.	Aquifer No.	Aquifer Vulnerability Classification	Confined / Unconfined	AVI	Comments	D	R	A	S	T	I	C	DRASTIC
163	8	A	Unconfined	-1.51	WT is shallow but well is screened @ 89-112'	5	9	8	10	10	6	10	175
164	6	A	Unconfined	-1.534	Assume shale is shaley gravel	5	9	7	8	9	5	1	135
165	6	A	Unconfined	-3.932		9	9	8	10	10	8	10	205
168	6	A	Unconfined	-5.078		9	9	8	9	10	9	10	208
171	9	A	Unconfined	-6	AVI undefined; zero resistance	10	9	8	10	10	10	10	220
177	9	A	Unconfined	-2.029	WT shallow but screen is @ 134.3-145'	5	9	8	10	10	6	10	175
179	20	B	Unconfined	-6	WT @ GL therefore aquifer is vulnerable but well is screened @ 80-84' & below CLAY @ 58-64'	10	9	7	8	9		10	162
180	9	A	Unconfined	-4.141		2	9	8	10	10	9	10	175
183	N/A		Confined	4.761		1	3	8	3	9	1	10	91
186	N/A		Confined	5.113	Top of aquifer taken as depth to bedrock	1	8	2	3	5	1	1	62
189	N/A		Unconfined	1.693		10	8	2	10	1	10	1	162
190	6	A	Unconfined	-0.962	The moderate vulnerability of this site may reflect the gravel w clay layer @ 15'-28'	3	9	8	10	9	5	10	159
191	6	A	Unconfined	-2.777	SWL interpreted to be 24', average of well 190 and 165; AVI calculated for unconfined aquifer but well is completed below clay & till layers	1	9	8	10	10	1	4	112
192b	20	B	Unconfined	-3.476	WT shallow therefore aquifer is vulnerable but well is screened @ 95-100' & below CLAY @ 86-91'	5	9	8	8	9	8	10	180
193	41	A	Unconfined	-4.261	Lithology inferred from surficial geology; assume SWL<=2m; AVI should be negative and DRASTIC should be high	10	9	8	8	5	8	10	201
194	41	A	Unconfined	-4.601	Lithology inferred from surficial geology	10	9	8	8	5	8	10	201
195	41	A	Unconfined	-3.371		9	9	8	8	10	7	10	196
196	41	A	Unconfined	-3.823		7	9	8	8	10	8	10	191
197	41	A	Unconfined	-3.736		7	9	8	9	10	8	10	193
198	41	A	Unconfined	-3.68	Although AVI of aquifer is low, well is completed into sand and gravel below clayey layer	7	9	8	9	9	8	10	192
199	60	C	Unconfined	2.922	The high AVI is due to the 1' clay layer, which may not be extensive	5	3	8	4	9	1	4	95
200	24	B	Unconfined	4.068	High AVI due to clay @ 1'-15'	9	9	8	3	10	1	10	156
201	24	B	Unconfined	-3.168		7	9	9	5	10	7	10	183

Appendix B. AVI and DRASTIC Values for the Study Wells (continued).

Well No.	Aquifer No.	Aquifer Vulnerability Classification	Confined / Unconfined	AVI	Comments	D	R	A	S	T	I	C	DRASTIC
202	35	A	Confined	4.152	High AVI due to clay @ 1'-18'; located at northern edge of Hopington aquifer	5	8	8	3	9	1	4	113
203	35	A	Unconfined	3.7	High AVI due to thick clay layer at ground surface (extensive?)	3	8	8	5	9	1	4	107
204	35	A	Unconfined	-2.636		5	8	7	5	10	7	2	139
205	33	C	Unconfined	3.7	Well is completed into the lower, West of Aldergrove aquifer; AVI & DRASTIC are calculated for the overlying Hopington aquifer	3	8	8	9	10	8	4	109
206	33	C	Confined	5.068	Hopington aquifer not present at this site	1	3	8	8	10	1	10	102
208	35	A	Unconfined	3.922	High AVI due to 10' layer of clay at ground surface (extensive?)	5	8	7	5	5	1	2	104
209	35	A	Unconfined	-1.684	Moderate AVI due to 1' of clay at bottom of vadose zone	5	8	8	9	10	8	10	179
210	33	C	Unconfined	4.735	AVI & DRASTIC calculated for underlying West of Aldergrove aquifer	1	8	8	5	10	1	10	96
211	35	A	Unconfined		No SWL		8		9	10			
212	N/A		Confined	4.264		5	6	8	9	9	1	10	135
213	N/A		Confined	4.44		5	6	8	8	10	1	4	116
215	50	C	Unconfined	-0.206		2	3	8	4	10	5	6	107
216	N/A		Confined	3.353		5	6	8	3	10	1	4	106
217	15	A	Unconfined	-2.587	Well completed into the Abbotsford-Sumas aquifer?	5	9	8	9	10	7	10	178
218	15	A	Unconfined	-2.3	Assume dug well through sand; is this well completed into the Abbotsford-Sumas aquifer?	7	9	7	9	10	7	4	167
219	27	C	Confined	4.152		2	6	7	8	9	1	2	91
220	15	A	Unconfined	3.926	Can also calculate AVI to SWL; High AVI due to clay & till @ 39'-59'	3	9	8	9	5	1	10	133
221	N/A		Confined	4.723		2	3	8	8	10	1	10	107
222	15	A	Confined	4.227	High AVI due to clay & till @ 2'-33'	5	9	8	8	9	1	10	145
223	16	A	Confined	4.203		3	6	8	5	9	1	10	117
224	16	A	Confined	3.594		2	6	8	4	3	1	4	86
225	15	A	Unconfined	-2.978	SWL interpreted from reported SWL in nearby wells	7	9	8	5	10	7	10	180
226	15	A	Unconfined	-3.534		5	9	8	5	10	8	10	175
227	15	A	Unconfined	-3.114	Assume open hole through sand & gravel	7	9	8	5	10	7	10	180
228	15	A	Unconfined	-4.164		2	9	8	5	10	9	10	165
229	15	A	Unconfined	-3.045	Assume SWL is 108' from well on property to south (92G009122#38)	7	9	8	5	10	8	10	185

Appendix B. AVI and DRASTIC Values for the Study Wells (continued).

Well No.	Aquifer No.	Aquifer Vulnerability Classification	Confined / Unconfined	AVI	Comments	D	R	A	S	T	I	C	DRASTIC
231	15	A	Unconfined	-4.037		9	9	8	5	10	8	10	195
232	15	A	Unconfined	-3.68	Assume dug well completed in sand & gravel	7	9	8	9	10	8	10	193
233	15	A	Unconfined	-3.601	Assume dug well completed in sand & gravel	7	9	8	5	10	8	10	185
234	15	A	Unconfined	-3.869		7	9	8	5	10	8	10	185
235	15	A	Unconfined	-5.124		9	9	8	3	9	9	10	195
236	15	A	Unconfined	-3.846		7	9	8	5	10	8	10	185
237	15	A	Unconfined	-3.358	Assume SWL @ bottom of well as SWL in irrigation well is ~56'	3	9	8	5	10	8	10	165
238	15	A	Unconfined	-3.534	Assume old well is through sand & gravel	5	9	8	5	10	8	10	175
239	15	A	Unconfined	-3.037	Assume cement tile is casing off sand, as from 30'-55'	9	9	8	5	10	7	4	172
240	15	A	Unconfined	-3.823		7	9	8	5	10	8	10	185
241	15	A	Confined	4.369	High AVI due to clay @ 0'-28'	5	9	6	5	9	1	4	115
242	15	A	Unconfined	-2.726		5	9	8	8	1	7	10	167
244	15	A	Unconfined	4.098	High AVI number due to clay @ 0'-15' but elevated NO3-N (3.78 mg/L); AVI similar to KRonneseth's	2	9	8	5	5	1	10	120
245	15	A	Unconfined	-4.848		7	9	9	9	10	9	10	201
246	15	A	Unconfined	-4.902		9	9	8	9	10	8	10	203
247	15	A	Unconfined	-3.964		9	9	8	8	10	8	10	201
248	15	A	Unconfined	-2.145		1	9	8	5	9	7	4	131
249	15	A	Confined	1.068	High AVI due to till @ 0'-30'; check with KRonneseth's AVI number	9	9	8	9	5	3	4	155
250	15	A	Unconfined	-3.307	Dug well assumed to be in sand and gravel; this well very close to Obs Well 301 where lithology is known	3	9	8	3	10	10	4	153
251	15	A	Unconfined	-6	FOSTER's Spring	10	9	8	9	5	10	4	195
252	15	A	Unconfined	-3.088	92'-132' is "buff" clay-is that fine sand?	2	9	8	5	10	8	10	160
253	15	A	Unconfined	-3.99	Assume open hole is through sand and gravel	5	9	8	5	9	9	10	179
254	15	A	Unconfined	-3.587	AVI is low but well screen @ 95-99', below till @ 65-72'	5	9	8	5	10	8	10	175
255	15	A	Confined	3.466	Located in area underlain by Sf-sandy till	3	9	8	5	10	1	10	130
256	9	A	Unconfined	-3.124		2	9	8	10	10	8	10	170
257	9	A	Unconfined	1.754		2	9	8	10	9	3	10	144
260	20	B	Confined	4.603	Assume upper shale & gravel is dry; high AVI due to silty clay @ 157'-205'	1	9	7	5	10	1	2	93
261	20	B	Unconfined	-2.937		1	9	8	5	10	8	10	155
262	N/A		Confined	4.603		5	6	8	3	5	1	4	101

Appendix B. AVI and DRASTIC Values for the Study Wells (continued).

Well No.	Aquifer No.	Aquifer Vulnerability Classification	Confined / Unconfined	AVI	Comments	D	R	A	S	T	I	C	DRASTIC
263	N/A		Confined	4.126	Sand & gravel @ 82'-84' is the producing zone, not bedrock	2	8	2	5	5	1	1	71
264	13	A	Unconfined	-3.756	Lithology inferred from surficial geology	7	9	8	9	10	8	10	193
265	11	A	Unconfined	4.152	Assume fine silty sand @ 30 (swl)-47' is saturated; high AVI due to clay @ 8'-25'	7	9	7	10	5	1	1	125
266	15	A	Unconfined	-1.937		2	9	9	4	10	6	10	151

FIGURE 1. Study area showing the study wells, the seventeen unconfined aquifers and two bedrock aquifers (the twelve confined aquifers are not shown).