# AVI: A METHOD FOR GROUNDWATER PROTECTION MAPPING IN THE PRAIRIE PROVINCES OF CANADA

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PRAIRIE PROVINCES WATER BOARD

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# INTRODUCTION

Groundwater contamination is an increasing water resource problem on a global scale. In North America, Europe, and elsewhere, very expensive programs are in place to remediate polluted groundwater and to develop new clean-up technologies. Further, in the past two decades, the development of prevention techniques has become an increasing priority; the consensus is that careful planning and prevention of groundwater contamination is our best long-term solution.

One prevention technique is groundwater protection mapping. The basic principle of this technique is that a given geographic region can be divided into zones which can each be assigned a rating of groundwater pollution vulnerability, from low to high, based on hydrogeologic and/or soil parameters. For such maps, the underlying assumption is that the potential source of groundwater contamination is at or near ground surface, and that groundwater flow is vertically downward. Groundwater protection maps can be used to help define protective land-use zones for large geographic regions, and further as a preliminary screening tool for land-use site selection. However, since groundwater protection maps are based on rather generalized, descriptive data for a given geographic region, they cannot be used to choose specific sites for land-use in which groundwater contamination is a major risk. For such cases, more detailed investigations are required, in which site-specific techniques, including contaminant-transport modelling and risk analysis, can be conducted.

Further, groundwater protection maps do not take into account subsurface drilling activities (oil and gas exploration, deep well disposal of liquid wastes, etc.), which may pose a hazard for subsurface groundwater resources. Such hazards are again best dealt with on a site by site basis, since detailed stratigraphic information at the drill site can be made available during drilling. Guidelines or regulations for well and borehole management practices are an important component of provincial groundwater legislation, and will also will be considered under Environment Canada's Green Plan (Environment Canada, 1991).

# THE PPWB AND GROUNDWATER PROTECTION MAPPING

In February, 1991, the Committee on Groundwater of the Prairie Provinces Water Board (PPWB, Regina, Saskatchewan) released a report entitled *An Evaluation of Existing Groundwater Legislation in the Prairie Provinces*. This report examined provincial legislation in Alberta, Saskatchewan and Manitoba pertinent to regulations and policies for allocation and protection of groundwater. It specifically outlines six types of activities relevant to groundwater protection, including at or near surface and subsurface activities (Table 1). Point source contaminants, deposited at or near surface, are noted to be the most important interprovincial concern. In order to address the issue of groundwater protection, this report contains, as its first recommendation, the following:

"The PPWB to prepare and publish a series of groundwater pollution hazard maps (constraint maps) at each interprovincial boundary to identify sensitive areas such as shallow aquifers and recharge areas." (PPWB, 1991, p. 33).

The stated purpose of these maps is to help the provinces control activities, including future developments, along their interprovincial borders.

In August of 1991, the PPWB and Environment Canada signed a memorandum of understanding, whereby a pilot "groundwater protection" mapping project would be carried out by Environment Canada, via personnel at the National Hydrology Research Institute. This pilot study is to examine a portion of the Saskatchewan-Alberta border region (18 miles either side of the border), from township 47 to 58 (NTS Maps 73E and 73F). In brief, the specific objectives are:

1. To map various degrees of susceptibility to groundwater pollution, and indicate areas where information is insufficient.
2. To recommend which guidelines or criteria should be used in the mapping.
3. To estimate the cost of extending the mapping program along the interprovincial borders.

The following sections report the results of the pilot mapping study, in the context of the three objectives outlined above, with reference to the accompanying pilot map.

Table 1. Activities and issues related to groundwater protection, as summarized by the Committee on Groundwater, Prairie Provinces Water Board (PPWB, 1991).

| | ACTIVITY | ISSUE | PROACTIVE | REACTIVE |
|---|---|---|---|---|
| 1. | Foreign Material Deposited as a Non-Point Source at or Near the Land Surface | Non-Point source contaminants must be managed in a manner compatible with local hydrogeological conditions. | Define aquifer sensitivity to non-point source contaminants and control land use accordingly. | Investigate groundwater degradation related to non-point source contaminants and remedy as required. |
| 2.* | Foreign Material Deposited as a Point Source at or Near the Land Surface | Point source contaminants must be managed in a manner compatible with hydrogeological conditions. | Site selection, design and construction of containment structures must be adequately addressed to prevent groundwater degradation. | Investigate groundwater degradation related to point source contaminants and remedy as required. |
| 3. | Foreign Material Introduced Below the Land Surface Through Drilling Activities | Drilling activities must recognize the location and characteristics of aquifers and employ methods that will prevent groundwater degradation. | The practices and procedures of both government and industries (developers) must identify aquifers and apply appropriate measures for their protection. | Investigate groundwater degradation related to drilling activities and remedy as required. |
| 4. | Foreign Material Introduced Below the Land Surface Through Mineral Extraction Activities. | Mining activities must recognize the location and characteristics of aquifers and employ methods that will prevent groundwater degradation. | The practices and procedures of both government and industries (developers) must identify aquifers and apply appropriate measures for their protection. | Investigate groundwater degradation related to mineral extraction activities and remedy as required. |
| 5. | Foreign Material Introduced Below the Land Surface Through General Construction and/or Operation Activities | General construction and/or operation activities must recognize the location and characteristics of aquifers and employ methods that will prevent groundwater degradation. | The practices and procedures of both government and industries (developers) must identify aquifers and apply appropriate measures for their protection. | Investigate groundwater degradation related to general construction and/or operation activities and remedy as required. |
| 6. | Management of Hazardous Wastes | Handing, storage and disposal of hazardous wastes must recognize the location and characteristics of aquifers and ensure that groundwater is not degraded. | Storage and disposal of hazardous wastes must not take place in hydrogeologically sensitive areas. | Investigate groundwater degradation related to the handling, storage and disposal of hazardous wastes and remedy as required. |

* Activity #2 is considered to be the most important interprovincial concern. Point source pollutants are most commonly associated with seepage from lagoons, holding ponds, landfills and underground storage tanks.

# 1. CHOOSING CRITERIA FOR GROUNDWATER PROTECTION MAPPING

Various protection mapping methods have been developed by, or under contract for different government agencies for use in their own country, province or state. As such, they have not received much international attention or critique. Comparisons of the mapping methods are generally not available.

Up to 7 parameters are used in the various groundwater protection mapping systems; these parameters may be either qualitative or quantitative, with various weighting schemes. The parameters are generally based on readily available information, such as driller's logs and geologic maps, so that they can be applied to wide geographic regions. However, some of the more complex mapping systems rely on estimated parameters to some degree. As a general rule, the choice and quantification of the parameters for the various systems have not been tested rigorously. Some parameters have a sound theoretical basis (e.g., geologic controls on permeability), others appear to be based on rather speculative concepts (e.g., effects of map-scale topography on infiltration and recharge rates). Weighting of the parameters is somewhat arbitrary; for example, a Delphi consensus approach has been used (DRASTIC system: Aller et al., 1987).

Within Canada, various provincial or federal organizations have developed or contracted their own groundwater vulnerability mapping schemes (e.g. McCormack, 1985; Norton and Scott, 1982; McRae, 1989; Roeper, 1990; Rutulis, 1990). One groundwater protection method that has received a lot of attention in the United States, and some consideration also in Canada is the DRASTIC system, which was developed in the mid-1980's by the National Water Well Association, in conjunction with the U.S. Environmental Protection Agency. In the next section, two methods, the DRASTIC system, and the simpler "Roeper method", which was developed recently for the Regina, Saskatchewan region (Roeper, 1990), will be outlined and critiqued. These examples were chosen because they represent end-members of the various mapping methods, in terms of complexity. This critique will, in part, form the basis for a new method of groundwater protection mapping in the prairie provinces of Canada, as given below.

## A critique of the DRASTIC system and the Roeper method

The DRASTIC system considers 7 parameters: depth to water, net recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity. The definition of these terms, and the choice of quantitative rating values are described by Aller et al. (1987). Relative weights for the parameters are shown in Table 2. In contrast, the Roeper method considers only 1 parameter: thickness of the "protective clay or till overburden" above the uppermost major aquifer in the profile.

Table 2. Outline of Parameters Used in the DRASTIC system and the Roeper Method

The DRASTIC System (Aller et al., 1987)

| Parameter | Weight |
|---|---|
| Depth to water | 5 |
| Net recharge | 4 |
| Aquifer Media | 3 |
| Soil Media | 2 |
| Topography | 1 |
| Impact of Vadose Zone | 5 |
| Hydraulic Conductivity | 3 |

The Roeper Method (Roeper, 1990)

| Parameter | Weight |
|---|---|
| Depth of protective cover above a major aquifer | 100% |

Without considering the details of each method, the following observations can be made:

1. The DRASTIC system tries to accommodate a large array of parameters. However, as acknowledged by Aller et al. (1987; p. 62), there is considerable overlap or redundancy in the parameters. For example, the soil media and vadose zone parameters overlap, since the soil zone is a subset of the vadose zone. Similarly, for surficial aquifers, the aquifer media parameter overlaps with soil zone and vadose zone parameters. The hydraulic conductivity parameter is sometimes completely redundant,

when it is derived from the aquifer media parameter, by inferring a typical hydraulic conductivity for that particular medium.

2. One of the parameters used by DRASTIC is net recharge. However, it is very difficult to obtain data on lumped-average net recharge for geographic segments on the prairies, and further, lumped-average recharge rates fail to consider the importance of processes such as depression-focussed recharge on a metre scale (Lissey, 1971; Keller et al., 1988). In fact, for a given climate, recharge is largely dependent on another parameter that is more easy to measure or estimate than recharge itself, i.e. the hydraulic conductivity of any confining layer(s) above the aquifer, or of a surficial aquifer itself. We conclude that it is more useful to consider the hydraulic conductivity parameter in generalized protection mapping on the prairies. Net recharge (or discharge) rate can be examined in detailed site-specific investigations.

3. DRASTIC also considers generalized, map-scale topography as a parameter. However, the effects of map-scale topography on movement of contaminants is debatable. Arguments can be constructed to suggest that greater relief may reduce groundwater contamination by enhancing runoff (per DRASTIC system), or increase groundwater contamination by enhancing depression-focussed recharge (Lissey, 1971; Keller et al., 1988). In any case, topography is not one of the most critical parameters. We conclude that topography, including catchment configurations, should be dealt with on a site-specific basis only, not during general groundwater protection mapping.

4. One of the most serious flaws in the DRASTIC system is the relatively arbitrary weighting scheme for the various parameters, which were determined by a Delphi consensus procedure, and which, according to Aller et al. (p. 17) are "... constant and may not be changed..". In fact, DRASTIC gives the same weight to a) the depth of unsaturated zone for a surficial aquifer and b) depth to aquifer for a confined aquifer. This is clearly inappropriate when one considers the travel time for vertical contaminant movement through an unsaturated zone of a surficial aquifer (typically hours to days, neglecting sorption) relative to vertical transport through a saturated confining aquitard layer (typically years to thousands of years, neglecting sorption). We conclude that DRASTIC gives too much importance to some parameters (e.g., topography) and not enough to the role of the confining layer. We would prefer to base the parameter weighting on physical theory, rather than using the Delphi consensus method, as for DRASTIC.

5. The Roeper method is, by contrast, a simple method that considers one of the most important parameters, depth of confining layer. However, Roeper uses a rather arbitrary subdivision of thickness ranges to define vulnerability zones (0 to 5 m; 5 to 10

m, > 10 m). It would seem better to use a system that considers a continuous range of depths of protective cover, considering that a 10.1 m cover is not as protective as, say, a 50 m cover.

6. Roeper considers only "major aquifers", which were determined in earlier studies in the region. As such, his method doesn't provide a means for choosing such major aquifers elsewhere. There is no obvious reason for not considering the vulnerability of "minor" aquifers, particularly if they are being used for water supply. In the prairies, approximately 90 % of the rural population depends on groundwater, and to a large extent the rural supply consists of the widely distributed minor aquifers.

7. In addition, the Roeper method doesn't consider the role of weathered or vadose zones, and doesn't take into account the type of confining layer, aside from a general differentiation between presence of surficial sands and silts, on the one hand, and clay or massive till on the other.

8. In general terms, the DRASTIC method appears to be overly complex in its selection of parameters, and arbitrary in its assignment of relative weights to these parameters, whereas the Roeper method is overly simplistic, and study-specific.

## The Aquifer Vulnerability Index (AVI) Method for Groundwater Protection Mapping

We propose a new index of groundwater vulnerability, based on two parameters:

1. d = thickness of each sedimentary layer above the uppermost, saturated aquifer surface, as recorded in driller's logs and/or provincial geologists' test hole data. For our purposes, we propose to define an aquifer as any sand or gravel unit that has a saturated thickness of at least 0.6 m (2 ft), or is < 0.6 m, but has at least one water well installed. In a few cases, wells have been completed in silt units, or other atypical sediments, and these are considered aquifers for the mapping exercise. Any > 0.6 m sand or gravel unit deeper than 5 m below surface is considered water-saturated, unless there is direct evidence on the driller's report to the contrary.

2. K = estimated hydraulic conductivity of each of these layers. Since K determinations are not available for the pilot map area, the estimates listed in Table 3 are reasonable. In the future, the estimates in this table may be modified as more information becomes available (e.g. depth of fractures in till or clay units) as a result of testing of these values.

Based on the two parameters, d and K, a single factor can be calculated, the hydraulic resistance $c = \Sigma d_i/K_i$, for layers 1 to i. This is a theoretical factor used to describe the resistance of an aquitard to vertical flow (e.g. Kruseman and de Ridder, 1990). Thus, the weighting of the two factors, 1) thickness and 2) hydraulic conductivity of each sediment layer above the uppermost saturated aquifer surface, is not arbitrary, but is based on physical theory. Hydraulic resistance (c) has the dimension Time, which, in the present application, indicates the approximate travel time for water to move by advection downward through the various sediment layers above the uppermost saturated aquifer surface. However, in a strict sense, c is not travel time for water or contaminants because other factors, such as hydraulic gradient, diffusion, and sorption are not considered.

Table 3. Hydraulic conductivity (K) estimates for various sediments in the Canadian Prairies. In reality, each of these sediment types have a range in K values over several orders of magnitude; the values shown here are approximate mean values for each sediment type.

| Sediment Type | Standard Code[1] | Hydraulic Conductivity |
|---|---|---|
| gravel | A | 1000 m/d* |
| sand | B | 10 m/d* |
| silty sand | C | 1 m/d* |
| silt | D | $10^{-1}$ m/d* |
| fractured till, clay or shale (0 to 5 m from ground surface) | E | $10^{-3}$ m/d** |
| fractured till, clay or shale (5 to 10 m from ground surface) | F | $10^{-4}$ m/d+ |
| fractured till, clay or shale (> 10 m from ground surface, but weathered based on color: brown or yellow) | F | $10^{-4}$ m/d+ |
| massive till or mixed sand-silt-clay | G | $10^{-5}$ m/d** |
| massive clay or shale | H | $10^{-6}$ m/d* |

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[1] short-form for use during interpretation of logs (see Appendix A)

*estimate based on Freeze and Cherry (1979)

**estimate based on Keller et al.(1988)

+assumes that fractures diminish downward

Table 4. Relationship of Aquifer Vulnerability Index to Hydraulic Resistance

| Hydraulic Resistance (c) | log(c) | Vulnerability (AVI) |
|---|---|---|
| 0 to 10 y | < 1 | extremely high |
| 10 to 100 y | 1 to 2 | high |
| 100 to 1,000 y | 2 to 3 | moderate |
| 1000 to 10,000 y | 3 to 4 | low |
| > 10,000 y | > 4 | extremely low |

The calculated c or log(c) values could be used directly to generate iso-resistance maps. However, in this method, each profile (e.g., well) is related to a qualitative Aquifer Vulnerability Index (AVI), as shown in Table 4.

Based on this scheme, a given profile requires at least 3.7 m of fractured till to have a less than extremely high vulnerability, at least 8.2 m of fractured till for a moderate vulnerability, a cover of at least 13.2 m of till to have a low vulnerability rating, and at least 46 m of till to have an extremely low vulnerability rating. On the other hand, the unweathered (> 10 m) portion of a continuous profile of clay or shale is assigned a lower estimated hydraulic conductivity than till, based on Table 3. Under this scheme, a 10.4 m clay and/or shale profile could be given a low vulnerability rating, and a 13.6 m clay and/or shale profile could be given an extremely low vulnerability rating.

The AVI method takes into account, although not in the same way, the various factors or parameters used by Roeper and DRASTIC, with the exception of topography and net recharge, as discussed above. It is important to point out further limitations of this AVI method:

Parameters ignored include climate, hydraulic gradient, horizontal flow, porosity and water content of the media, and sorptive or reactive properties of the layers, which are contaminant-specific. These parameters can be considered in site-specific studies. For example, site studies should include an investigation of the local catchment configuration to determine the risk of transport of contaminants in runoff to adjacent areas where groundwater vulnerability is mapped as being high.

The AVI method for mapping groundwater vulnerability in the Prairies of western Canada is based mainly on water well drillers' logs. These records vary in quality and descriptive terminology, but most contain fairly detailed records of types of sediment, from surface to the nearest-to-surface aquifer. Some indicate static water levels, or whether sands and gravels are water-bearing or dry. These records comprise the most extensive data set available for stratigraphy of the shallow subsurface of the prairies, and provide the information that the AVI system requires. The information obtained from private well driller's logs is complemented by provincial test-hole logs, which can be included in the database used for mapping groundwater vulnerability. Holes with only geophysical logs (e.g. spontaneous potential, resistivity), obtained primarily during oil and gas exploration, can also be used, if stratigraphic interpretations are available.

The AVI method considers only nearest-to-surface aquifers, and considers each to be of equal value. As one limitation, the AVI method does not consider aquifer water quality. Many near-surface aquifers have high concentrations of dissolved ions, often in excess of drinking water standards, due to natural hydrogeochemical processes (e.g. till weathering reactions). However, aquifer quality criteria would require further investigation and evaluation by the provinces, prior to development of a scheme for designating certain aquifers as "unprotected" due to poor quality. The AVI method does not consider groundwater availability; at a given site there may be a series of aquifers within the stratigraphic profile, but AVI considers only the vulnerability of the uppermost aquifer.

## 2. APPLICATION OF AVI: PRAIRIE PROVINCES PILOT STUDY

The AVI method, as described above, was used in our pilot study to examine a portion of the Saskatchewan-Alberta border region, as defined above. This involved the compilation of the stratigraphy, identification of aquifers, and calculation of log(c) and the corresponding AVI in approximately 2000 water well logs available for this pilot map area.

The well logs used in this mapping exercise included water well logs and provincial testhole records. Stand-alone geophysical E-logs were not used; interpretation of these records was considered to be overly time consuming for this pilot project.

The records used gave generalized well locations, usually to a quarter or sixteenth (LSD) of a section. If the locations of two or more wells were redundant, only the well with the highest vulnerability (lowest c) was included for mapping. Well logs that had incomplete stratigraphic information, or too general location (e.g. section only) were also excluded. The program WELLMAP1 converted these DLS descriptions to UTM coordinates for the approximate centres of each quarter section or LSD unit.

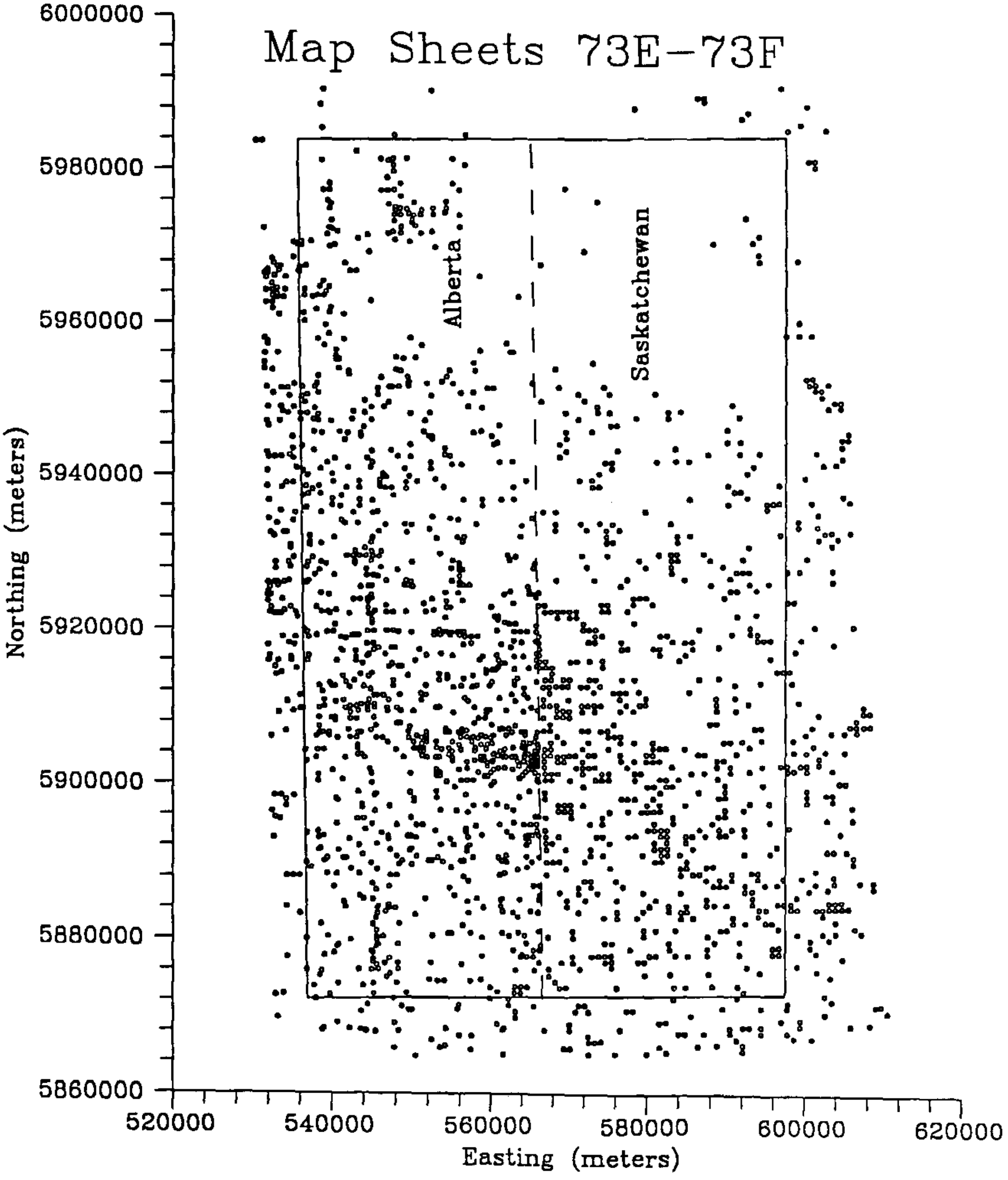
Appendix A provides further details on the methods in which water well and test hole data were used in this study, and Appendices B and C give the resulting log (c) values for each well or testhole. As noted above, in this project the log(c) values shown in these appendices were converted to AVI units, as shown on Table 4.

In this study, the method for plotting zones of iso-vulnerability, based on contours of iso-resistance, was the computer program SURFER (Golden Software Inc). Contours were selected to display log(c), with a unit interval, on a 250 by 250 node grid, using a kriging technique. As shown in Fig. 1, well data points from just outside the pilot map area were also considered, to avoid erroneous "edge effects" during generation of the AVI zones. The 1:250,000 scale AVI map that was generated with SURFER was superimposed on the base topographic maps for the pilot area, giving corresponding landmarks, such as towns, roads and bodies of water.

The above SURFER plotting method does not consider lateral continuity or discontinuity of aquifers rigorously. These factors should be considered during any site specific investigations within the map area. On the other hand, the close spacing of the data ($\leq$ 8 km, for a map of approximately 60 by 110 km) means that much of the lateral continuity of aquifer vulnerability does appear on the map. The choice of a maximum allowable 8 km spacing of data points (equivalent to a 4 km radius around each well) is based on observation of the well distribution in the majority of the map area (the "settled" portion). Zones where the spacing of wells exceeded 8 km (north northeastern portions, see pilot map) have been labelled as lacking sufficient information for vulnerability mapping. Geophysical E-logs may prove to be useful in the future to reduce these unmapped regions.

Based on the AVI method, all surficial aquifers have extremely high vulnerability, because of the high hydraulic conductivity of sands and gravels (Table 3). On the Prairies, some surficial sand and gravel aquifers occur in the flat valley bottoms of deep, glacial meltwater channels, presently occupied by rivers or creeks. However, there is little supporting well data for these aquifers (e.g. Saskatchewan Research Council, 1988). For this pilot map project, the outlines of these inferred meltwater channel aquifers were extracted from the SRC aquifer maps for the St Walburg (73F) map sheet (Saskatchewan Research Council, 1988). The same criteria (i.e. flat valley bottoms of deep meltwater channels, M. Millard, personal communication) were used

Fig. 1. Density distribution of well data used for pilot map. Each circle represents a single well or testhole. Note that some of the data lie outside the map boundary, as shown in solid lines. Data are lacking in the sparsely populated north-northeastern portion of the map.



to map meltwater channel aquifers on the Alberta side of the pilot map area, based in part on the Quaternary Geology map of Central Alberta (Alberta Research Council, 1990) and on 1:100,000 NTS topographic maps of the eastern half of the Vermilion map sheet (73E). These inferred aquifers were digitized using a digitizing table and the program SIGMASCAN (Jandel Scientific). These digitized files were imported into SURFER, and superimposed onto the contoured AVI map generated from well data. In places, the edges of the vulnerable meltwater aquifers truncate the AVI zone boundaries generated with SURFER at abrupt angles. This is reasonable since the meltwater channels truncate the underlying sedimentary units. The meltwater channel aquifers shown on the pilot map (North Saskatchewan River, Battle River, Vermilion River, and Big Gully Creek valleys) comprise a very small percentage of the total map area.

Note the total percentage of the map area that has high or extremely high vulnerability; approximately 50 % of the map area. The distribution of vulnerability is not a random scatter pattern, but there are large, continuous regions of either high or low vulnerability. Further, the patterns of AVI zones cross the Alberta-Saskatchewan boundary with no disruptions. However, there is a significant, and fairly abrupt change in the pattern of AVI zones between the central and south-southwest portion of the pilot map. This change is due to heterogeneity of the surficial geology of the map area. The largest continuous area of high to extremely high vulnerability occurs in the central portion of the map area. This area corresponds approximately to an array of surficial ice-contact fluvial and fluvio-lacustrine sand and gravel deposits, as shown on a Land System map for the St. Walburg (73F) sheet (Saskatchewan Parks and Renewable Resources, 1981), and the Quaternary Geology map for Central Alberta (Alberta Research Council, 1990). In contrast, some of the zones where aquifers are highly vulnerable have a thin (< 8 m) till or clay cover.

Continuous regions of high to extremely high vulnerability shown on the pilot map should not be interpreted as indicating one continuous aquifer. There may be lateral pinchouts that are not shown, and 2 vertically overlapping vulnerable aquifers would also appear as one continuous zone of high vulnerability.

In other subregions of the pilot map, there are only scattered, small subregions of vulnerable aquifers present (e.g. south-southwestern and northwestern portions). In these regions a thick till sequence dominates the uppermost portion of the stratigraphic column, in a glacial moraine setting (e.g. Alberta Research Council, 1990) . Such regions would be suitable areas to perform follow-up site-specific testing for such activities as landfill disposal of industrial wastes. Future drilling may encounter more scattered, small, near-surface aquifers in this till-dominated terrain. Thus, the vulnerability rating for any given point on the map should be viewed as an approximation that should only be used for preliminary screening of potential sites.

There is considerable detail on the pilot map that may be used to guide land use regulation, or as a screening tool for site selection as noted above. This map could also be used together with land use information, particularly in a Geographic Information System (GIS) environment, to determine the most likely areas where groundwater contamination problems are prevalent today, or could occur in the future.

It will be possible to link this ongoing mapping with a GIS system, if this route is preferred. This conversion could be done quite readily since the spreadsheet files created so-far (LOTUS 123-compatible) are a common, PC-based format that can be translated directly into a GIS environment. For example, the SPANS GIS system can import data either directly from a LOTUS 123 or compatible spreadsheet (.WK1), or from a spreadsheet print output file (ASCII). The SPANS system has a contouring program that can be used in place of SURFER, to give essentially the same groundwater protection map. Alternatively, one can import a SURFER plot file (ASCII or .DXF format) to transfer the graphic representation, as contoured by SURFER, to the SPANS GIS environment.

One of the advantages of transferring the mapping program to a GIS environment would be the possibility of comparing the AVI plot, as one layer, with other plots for the same area. For example, one could compare AVI values to land-use or groundwater quality distributions. A new map could be produced by merging this information within the GIS system (e.g. applying Multiple Criteria Modelling module of the SPANS GIS system).

## 3. ESTIMATED COST OF CONTINUING THE MAPPING PROJECT ALONG THE INTERPROVINCIAL BORDERS

The following expenses apply to the pilot mapping project:

Table 5. Expenses Through March 31, 1991, PPWB Pilot Project

| Item | Cost |
|---|---|
| Maps, Well Data | 435.54 |
| Cross Sections<br>(Saskatchewan Research Council) | 53.50 |
| Well Data<br>(Alberta Environment) | 146.69 |
| Maps<br>(Alberta Research Council) | 25.00 |
| SURFER<br>(Golden Software Inc.) | 508.25 |
| Photocopies<br>(Reproduction Graphic Design) | 13.69 |
| Travel to Winnipeg (COG mtg) | 702.01 |
| HP 7475A Color Plotter | 1705.00 |
| TOTAL | 3589.68 |

In addition, NHRI staff have spent approximately 400 to 500 hours working on this project. The bulk of this time (60 to 70 %) was spent transferring well data to a spreadsheet format, interpretation of the data, calculations, and generating the map based on the data. Approximately 30 to 40 % of the time was spent researching the topic, setting up the mapping methodology, writing the report, and various other activities.

On average, the remaining interprovincial boundary areas that could be mapped, using the AVI method, have lower well density than the pilot map area. It will take approximately 300 h per map sheet length (interprovincial border region only). This time translates into approximately $4,000 to $12,000 per map sheet length (excluding publication costs), depending on whether the work is contracted to a private consultant, or is assigned to a student under the supervision of one of the PPWB agencies. For completing the work along the interprovincial boundaries (18 miles wide on each side, from 49°00'N to 55°00'N on the Saskatchewan-Alberta border, and from 49°00'N to 53°00'N on the Saskatchewan-Manitoba border), this would involve an additional 9 map sheet lengths, for a total projected cost of approximately $36,000 to $110,000 (excluding publication costs). Due to very limited well data, it is not be feasible to map the groundwater vulnerability above 55° along the Saskatchewan-Alberta border, and above 53° along the Saskatchewan-Manitoba border.

Some of the provincial representatives on the PPWB COG committee have expressed an interest in possibly becoming more directly involved in the border region groundwater vulnerability mapping program. Provincial participation could take the form of providing well drillers' logs in digitized (ASCII or other LOTUS 123-compatible) format at no or low cost. All data available for each well do not need to be included in the spreadsheet; the well drillers' logs can be truncated to include only the stratigraphy above the uppermost saturated aquifer surface. If the provinces provide digitized well drillers' logs, and reports accompanying the maps are limited to brief notes only, we estimate that the cost of mapping would be reduced by 50%: $2,000 to $6,000 per map sheet length; $18,000 to $55,000 total.

If the provinces provided UTM co-ordinates and also gave calculated AVI values for each well, the cost to PPWB would be approximately 20% of the original estimate: $800 to $2,400 per map sheet length; $7,200 to $22,000 total.

The degree of participation on the part of the provinces is a key ingredient for the final budget of the ongoing mapping program.

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# APPENDIX A

## ORGANIZATION OF WELL DATA AND CALCULATION OF log(c) VALUES

The data from the drillers' well logs for the pilot map area was entered into a simple database using Microsoft EXCEL (LOTUS 123 compatible). This database provides a "form" screen for ease of entry, and allows for future manipulation of data (i.e. reports, etc.).

Table A1 gives an example of a portion (several wells) of the spreadsheet generated for the pilot study area, based on well drillers' records. The information included well identification, as given or assigned during input (column 1); well location (columns 2 through 5); depth of lower boundary (column 6) and type (column 7) for each sediment layer, in order from ground surface; inferred uppermost aquifer (column 8) and depth of static water level or point at which water was "hit", if available (column 9). The latter two columns were recorded as information only, to help determine the depth of the uppermost water-saturated aquifer surface. However, in general, all sands and gravels below 5 m from ground surface were considered water-saturated, unless the well log specifically indicated otherwise.

After entry was completed, the well locations (columns 2 to 5) were exported to space separated ASCII format and run through the program WELLMAP1 (written by D. K. Bingham, Alberta Environment, 1990), which converted legal land descriptions, based on the Dominion Land Survey township system, to UTM co-ordinates. This conversion required a separate file containing digitized UTM co-ordinates for the NE corner of each section in the pilot map area. The UTM co-ordinates for each well were then added to the spreadsheet (columns 2a and 3a of Table A1).

Columns were added to the spreadsheet for codes and calculation of log(c), where c = hydraulic resistance, for each well (Table A1). These log(c) values were later converted to the Aquifer Vulnerability Index (AVI), as shown in Table 4 of this report.

Column 10 is the assigned standard sediment code for each layer (A through H), and column 12 is the corresponding hydraulic conductivity (K) estimate, based on Table 3 of this report. Some rules of thumb were applied: topsoil was lumped together with the next unit down, boulders were included with adjacent till, and ledges, concretions or rock layers were grouped with adjacent shales.

Column 11 is the thickness d (in m) based on depth ranges in column 6 (in ft). Columns 13 through 16 are the calculations of log (c) for each well based on columns 11 and 12.

Abbreviated forms of the spreadsheet data used for the pilot map, including the K, d, and log(c) values, are given in Appendices B (Alberta) and C (Saskatchewan).

Finally, the log(c) values, along with the well ID and the UTM coordinates (columns 1, 2a, 3a and 16 of Table A1) were exported to an ASCII file. This ASCII file was used for input into the SURFER contouring package. Within SURFER, contours were selected to display log(c), with unit interval, using a kriging technique. The legend on the map is given in AVI units, rather than the corresponding log(c) values.

The various procedures of the AVI mapping method described above are summarized in Fig. A1.

Table A1. Examples of spreadsheet data based on well drillers's logs, and calculations of log(c)

| COLUMN 1 | 2a | 3a | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WELL# | NORTHING | EASTING | QT | SC | TWP | RG | FT | LITHOLOGY | AQUIFER | WATER HIT | CODE ('K') | THICK (meters) ('d') | CODE VALUE ('K' = ) | d/K | TOTAL (DAYS) | TOTAL (YEARS) (c) | LOG(YEARS (log(c)) |
| 71112 | 5917090 | 584916 | SE | 14 | 051 | 26 | 1 | TOPSOIL | N | 16 | | | | | | | |
| 71112 | | | SE | 14 | 051 | 26 | 15 | CLAY | N | | | | | | | | |
| 71112 | | | SE | 14 | 051 | 26 | 16 | WET BLUE CLAY | N | | E | 4.9 | 0.001 | 4900 | | | |
| 71112 | | | SE | 14 | 051 | 26 | 19 | SAND WITH WATER | Y | | | | | | | | |
| 71112 | | | SE | 14 | 051 | 26 | 24 | HARD BLUE CLAY | N | | | | | | | | |
| 71112 | | | SE | 14 | 051 | 26 | 25 | SAND | N | | | | | | 4900 | 13 | 1.1 |
| 39051 | 5917810 | 577648 | NW | 18 | 051 | 26 | 1 | BLACK TOPSOIL | N | 37 | | | | | | | |
| 39051 | | | NW | 18 | 051 | 26 | 14 | FINE YELLOW SAND | N | | B | 4.3 | 10 | 0.43 | | | |
| 39051 | | | NW | 18 | 051 | 26 | 23 | BROWN TILL | N | | E | 0.7 | 0.001 | 700 | | | |
| 39051 | | | NW | 18 | 051 | 26 | 30 | BROWN CLAY | N | | F | 5 | 0.0001 | 50000 | | | |
| 39051 | | | NW | 18 | 051 | 26 | 37 | SOFT BLUE TILL | N | | G | 1.3 | 1E-05 | 130000 | 180700 | 495 | 2.7 |
| 39051 | | | NW | 18 | 051 | 26 | 57 | FINE BROWN SAND | Y | | | | | | | | |
| 39054 | 5919510 | 581705 | NE | 21 | 051 | 26 | 3 | TOPSOIL | N | 16 | | | | | | | |
| 39054 | | | NE | 21 | 051 | 26 | 14 | YELLOW SANDY CLAY | N | | E | 4.2 | 0.001 | 4200 | | | |
| 39054 | | | NE | 21 | 051 | 26 | 18 | YELLOW SAND & GRAVEL | Y | | | | | | 4200 | 11 | 1.1 |
| 77709 | 5919540 | 583342 | NE | 22 | 051 | 26 | 2 | TOPSOIL | N | 13 | | | | | | | |
| 77709 | | | NE | 22 | 051 | 26 | 15 | BROWN SANDY CLAY | N | | E | 4.6 | 0.001 | 4600 | | | |
| 77709 | | | NE | 22 | 051 | 26 | 22 | SAND WITH CLAY STREAKS | Y | | | | | | 4600 | 13 | 1.1 |
| 39058 | 5919550 | 582538 | NW | 22 | 051 | 26 | 2 | TOPSOIL | N | 41 | | | | | | | |
| 39058 | | | NW | 22 | 051 | 26 | 7 | SANDY YELLOW CLAY | N | | E | 5 | 0.001 | 5000 | | | |
| 39058 | | | NW | 22 | 051 | 26 | 24 | STONEY YELLOW TILL | N | | F | 5 | 0.0001 | 50000 | | | |
| 39058 | | | NW | 22 | 051 | 26 | 41 | STONEY GREY TILL | N | | G | 2.5 | 1E-05 | 250000 | | | |
| 39058 | | | NW | 22 | 051 | 26 | 43 | YELLOW SAND | Y | | | | | | 305000 | 835 | 2.9 |
| 72857 | 5918736 | 584905 | SE | 23 | 051 | 26 | 7 | TOPSOIL | N | 40 | E | 5 | 0.001 | 5000 | | | |
| 72857 | | | SE | 23 | 051 | 26 | 18 | BROWN CLAY | N | | F | 5 | 0.0001 | 50000 | | | |
| 72857 | | | SE | 23 | 051 | 26 | 40 | BLUE CLAY | N | | G | 2.2 | 1E-05 | 220000 | | | |
| 72857 | | | SE | 23 | 051 | 26 | 42 | MEDIUM GREY SAND | Y | | | | | | | | |
| 72857 | | | SE | 23 | 051 | 26 | 46 | BLUE CLAY | N | | | | | | | | |
| 72857 | | | SE | 23 | 051 | 26 | 50 | FINE-MEDIUM GRAVEL | Y | | | | | | 275000 | 753 | 2.9 |

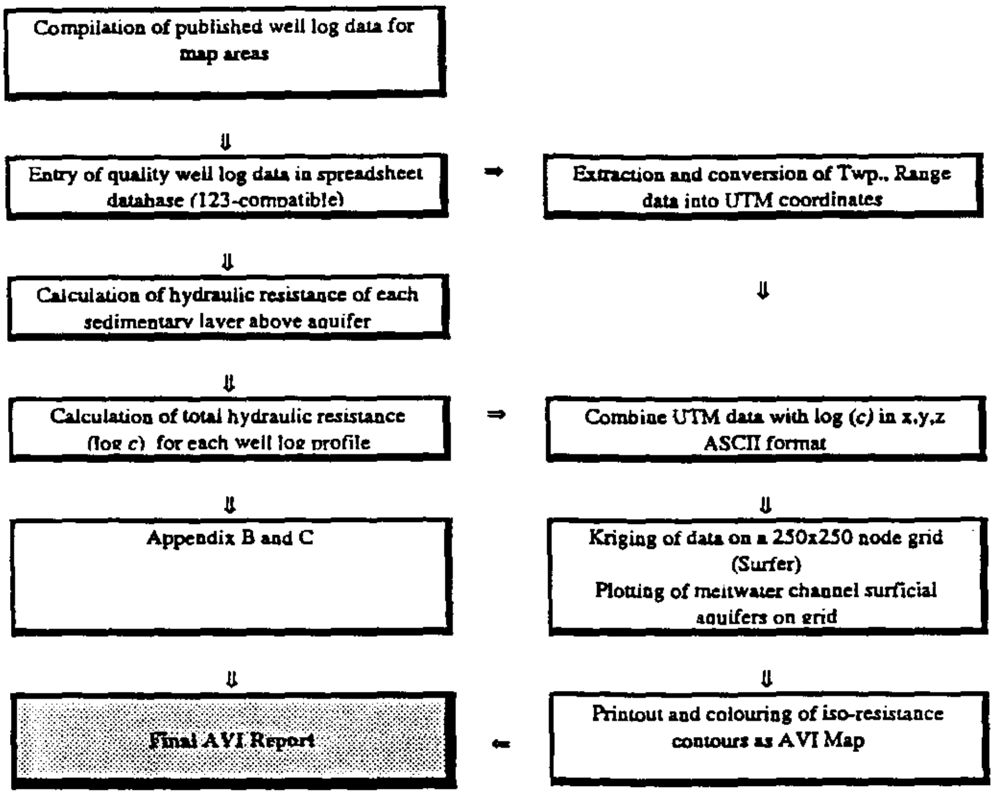

Fig. A1. Flow chart indicating the sequence of the procedures required to generate the AVI map.

# APPENDICES B AND C

Appendices B (Alberta data) and C (Saskatchewan data) containing log (c) values for water wells used in the study have been left out of this report. This information is available upon request from:

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# AVI: A METHOD FOR GROUNDWATER PROTECTION MAPPING IN THE PRAIRIE PROVINCES OF CANADA

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