GROUNDWATER VULNERABILITY MAPPING ALONG THE ALBERTA-SASKATCHEWAN BOUNDARY

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FOREWORD

Groundwater is a vital resource for the prairie provinces. It is estimated that 90% of the rural population relies directly on groundwater as its primary source of water. As well, groundwater contributes significantly to surface water flow especially during dry periods, and is an integral part of wetland ecosystems.

Groundwater contamination is a growing concern throughout the world. Because of the difficulties and expense to clean-up an aquifer after it is contaminated, there is a need to take measures to protect groundwater from being polluted.

Recognizing the growing importance of groundwater and the need to ensure its sustainability, the Prairie Provinces Water Board contracted the National Hydrology Research Institute to develop a procedure to help protect interprovincial aquifers from surface contamination. That project was completed in 1992 and provides the basis for the maps contained in this report.

The six groundwater vulnerability map sheets contained in this report are intended to be a preliminary guide to help define an area's susceptibility to contamination from surface sources. Because of limitations of the accuracy of the data and the scale used to display the information, there remains a need to do detailed site investigations.

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Introduction

In February 1991, the Committee on Groundwater of the Prairie Provinces Water Board (PPWB) released a report that examined provincial legislation, regulations and policies in Alberta, Saskatchewan and Manitoba pertinent to allocation and protection of groundwater (PPWB, 1991). It specifically identified six types of activities that are relevant to groundwater protection, including surface or near surface and subsurface activities. Point source contaminants, deposited at or near the surface, were noted to be the most important potential interprovincial concern. On the basis of this report the Committee recommended and the Board agreed to prepare and publish a series of groundwater vulnerability maps at each interprovincial boundary to identify sensitive areas such as shallow aquifers and recharge areas. The basic premise of groundwater vulnerability (or protection) mapping is that land can be divided into areas that can be assigned ratings of groundwater pollution vulnerability based on hydrogeologic and/or soil parameters. These maps can then be used to help control activities, including future developments along the interprovincial borders.

From August 1991 to March 1992, the National Hydrology Research Institute (NHRI) of Environment Canada undertook a pilot groundwater vulnerability mapping project for the PPWB. The purpose of the pilot study was to determine the guidelines or criteria that should be used in the mapping, to test their suitability for mapping degrees of susceptibility to groundwater pollution and to estimate the cost of extending the mapping program along the interprovincial borders (Van Stempvoort *et al.*, 1992; Van Stempvoort *et al.*, 1993). After review of the pilot study, the PPWB contracted NHRI to proceed with mapping the rest of the map sheets on the interprovincial boundaries in the Prairie Provinces (Figure 1).

This report presents the results of the groundwater vulnerability mapping along the Alberta-Saskatchewan boundary. Its purpose is to:

i) briefly review the criteria for groundwater vulnerability mapping;

ii) describe the aquifer vulnerability index (AVI) method that was developed to meet the needs of this mapping project; and

iii) discuss the application of the AVI method to groundwater vulnerability mapping along the boundary.

Figure 1 - Location of the Prairie Provinces

Criteria for Groundwater Vulnerability Mapping

Various groundwater vulnerability mapping methods were reviewed and evaluated by Van Stempvoort *et al.* (1992; 1993) as part of the pilot study. These methods range in complexity from relatively simple systems with only one or two parameters to relatively complex systems such as the DRASTIC system (Aller *et al.*, 1987) that uses seven parameters (Table 1). Van Stempvoort *et al.* (1993) state:

> "These parameters may be either qualitative or quantitative, with various weighting schemes. The parameters are generally based on readily available information, such as soil survey data, 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 to some degree on estimated parameters. 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), whereas 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)."

Some of the early groundwater vulnerability mapping in Canada (Ontario MOE, 1982; McCormack, 1985; Turner, 1989) used qualitative methods that considered only surficial geology and/or soil survey information. While these surface-information-based methods may be useful, they fail to consider the most important parameters that determine groundwater vulnerability to surface derived contaminants, that is, the thickness and permeability of layers above the nearest-to-surface aquifer.

Recently, methods (Roeper, 1990; Manitoba Natural Resources, 1990) have been developed that take the thickness of the protective layer into account. This is a significant improvement on earlier methods that were based on surficial criteria but these methods which are designed to determine the vulnerability of individual aquifers require prerequisite knowledge about the distribution of aquifers in an area. They cannot be used to determine the vulnerability of groundwater in areas where aquifers have not been

Table 1. A comparison of parameters used in some methods to map groundwater vulnerability (from Van Stempvoort *et al.*, 1993).

Parameter: Method: Author(s) Date/Location	Soil Type or Surficial Geology	Thickness of Aquitard Cover	Hydraulic Conductivity of Cover	Recharge or Infiltration Rate	Depth to Water Table	Water Use	Land Use	Aquifer Media	Topography
MOE, Ontario 1982/Ontario	Y	N	I	I	N	I	N	N	I
McCormack 1985/Quebec	Y	N	I	I	N	N	N	N	I
McRae 1989/Canada	Y	N	I	I	Y	N	N	N	Y
Turner 1989/Manitoba & Saskatchewan	Y	N	I	I	N	Y	Y	N	N
Roeper 1990/Saskatchewan	I	Y	I	I	N	N	N	N	N
MNR, Manitoba 1990/Manitoba	Y	Y	I	I	N	N	N	N	N
DRASTIC Aller *et al.* 1987/United States	Y	Y	I	Y	Y	N	N	Y	Y
AVI Method Van Stempvoort *et al.* 1992/Alberta & Saskatchewan	I	Y	Y	I	I	N	N	N	N

Y = parameter used

N = parameter not used

I = parameter considered indirectly and/or related directly to other parameters mapped or to determine the vulnerability of unmapped minor aquifers that may be used for water supply.

Therefore, it was concluded that the groundwater vulnerability mapping should use readily available data and not require information on the distribution of aquifers, infiltration or recharge rates, etc. for the area to be mapped. It was also considered desirable to account for the thickness of the various layers within the protective cover above the nearest-to-surface aquifer. Finally, the method had to be relatively simple and, therefore, a low cost approach to vulnerability mapping.

The Aquifer Vulnerability Index (AVI) Method

The Aquifer Vulnerability Index method (Van Stempvoort *et al.*, 1992; Van Stempvoort *et al.*, 1993) is a measure of groundwater vulnerability based on two physical parameters:

i) thickness (d) of each sedimentary layer above the uppermost, saturated aquifer surface;

and

ii) estimated hydraulic conductivity (K) of each of these sedimentary layers.

The hydraulic resistance "c" of a sedimentary layer is defined by the expression (e.g., Kruseman and de Ridder, 1990):

$$c = d/K \qquad (1)$$

where d = thickness of the sedimentary layer
K = hydraulic conductivity of the layer.

To obtain the total hydraulic resistance for several sedimentary layers above an aquifer the hydraulic resistances for each sedimentary layer are summed, i.e.,:

$$c_t = \Sigma d_i/K_i \qquad (2)$$

for layers 1 to i.

The hydraulic resistance describes the resistance of the layers to vertical flow. It has a dimension of Time, which indicates the approximate travel time for water to move by advection downward through the various sedimentary layers under a hydraulic gradient of one. However, it should be noted that c is only an approximate travel time for water and contaminants. Factors such as hydraulic gradient, diffusion, and sorption are not considered.

The areal distribution of hydraulic resistance can be computed from borehole data. The thickness (d) of each sedimentary layer (e.g., sand, till, gravel) above the nearest-to-surface aquifer is obtained from logs of water well records and/or testholes. An aquifer is defined as any potential water-bearing unit that has a thickness of at least 0.6 m (2 ft.), or is less than 0.6 m and has at least one water well installed. In a few cases, domestic wells have been completed in silt or clay dominated units, and these are considered aquifers for AVI mapping.

Any potential water-bearing unit deeper than 5 m below ground surface is considered water-saturated, unless there is direct evidence on the water well contractor's report to the contrary.

Since hydraulic conductivity (K) determinations may not be available for each sedimentary unit, a table of estimated values is required for a given region (e.g., Freeze and Cherry, 1979). Along the interprovincial boundaries in the Prairie Provinces, the estimates listed in Table 2 are believed to be reasonable.

Table 2. Hydraulic conductivity (K) estimates for various sediments in the Canadian Prairies

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

[a] 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.

[b] estimate based on Freeze and Cherry (1979)

[c] estimate based on Keller *et al.* (1988)

[d] assumes that fractures diminish downward

After the c or log(c) values are calculated for each borehole the values are then used directly to generate iso-resistance contour maps. However, rather than using numerical values for presentation of information in this method, the hydraulic resistance is related to a qualitative Aquifer Vulnerability Index (AVI), as shown in Table 3.

Considering this scheme, and the K estimates given in Table 2, a profile on the Prairies will have an extremely high vulnerability if 3.7 m or less of fractured clayey till covers the aquifer. On the other hand, a cover of more than 46 m of clayey till or 13.6 m of massive clay and/or shale will have an extremely low vulnerability rating.

Table 3. Relationship of aquifer vulnerability index to hydraulic resistance (from Van Stempvoort *et al.*, 1993)

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

Capabilities and Limitations of the AVI Method

Groundwater vulnerability maps can be used to help define protective land-use zones over large geographic regions, or can be used as a preliminary screening tool for site selection. However, since groundwater vulnerability maps are based on regional-scale geological or soil data, they alone cannot be used to choose specific sites for land-use in which groundwater contamination is a major risk. For such cases, detailed site-specific investigations are required and can include contaminant-transport modelling and risk analysis.

The AVI maps in this study were generated as an information "layer" within the SPANS geographic information system (GIS) (Intera Tydac Technologies Inc., 1991). One of the advantages of using this mapping program within a GIS is the possibility of merging the AVI maps with other geographic information for the same map area. For example, one could compare the AVI maps with other GIS data such as land-use, or distributions of groundwater quality or yield. New maps could be produced by merging these layers of information. Such maps could be used to determine the most likely areas where groundwater contamination may be a problem today, or could occur in the future.

The AVI method like other groundwater vulnerability mapping methods assumes that potential sources of contamination are at or near ground surface. The maps do not take into account subsurface activities (oil and gas exploration, deep well disposal of liquid wastes, etc.), that may pose additional hazards to groundwater resources. Such hazards are best dealt with on a site by site basis, since detailed stratigraphic information at the site will be made available during drilling.

The AVI method assumes that groundwater flow is vertically downward and lateral spread of contamination (e.g., from high vulnerability areas to low vulnerability areas) is insignificant. The role of low permeability layers and the aquifer itself on the lateral spread of contamination adds a dimension of complexity to the basic controls on groundwater vulnerability. Certainly, lateral flow in aquifers and other layers is important. However, the incorporation of detailed information for lateral flow on a map of regional groundwater vulnerability would be difficult. Detailed information on aquifer boundaries, flow paths, etc. would be required. Such information is generally not available and would have to be obtained from detailed, site investigations, or studies of major aquifer systems.

Van Stempvoort *et al.* (1992; 1993) have noted some other limitations of the AVI method for mapping groundwater vulnerability. These include:

i) Certain parameters are ignored including climate, hydraulic gradient, porosity and water content of the porous media. Sorptive or reactive properties of the layers, which may be contaminant-specific are also not considered.

ii) The water well contractors' logs comprise the most extensive, available dataset for stratigraphy of the shallow subsurface of the Prairies, and provide the basic information that the AVI method requires. Most contain a record of sediment types from surface to the nearest-to-surface aquifer. Some indicate static water levels, or whether sands and gravels are water-bearing or dry. However, the water well contractors' logs vary considerably in quality and descriptive terminology. The information obtained from private well logs is complemented by provincial testhole logs that can be included in the database used for mapping groundwater vulnerability. Holes with only geophysical logs (e.g., spontaneous potential, resistivity), that are obtained primarily during oil and gas exploration, can also be used, if stratigraphic interpretations are available.

iii) The AVI method considers only nearest-to-surface aquifers, and considers each aquifer to be of equal value. 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. It does not distinguish between surficial and bedrock aquifers.

iv) The AVI method does not consider groundwater quality. Many near-surface aquifers in western Canada 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 prior to development of a scheme for designating certain aquifers as "unprotected" due to poor water quality.

v) The estimates of K for various sediment types used in the AVI method are approximations. In reality, K may vary by several orders of magnitude for each sediment type (Freeze and Cherry, 1979). Thus, the calculated values of hydraulic resistance and the corresponding AVI contours are also approximations that indicate regional patterns of groundwater vulnerability.

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

vii) In contrast to earlier methods, the AVI method uses the definition of hydraulic resistance, c, to compute a physically based value from the two parameters, K and d. However, the AVI method assigns ranges of log(c) values to a qualitative Aquifer Vulnerability Index in a subjective way.

Application To Alberta-Saskatchewan Boundary

Groundwater vulnerability maps have been constructed from 49° N to 55° N latitude on the Alberta-Saskatchewan boundary. Six maps were prepared on a 1:250,000 horizontal scale with each map covering one degree of latitude. The maps extend from the U.S. boundary north to the limit of the "settled" portion along the boundary. These are the same areas that were used for preparation of the hydrogeologic profile along the Alberta-Saskatchewan boundary (PPWB, 1985). A map showing groundwater vulnerability and a map showing distribution of data points is included for each area. For the map of data points the hydraulic resistance for each data point has been colour coded according to the ranges for groundwater vulnerability shown on the map legends.

Maps are presented herein for the following areas:

Map No. 1: Sheet 72E (Foremost, Alberta) & 72F (Cypress, Saskatchewan)
Map No. 2: Sheet 72K (Prelate, Saskatchewan) & 72L (Medicine Hat, Alberta)
Map No. 3: Sheet 72M (Oyen, Alberta) & 72N (Kindersley, Saskatchewan)
Map No. 4: Sheet 73C (Battleford, Saskatchewan) & 73D (Wainwright, Alberta)
Map No. 5: Sheet 73E (Vermilion, Alberta) & 73F (St. Walburg, Saskatchewan)
Map No. 6: Sheet 73K (Waterhen River, Saskatchewan) & 73L (Sand River, Alberta)

Digital copies of well records from the Alberta and Saskatchewan water well databases were used to prepare these maps. As well as the water well contractors' reports, these databases contain testholes drilled by various government departments such as Alberta Environmental Protection, the Alberta Research Council, the Saskatchewan Research Council, and the Geological Survey of Canada. Maps and reports produced by these organizations provided the basic geologic framework for evaluation of the AVI maps.

An area approximately 30 km on either side of the boundary was chosen for mapping. All data points within this area have been considered. Well data points from just outside the map area were also used to avoid "edge effects" during generation of the AVI contours. A total of 7260 points was used to construct the AVI maps along the Alberta-Saskatchewan boundary. All maps on the boundary were contoured together and, therefore, the number of data points on individual map sheets has not been determined. The estimated number of points for each map is given in the discussion of the individual map sheets.

A maximum allowable spacing of 6 km between data points (equivalent to a 3 km radius around each well) was chosen based on the well distribution in the majority of the maps (the "settled" portion). This spacing of the data means that the lateral continuity of groundwater vulnerability is maintained reasonably well. Zones where the spacing of wells exceeded 6 km have been labeled as lacking sufficient data for vulnerability mapping. Stand-alone geophysical E-logs from oil exploratory wells and structure testholes were not used in this mapping exercise because interpretation of these records was considered to be too time consuming for this project. Geophysical E-logs may prove useful in the future to reduce these unmapped regions.

In preparing these maps two stages of data selection and interpretation were made:

i) each water well record was screened for minimum data requirements and a single well was selected for those legal subdivisions (LSD) or quarter sections that have more than one well in them; and

ii) an aquifer horizon, if present, was selected for each well.

a) Selection of a Representative Well

To produce the groundwater vulnerability maps using automated methods the well records must be referenced to an x-y coordinate system such as UTM or geographic coordinates. Because x-y coordinates are not generally available on the provincial water well databases it was necessary to develop them as part of this mapping exercise. To avoid a large expenditure of time in developing these coordinates a computer program provided by Alberta Environmental Protection was used to convert the Dominion Land Survey coordinates to UTM coordinates. For each well in an LSD or quarter section the program computes the UTM coordinates for the centre of that LSD or quarter section and assigns the value to the well. If two or more wells exist within an LSD or quarter section, they will have the same x-y coordinate. This can cause some problem for automated contouring programs because wells with the same x-y coordinates may have different z coordinates and the program may fail when attempting to process these conflicting values. Therefore, the well records were screened and a single well was selected to represent the area in those LSDs or quarter sections that had more than one water well record. All wells were also checked and some were eliminated if they had missing data. The screening criteria used to select these wells were the following:

i) Wells that were not located to the nearest LSD or quarter section were generally eliminated. In a few cases, wells that were located by section only were arbitrarily given a quarter section location of NE in areas with limited data.

ii) Wells that had missing log intervals were generally eliminated. In areas with limited data the well may have been kept if the interval was less than a metre or two and within the top 10 m. The shallow geologic materials are assumed to be affected by fracturing and weathering and are commonly assigned permeability codes of E and F.

iii) Wells that had the highest AVI (i.e., the shallowest aquifer) were generally selected to represent the LSDs or quarter sections. In a few cases the selected wells may not be completely representative of wells in that area. For example, if a deep productive aquifer exists in an area, many of the drillers tend to target this zone for water well completion. However, a shallower thin aquifer in which one or two water wells have been completed may exist within the area and these wells were generally selected because they had higher AVIs.

Considering the above criteria approximately one third of the well records were rejected. The largest numbers of well records were rejected due to multiple wells in an LSD or quarter section. The provision of a more accurate well location would permit a greater subset of the data to be used and would enhance the accuracy and reliability of the maps.

b) Selection of an Aquifer Interval

Criteria used in the selection of aquifers and assumptions made during coding of the AVI are the following:

i) Any sand or gravel unit greater than or equal to 0.6 m (2 ft.) and deeper than 5 m below surface is considered saturated, unless there is evidence to the contrary. Static water levels were used to some extent to determine the top of the saturated zone. However, these levels are not considered to be completely reliable particularly where more than one aquifer zone has been penetrated by the well. Descriptors such as water-bearing, saturated or dry have been used whenever possible to determine the aquifer interval.

ii) Any sand or gravel unit 0.6 m (2 ft.) or greater in thickness and less than 5 m deep is considered saturated if there is direct evidence from descriptors and water levels or the well is shallow and the sand and gravel unit is the only possible aquifer interval.

iii) Any sand or gravel unit less than 0.6 m (2 ft.) in considered to be the aquifer interval if it is the only possible aquifer interval in the borehole.

iv) Unusual aquifer materials were occasionally selected as the aquifer interval in some areas. Coal was selected as an aquifer where greater thicknesses were present and other more obvious aquifers were not present. Silt was also occasionally picked as an aquifer when thicknesses were greater than a few metres and other possible aquifer intervals were not present.

v) Roadbed or fill at the top of the geologic log has been ignored when coding the AVI (i.e., the log is considered to begin at the bottom of the fill material). It is assumed that these fill materials are added to the existing land surface and, therefore, their presence is not representative of the surrounding land levels or materials.

vi) A few wells have no apparent aquifer interval and the total depth of the well has been coded in the AVI. These wells tend to be shallow and may have been drilled for geotechnical rather than hydrogeological purposes. They tend to give higher vulnerability indices, however, because the total thickness of materials above an aquifer has not been penetrated by the borehole.

vii) The use of ambiguous lithologic descriptions presented particular problems for coding of till, clay and shale. In Table 2 massive clay or shale is assigned a lower permeability than till. However, the terms, till and clay, are used interchangeably in most logs and clay has usually been coded as G (i.e., coded as till) even though it may be a relatively impermeable massive clay. Poorly consolidated bedrock materials are also frequently described by water well contractors without reference to their degree of lithification. Bedrock materials are described, for example, as clay, silt, sand, etc. rather than claystone, mudstone or shale, siltstone, sandstone, etc. although they may be slightly indurated. Use of the terms for indurated material is favoured because it provides a ready distinction between drift and bedrock materials. In several logs unconsolidated geologic materials including till were logged beneath shale or other bedrock materials. While this is not impossible it is improbable and one must be suspicious of the record.

For each water well or testhole, log(c) values were calculated (Eqn 2) using a spreadsheet (Appendix A). The UTM coordinates and log(c) values were then imported into the SPANS geographic information system (Intera Tydac Technologies Inc., 1991). The data were contoured using a triangulated irregular network method (quad level = 15). The contour maps show the Aquifer Vulnerability Index, from extremely low to extremely high, that corresponds to unit intervals of log(c) values (Table 3).

Conclusions

Groundwater vulnerability maps generated by the AVI method can be easily and economically produced from provincial water well databases that are amenable to electronic processing. Such maps encourage consideration of aquifer protection in land use planning and assist in public education about the importance of groundwater. The amount of detail on each map depends on the density of the well data. The maps should not be used alone but should be used in conjunction with other information including geologic and hydrogeologic data to choose specific land use sites. Information on groundwater quality and aquifer boundaries, porosity and hydraulic gradients are also important considerations for site selection. Data at sites where groundwater contamination is a major risk should be collected through detailed site-specific investigations.

The AVI method is not designed to be a detailed aquifer vulnerability mapping methodology because

i) it does not differentiate aquifers within a stratigraphic profile but rather considers only the nearest-to-surface aquifer at each site; and

ii) it does not consider parameters such as porosity, hydraulic gradients, groundwater quality and sorptive or reactive properties of geologic materials.

For detailed aquifer vulnerability mapping, a method for identification and classification of aquifers is needed. High priority aquifers would be identified based on parameters such as groundwater use and aquifer susceptibility to contamination. Detailed studies of high priority aquifers would then be undertaken to define aquifer boundaries, hydrogeologic properties, groundwater flow systems and recharge/discharge areas that could be used for specific site selection, aquifer protection through land use regulation, etc.

The AVI method has been used to produce groundwater vulnerability maps on a 1:250,000 horizontal scale for six map areas along the Alberta-Saskatchewan border. This relatively simple method is useful for determining susceptibility of groundwater to contamination over large geographic areas. The accuracy and reliability of the method for determining groundwater vulnerability would be improved if the following were implemented:

i) well locations are obtained by using, for example, a Global Positioning System to generate precise geographic coordinates which would allow a larger subset of the provincial water well records to be used;

ii) reliable lithologic logs are collected at the time the well is being drilled preferably using a standardized method for reporting and storing well data in digital format (e.g. field data acquisition system); and

iii) geophysical E-logs from oil exploratory wells and structure test holes are interpreted and used in the mapping.

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APPENDIX A

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

Digital data extracted from provincial water well databases for each of the map areas were entered into simple Microsoft EXCEL and LOTUS 123 spreadsheets. Each well record was then screened for minimum data requirements and a single well was selected for those legal subdivisions or quarter sections that have more than one well in them. The selection criteria are described in the main report. Table A1 gives an example of a portion (several wells) of a spreadsheet based on these records. The information includes well location (columns A through E); depth of lower boundary (column M) and type (column N) for each sedimentary layer from ground surface. Depths, in feet, were obtained from the provincial databases. These were converted to metres during data entry. The depth of the static water level, if available, was also included in the working spreadsheets to help determine the depth of the uppermost saturated aquifer. However, these levels are not considered to be completely reliable particularly where more than one aquifer zone has been penetrated by the well. All sands and gravels below 5 m from ground surface were generally considered saturated unless the well log specifically indicated otherwise. The static water levels have not been retained on the final spreadsheets. The lithologic log immediately above the aquifer interval has been underlined in the spreadsheets to indicate the top of the aquifer selected for each well. Details on the criteria used to select the aquifer intervals are discussed in the main report.

After entry was completed, columns were added to the spreadsheet for codes and calculation of log(c), where c = hydraulic resistance, for each well. Column H is the assigned standard code (A through H) for the hydraulic conductivity of the sedimentary layers based on Table 2 of this report. Standard letter codes were used for manual coding of hydraulic conductivity because it was easier and quicker to enter letter codes than numeric values in the spreadsheets. Numeric values were substituted for the letter codes during calculations of log(c). Some rules of thumb were applied during coding: 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.

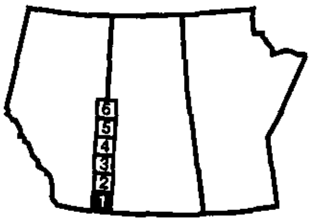
Column I is the thickness, d, based on depth ranges in column M. Till, clay or shale less than 10 m below ground surface is assumed to be affected by fracturing and weathering (see Table 2). Therefore, thick till, clay or shale layers near the surface are frequently subdivided into depth ranges of 0 to 5 m, 5 to 10 m and greater than 10 m. Columns J through L are the calculations of log (c) for each well based on columns H and I. Column J is the hydraulic resistance, d/K, for each sedimentary layer. Column K is the sum of the hydraulic resistances for sedimentary layers above the uppermost aquifer in each well. Column L is the log of the sum in column K.

The well locations (columns A to E) were then exported in a space separated ASCII format and run through the program WELLMAP1 (written by D. K. Bingham, Alberta Environmental Protection). This program converted land descriptions, based on the Dominion Land Survey system, to UTM coordinates. The conversion required separate files containing UTM coordinates for the NE corners of all sections in the map areas. For Saskatchewan, the UTM coordinates for the northeast corners were obtained from the Saskatchewan Property Management Corporation. For Alberta, the UTM coordinates for the section corners were provided by Alberta Environmental Protection. After conversion, the UTM coordinates for the wells were then added to the spreadsheet (columns F and G).

Finally, the log(c) values, along with the UTM coordinates (columns F, G and L of Table A1) were exported to an ASCII file. This file was used for input into the SPANS geographic information system contouring package. The data were contoured using a triangulated irregular network method (quad level = 15). A contour interval corresponding to unit intervals of log(c) values was selected for contouring. These contour intervals were equated to aquifer vulnerability indices (AVIs) as shown in Table 3 of the main report. The legend on the maps is given in AVI units, rather than the corresponding log(c) values.

Table A1 - Sample of spreadsheet data used to prepare AVI maps

A	B	C	D	E	F	G	H	I	J	K	L	M	N
QTR	SEC	TWP	RGE	WM	NORTHING (METRES)	EASTING	CODE	THICK (M)	YEARS		LOG(c)	DEPTH (M)	LITHOLOGY
SW	4	1	26	1	5429211	360440	E	5.0	13.7	753.4	2.88	12.2	BLUE CLAY
SW	4	1	26	1			F	5.0	137.0			19.8	SAND AND GRAVEL
SW	4	1	26	1			G	2.2	602.7			22.9	SANDSTONE
SE	10	1	26	1									
SE	10	1	26	1	5430854	362825	E	5.0	13.7	85.5	1.93	7.6	BLUE CLAY
SE	10	1	26	1			F	2.6	71.8			15.2	SAND AND GRAVEL
SE	10	1	26	1								22.9	SHALE
SE	10	1	26	1								30.5	SANDSTONE
NE	14	1	26	1									
NE	14	1	26	1	5432434	363677	E	5.0	13.7	1164.4	3.07	13.7	BLUE CLAY
NE	14	1	26	1			F	5.0	137.0			19.8	GRAVEL AND STONES
NE	14	1	26	1			G	3.7	1013.7			38.1	SANDSTONE
SW	14	1	26	1									
SW	14	1	26	1	5433258	364462	E	5.0	13.7	16900.8	4.23	5.2	BROWN TILL
SW	14	1	26	1			F	0.2	4.9			5.5	COARSE GRAVEL
SW	14	1	26	1			A	0.3	0.0			10.7	BROWN TILL
SW	14	1	26	1			F	5.2	142.5			19.8	GREY TILL
SW	14	1	26	1			G	9.1	2493.2			23.2	SOFT GREY SHALE OR CLAY
SW	14	1	26	1			H	5.2	14246.6			25.0	GREEN SHALE
SW	14	1	26	1								25.6	HARD SHALE
NW	22	1	26	1									
NW	22	1	26	1	5434924	362058	E	2.4	6.6	6.6	0.82	2.4	SANDY CLAY
NW	22	1	26	1								6.4	GRAVEL SAND& CLAY
SW	24	1	26	1									
SW	24	1	26	1	5434116	365318	E	5.0	13.7	3758.9	3.58	0.9	TOPSOIL
SW	24	1	26	1			F	8.7	238.4			1.8	TILL, LIGHT BROWN
SW	24	1	26	1			G	0.6	164.4			5.5	TILL, BROWN
SW	24	1	26	1			H	1.2	3342.5			13.7	TILL, GREY BROWN
SW	24	1	26	1								14.3	TILL, GREY
SW	24	1	26	1								15.5	SHALE, GREY, FIRM, SILTY CLAY
SW	24	1	26	1								16.8	SILTY SANDSTONE, GREEN, FAIRLY HARD SHALE
SW	24	1	26	1								18.6	SANDSTONE, GREEN, HARD
SW	24	1	26	1								22.9	SILTY SANDSTONE, GREEN, FAIRLY HARD
SW	24	1	26	1								23.2	SHALE, GREY AND GREEN, HARD, SILTY



MAPS 72E & 72F

72E Foremost, Alberta
72F Cypress, Saskatchewan

2

The Cypress Hills are the dominant physiographic feature of this map sheet. Drift cover is generally thin throughout most of the area and Cretaceous and Tertiary bedrock is exposed in the Cypress Hills. The upland was largely unaffected by glaciation. The greatest thickness of drift occurs farthest away from the Hills in the northern and southern extremities of the area.

Surficial geologic mapping for Saskatchewan (SRC, 1987) and Alberta (Westgate, 1968) indicates that till is the predominant cover where glacial sediments are deposited. Borneuf (1976) notes that surficial deposits have minor importance as sources of groundwater but there are some local occurrences of important drift aquifers in the map area. The valleys of Battle, Middle, Medicine Lodge and Boxelder Creeks and the Frenchman River follow, for at least part of their course, glacial meltwater channels that contain alluvial and glaciofluvial gravel, sand and silt. Westgate (1968) also mapped several large and small eskers made up of sand and gravel in the southeast corner of Alberta. These deposits provide sufficient quantities of groundwater for livestock and domestic water supplies. Mapping by SRC (1989) has also identified surficial sand and gravel that extend into the area in townships 10 and 11, range 27 and along the boundary in townships 11 and 12.

In Saskatchewan, intertill sand and gravel are found in townships 4 and 5, ranges 28 and 29. Their depth ranges from 30 to 45 m (SRC, 1989). Sand and gravel lying between till and the bedrock surface are found from 25 to 35 m deep in townships 10 and 11, range 27 near Maple Creek, Saskatchewan (Whitaker, 1976; SRC, 1989). This latter deposit is used for the town water supply. PPWB (1985) also notes that buried gravels resting on the bedrock surface are present near Irvine, Alberta, where the depth to bedrock can be 60 m. It goes on to state, however, that the water is high in sodium and sulphate and its quality is marginal.

A cross-section along the boundary (PPWB, 1985) identified two buried bedrock valleys. The Jaydot Valley crosses the boundary in the northern part of township 3 and the southeasterly-trending Wild Horse Valley crosses into the U.S. in the southwestern part of township 1, range 1. Three, coal testholes in the Wild Horse Valley in townships 3 and 4, ranges 3 and 4 found significant thicknesses of sand and gravel. It is expected that good well yields should be available in this area.

A northerly-trending unnamed valley located 2 km west of the boundary in townships 9 to 11 crosses into Saskatchewan at the southeast corner of township 12 (Westgate, 1968; PPWB, 1985). There are insufficient testhole data to determine the nature of the channel deposits but it is noted that the town of Irvine draws water from an aquifer in this valley.

There are numerous bedrock aquifers within the area. The youngest of these aquifers, the Tertiary Cypress Hills Formation, is composed of quartzite and chert gravel and conglomerate interbedded with sandstone, silt and clay. It caps the highest portions of the Cypress Hills. The underlying Tertiary Ravenscrag Formation and Cretaceous Frenchman, Battle, Whitemud and Eastend Formations are composed of interbedded fine- to coarse-grained sand, silt, shale and lignite. The sand, siltstone and coal beds form the main aquifers. The thickness of the Eastend to Cypress Hills Formations is greater than 200 m (SRC, 1989). These formations are confined to the higher parts of the Cypress Hills and peripheral contact springs drain all of these aquifers.

The Bearpaw Formation underlies the Eastend Formation and is composed of a dark marine shale with interbedded siltstone and sandstone. Three sandstone members occur in the upper part of the Bearpaw Formation. These sandstone members are confined to townships 6 to 9 in the map area and become thinner to the east (Furnival, 1950) and north (Whitaker, 1976: PPWB, 1985).

Underlying the Bearpaw Formation, the Judith River Formation is composed of interbedded fine-grained sandstone, siltstone and shale. The formation is found throughout the map area and subcrops beneath the drift in the northwestern (townships 11 and 12) and southwestern (townships 1 to 3) parts of the area. More than 180 m of Judith River Formation sediments are found south of the Cypress Hills upland. These sediments are less than 100 m thick at the northern edge of the map (SRC,1989). Sandstone and coal seams near the top of the formation may provide potable water in the subcrop areas.

The sandstone beds of the Milk River Formation underlying the Judith River Formation are only found in the extreme southwest corner of the map area. North and east of this area the sandstone grades to shale and is included in the Lea Park Formation. Several flowing wells have been drilled to the Milk River Formation in township 1, range 2 but the groundwater quality is only suitable for livestock use (PPWB, 1985). The base of groundwater exploration has been defined by the PPWB (1985) to be the base of the Judith River Formation. However, they note that the slightly saline water from the Milk River Formation could provide stock water in the extreme southern portion of the map.

Approximately 900 well and testhole records were used to prepare the AVI map. Except for isolated clusters, data points for townships 1 to 8 are sparse and the distribution of groundwater vulnerability in this area is a simplified interpretation of the actual conditions. A few areas are outside the maximum allowable spacing of 6 km between data points but these areas are small and isolated and, therefore, have not been blanked out on the map.

The high vulnerability in townships 6 to 9 in Alberta is most likely associated with the sand and gravel that outcrop in the Cypress Hills and with erosional deposits around the margins of this upland. Higher vulnerabilities in Saskatchewan are also associated with the Saskatchewan portion of the Cypress Hills. In addition, higher vulnerabilities are related to valley fill sediments along the present-day valley of Battle Creek. An area of high vulnerability in the extreme northeast corner of the map is likely due to surficial sand and gravel that have been mapped in this area (SRC, 1987; SRC,1989).

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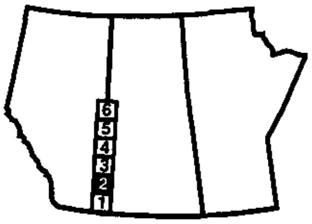

MAPS 72K & 72L

72K Prelate, Saskatchewan
72L Medicine Hat, Alberta

3

Drift cover throughout the map area ranges from 50 to 60 m in the southern part to more than 120 m over buried valleys (Carlson, 1970; Stevenson and Borneuf, 1977; PPWB, 1985). Surficial geologic mapping for Alberta (Berg and McPherson, 1972) and Saskatchewan (SRC, 1987) indicates that this area is fairly extensively underlain by till and glaciolacustrine deposits. However, glacial meltwater channels in townships 12 to 16 and the South Saskatchewan and Red Deer River valleys contain glaciofluvial and alluvial deposits of gravel, sand and silt that may form significant aquifers. Extensive surficial deposits of sand are found west of the South Saskatchewan River in townships 19 to 22, ranges 1 to 3. East of the river they extend in a band from the northern part of township 18, range 3 to township 21, range 27. An area of glaciofluvial and glaciolacustrine sand also extends south and east from Many Island Lake situated on the boundary in township 13 and the southern part of township 14.

In Saskatchewan, an intratill, sand and gravel aquifer of the Floral Formation is found at a depth of about 25 m in township 19, ranges 27 to 29. Interglacial sand and gravel between the lowermost till of the Floral Formation and the uppermost till of the Sutherland Group are found in township 13, range 27. Their depth ranges from 21 to 55 m. They also occur at about the same depth in township 21 and the northern part of township 20, ranges 27 to 29 (SRC, 1990). In Alberta, the villages of Hilda and Empress obtain water from gravel units within the till. The gravel unit at Empress is expected to have a hydraulic connection with the nearby Red Deer River (PPWB, 1985).

PPWB, 1985 indicates that two major buried valleys, the Calgary and Lethbridge Valleys (Carlson, 1970), join about 24 km west of the boundary to form a single valley that passes into Saskatchewan at townships 22 and 23. This valley has been named the Tyner Valley in Saskatchewan (David and Whitaker, 1973). Empress Group sediments consisting of interbedded sand, silt and gravel fill the lower part of these valleys (Stevenson and Borneuf, 1977; SRC, 1990) and form important aquifers in the area.

Other linear depressions have been identified on the bedrock surface in this area (Carlson, 1970; David and Whitaker, 1973; PPWB, 1985) but their exact delineation is difficult due to a shortage of testhole control. A northeasterly-trending unnamed valley crosses the boundary in the northern part of township 18 and joins the Tyner Valley in townships 21 and 22, range 27. SRC (1990) has mapped Empress Group sediments in this valley and a basal sand unit within the valley fill has been identified near Hilda, Alberta (Bland, 1975). In Saskatchewan, the depth to Empress Group aquifers is generally greater than 100 m. In present-day river valleys, however, the depths would not be as great.

Remnants of the Bearpaw Formation are present mainly in the central portion of the map from townships 15 to 22. The Bearpaw Formation is a dark marine shale with interbedded siltstone and sandstone. In Saskatchewan, the Matador sandstone member is only present townships 16 and 17, ranges 28 to 30 (SRC, 1990).

The Judith River Formation underlies the Bearpaw Formation and is composed of fine-grained sandstone, siltstone and shale. The sandstone and coal seams near the top and base of the formation are potential aquifers. The Judith River Formation ranges up to 125 m in thickness throughout the map area except for the northeast corner where the formation has been eroded in the Tyner Valley. The Lea Park Formation underlies the Judith River Formation and is composed of a thick sequence of dark grey marine shales. The Ribstone Creek sandstone is a tongue of the Judith River Formation within the upper part of the Lea Park Formation. Mapping by PPWB (1985) shows the Ribstone Creek to be present along the boundary but hydrogeological cross-sections prepared by Tokarsky (1987) do not show the Ribstone Creek in the Alberta portion of the area. McLean (1971) indicates that the Ribstone Creek merges with the Judith River Formation near the border; it may not be identifiable as a separate aquifer in the Alberta portion of this area.

PPWB (1985) has placed the base of groundwater exploration at the base of the Judith River Formation. In Saskatchewan, the Ribstone Creek tongue is also considered a potential aquifer and David and Whitaker (1973) have placed the base of groundwater exploration at the base of the Ribstone Creek tongue. David and Whitaker (1973) indicate that drift aquifers are the principal source of groundwater in the Saskatchewan portion of the map area. They are commonly the only aquifers where the Lea Park Formation forms the bedrock surface.

Approximately 1500 wells and testhole records were used to prepare the AVI map. The density of data points is fairly uniform throughout the map and good control on the lateral continuity of groundwater vulnerability would be expected.

A zone of higher vulnerability is generally associated with glaciofluvial and alluvial deposits in the South Saskatchewan and Red Deer River valleys and with surficial sand deposits east and west of the South Saskatchewan River. An area of low to extremely low vulnerability between the South Saskatchewan and Red Deer Rivers in range 3 may not be entirely indicative of conditions in this area. The area west of the South Saskatchewan River in townships 19 and 20, range 3 is covered by extensive surficial sand deposits but the area is shown to have a low vulnerability. There are few data points in township 19 and the southern part of township 20 and control on the distribution of the vulnerability zones in this area may be lacking.

The area of high vulnerability in the southeast corner of the map is generally associated with an area of glaciofluvial, glaciolacustrine and eolian deposits in this area (SRC, 1987).

The intertill, intratill and bedrock valley aquifers are not indicated by any pattern of groundwater vulnerability in the map area. These aquifers generally are covered by 20 m or more of fractured clayey till and their vulnerability would be expected to be low.

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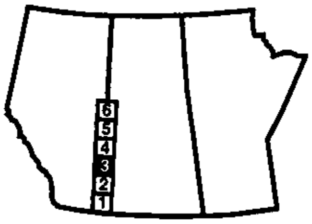

MAPS 72M & 72N

72M Oyen, Alberta

72N Kindersley, Saskatchewan

4

The surficial deposits in this map area are generally less than 50 m thick but may attain a thickness of 100 m or more over buried bedrock valleys. Much of the Saskatchewan portion of the area is covered by till and glaciolacustrine deposits (SRC, 1986). Minor glaciofluvial and glaciolacustrine deposits possibly containing coarser grained materials are found at the surface in townships 31 and 32. Elsewhere, isolated sand and gravel deposits are found in areas of hummocky moraine but they are not expected to be extensive or to form significant aquifers in the area. Kunkle (1962) outlined areas in Alberta underlain by shallow, lacustrine sand, outwash sand and gravel and alluvial deposits that could have good groundwater potential. The areas include the Sounding Creek valley in townships 30 to 33, ranges 2 and 3 and the headwaters of a tributary of the Red Deer River in townships 24 to 26, range 2. Less extensive areas were also identified along the boundary in townships 28, 32 and 33, range 1.

In townships 34 and 35 in Saskatchewan, an area of intratill, silt, sand and gravel of the Floral Formation has been mapped at depths of 10 to 20 m. Around Alsask, sand and gravel between the lowermost till of the Floral Formation and the uppermost till of the Sutherland Group are found at depths of 10 to 15 m. The confined aquifer in this area is characterized by flowing wells. Intertill and/or intratill deposits 25 to 35 m deep in the Sutherland Group are found in township 26 and the southern part of township 27, range 27 (SRC, 1988).

Based on mapping by Carlson (1970) and Christiansen *et al.* (1980), PPWB (1985) identified the southerly-trending Eyre Valley in Saskatchewan as the principal buried bedrock valley in the area. A southeasterly-trending tributary, the Sibbald Valley, crosses the boundary at township 27. A second, less-pronounced, unnamed, easterly-trending valley crosses the boundary in the northern part of township 31 and may be another tributary to the Eyre Valley. The cross-section along the boundary (PPWB, 1985) does not show any Empress Group sediments filling these valleys but Borneuf (1979) found minor sand and gravel lenses in the Sibbald Valley. SRC (1988) has mapped Empress Group clay, silt, sand and gravel deposits at depths of 50 to 100 m along the Eyre Valley. SRC (1988) has also mapped a sand deposit on the bedrock upland west of the Eyre Valley in township 24, ranges 28 and 29. The depth to this sand deposit varies from 35 to greater than 100 m as one approaches the Eyre Valley.

Except in the area of the bedrock valleys where the underlying Judith River and Lea Park Formations have been exposed, the bedrock beneath the drift is the marine Bearpaw Formation shale. The sandstone members in the Bearpaw Formation are scarce throughout the map area but SRC (1988) has mapped middle and lower silt and sand members in townships 31 to 35, ranges 26 and 27. The lower sand member also extends into the map area in township 26, ranges 26 and 27.

The Judith River Formation is an interbedded fine-grained sandstone, siltstone and shale. The sandstone and coal seams near the top and bottom of the formation are potential aquifers throughout the map area. The thickness of the Judith River Formation ranges from 0 where it is eroded in the Eyre Valley to greater than 100 m.

The Lea Park Formation underlies the Judith River Formation and is composed of a thick sequence of dark grey marine shales. The Ribstone Creek, a sandstone tongue of the Judith River Formation within the upper part of the Lea Park Formation is found north of township 27 in the map area. The effective base of groundwater exploration is considered to be the top of the Lea Park Formation throughout much of the area (Christiansen *et al.*, 1980; PPWB, 1985; Tokarsky, 1987) but the Ribstone Creek tongue may be a possible aquifer in the northwest corner of the area (Tokarsky, 1987).

Approximately 1700 well and testhole records were used to prepare the AVI map. The density of data points is fairly uniform throughout the area and, therefore, good control on the lateral continuity of groundwater vulnerability would be expected.

The areas of higher vulnerability in Alberta generally coincide with areas of shallow sand and gravel identified by Kunkle (1962). The apparent lack of shallow sand and gravel in Saskatchewan (SRC, 1986; SRC, 1988) does not account for the distribution of high vulnerability areas in Saskatchewan. The shallow intertill sand and gravel in the Alsask area may account for some higher vulnerability in townships 27 and 28, ranges 28 and 29. The rest of the intertill, intratill and bedrock valley aquifers are generally greater than 20 m deep and would be expected to have a low vulnerability.

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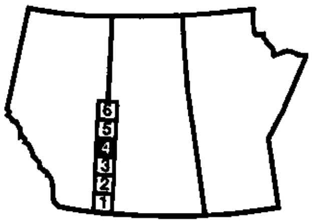

MAPS 73C & 73D
73C North Battleford, Saskatchewan
73D Wainwright, Alberta

5

Thickness of the drift ranges from a few metres to more than 150 m over buried bedrock valleys. In Alberta, a large portion of the area is underlain by surficial deposits of eolian sand and glaciofluvial and glaciolacustrine sand and gravel. A large, outwash, sand and gravel plain in townships 42, 43 and the southern part of 44, range 3 is thought to be deltaic in origin (Bayrock, 1967). An area of eolian and glaciofluvial sand and gravel between Manitou Lake, Saskatchewan and Chauvin, Alberta straddles the boundary in townships 40 to 43. Commercial gravel deposits have been developed southwest of Chauvin (Bayrock, 1967) and high well yields can be obtained. Smaller areas of eolian and glaciolacustrine sand are found south of the Battle River in ranges 1 and 2 and between Provost and Sounding Lake in townships 37 to 39, ranges 2 and 3. Outwash sand and gravel deposits in township 37, ranges 1 and 2 are generally quite thin.

Extensive surficial deposits of sand and gravel are not as common in Saskatchewan (SRC, 1987). Nevertheless, silt, sand and gravel near the top of the Floral Formation are found at depths of 20 to 36 m in township 35, range 27; at 10 to 60 m in townships 36 and 37, ranges 26 and 27 and at 1 to 26 m in township 40, ranges 26 and 27. Deeper, glacial, sand and gravel deposits at the base of the Floral Formation and within the Sutherland Group are also found extensively throughout the Saskatchewan portion of the area (SRC,1988).

Glaciofluvial and alluvial sand and gravel deposits are found along the Battle River valley, along the Sheppard Slough valley southeast of Macklin and along the Eyehill Creek valley from southwest of Macklin to Manitou Lake. The latter two valleys, which join near Macklin, extend westward into Alberta and form an aquifer near St. Lawrence Lake in township 39, range 1. This aquifer is used by the town of Provost (Tokarsky, 1977).

Mapping by PPWB (1985) has identified a major buried bedrock valley called the Battleford Valley in Saskatchewan (Christiansen, 1967) and the Wainwright Valley in Alberta (Carlson and Topp, 1971). This valley crosses the boundary at townships 42 and 43. A southwesterly-trending, unnamed tributary of the Battleford Valley in Saskatchewan crosses the boundary in township 39 but does not appear to extend any great distance into Alberta. These valleys contain up to 15 m of chert gravel and sand and provide important aquifers.

The Bearpaw Formation is the youngest bedrock formation subcropping beneath the drift in the map area. This formation, which is composed of dark marine shale interbedded with siltstone and sandstone, becomes discontinuous north of township 37 and completely disappears north of township 41. Minor thin sandstone beds are used locally in the upland area at the southern edge of the area but these beds can only provide very low quantities of groundwater.

The underlying Judith River Formation becomes discontinuous immediately south of the Wainwright-Battleford Valley and some small outliers of this formation are found north of the valley. The Judith River Formation, which is composed of interbedded fine-grained sandstone, siltstone and shale, forms the most important bedrock aquifer south of township 41 where its thickness may be greater than 350 m.

The Ribstone Creek sandstone, a tongue of the Judith River Formation within the upper part of the Lea Park Formation, is the most important bedrock aquifer north of township 41. The Victoria tongue is another sandstone tongue of the Judith River Formation within the upper part of the Lea Park Formation. North of the Wainwright-Battleford Valley it is used locally where the Ribstone Creek tongue is thin, poorly developed or absent due to erosion. Yield and quality are similar to the Ribstone Creek tongue.

The Lea Park Formation is a thick sequence of dark grey marine shales. No aquifers are found in this formation. Mapping (PPWB,1985; Tokarsky, 1987) has placed the base of groundwater exploration at the base of the Victoria tongue north of the Wainwright-Battleford Valley. Between township 41 and the Wainwright-Battleford Valley, the base of groundwater exploration is at the base of the Ribstone Creek tongue (PPWB, 1985; Tokarsky, 1987). Although PPWB (1985) has placed the base of groundwater exploration at the base of the Judith River Formation south of township 41, mapping by Tokarsky (1987) would suggest that the base of the Ribstone Creek tongue should be the base of groundwater exploration throughout the remainder of the area.

Approximately 1900 well and testhole records were used to prepare the AVI map. The density of data points is fairly well distributed except for a zone extending northwestward from townships 42 and 43 in Saskatchewan to townships 43, 44 and the southern part of 45 in Alberta. In this area the density of data points is quite low and the distribution of groundwater vulnerability shown on the map may be a simplified interpretation of the actual situation.

The high vulnerability in townships 41 to 43 in Saskatchewan is associated with the outwash sand and gravel in townships 42 and 43 and the eolian and glaciofluvial sand between Manitou Lake and Chauvin. The area of high vulnerability in townships 36 to 38, ranges 2 and 3 is also associated with surficial eolian and glaciolacustrine sand in this area. In his study of the hydrogeology of the Wainwright area, Topp (1974) states:

> "The geologic setting, while providing ample potential for groundwater development, offers similar potential with respect to groundwater pollution. Careful consideration must be given to the selection of sites for sewage and garbage disposal"

Although meltwater channels and the valley of the Battle River are found in this area, trends in groundwater vulnerability associated with sand and gravel deposits along these channels are not prominent. Similarly, trends are not associated with the intertill, intratill and bedrock valley aquifers because these aquifers are generally greater than 20 m deep and would be expected to have a low vulnerability. The other areas of high vulnerability are apparently related to isolated sand and gravel deposits in the till and glaciolacustrine clay. Generally lower vulnerabilities are found along the boundary from townships 35 to 37 and in the northwest corner of the map area.

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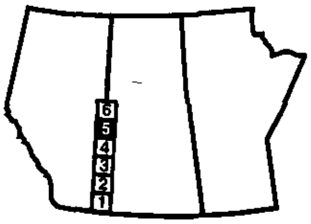

MAPS 73E & 73F

73E Vermilion, Alberta
73F St. Walburg, Saskatchewan

6

Drift thickness ranges from less than 15 m to greater than 120 m and is greatest over the buried bedrock valleys in the map area (Ozoray *et al.*, 1994). Surficial geologic mapping for Saskatchewan (SRC, 1987) and Alberta (Shetson, 1990) shows that the area is predominantly covered with till. Alluvial and glaciofluvial gravel, sand and silt are found along the Battle River, the North Saskatchewan River, Vermilion River and Big Gully Creek valleys and along glacial meltwater channels in townships 54 and 55, ranges 25 and 26. Eskers and isolated sand and gravel deposits in hummocky moraine are found at numerous sites throughout the area. However, these surficial deposits are small and comprise a very small percentage of the total map area.

Interglacial sand and gravel between the lowermost till of the Floral Formation and the uppermost till of the Sutherland Group are found in townships 48 to 51, ranges 25 to 28. Their depth ranges from 20 to 45 m. Similar deposits also occur at depths greater than 45 m in townships 54 to 57, range 26 (SRC, 1988). Sand and gravel lenses in the till are the only source of groundwater where the Lea Park Formation subcrops in the northern portion of the map area (Currie and Zacharko, 1976).

PPWB (1985) has identified two major buried bedrock valleys that intersect on the boundary a short distance north of the city of Lloydminster. These are the northeasterly-trending Rex Valley and the southeasterly-trending Lloydminster Valley. Other valleys that occur in the area are the Vermilion Valley in townships 54 to 58, ranges 2 and 3 and the Bronson Lake Valley in townships 54 to 58, ranges 25 and 26. The Bronson Lake Valley joins the Rex Valley just east of the map area.

The Rex and Lloydminster Valleys are both steep-walled, deep, narrow valleys. Two thick sand aquifers have been identified within the Lloydminster Valley. Several industries and the town of Lashburn, Saskatchewan draw groundwater from the lower sand that rests on bedrock. Thick intervals of sand and gravel are also present in the Rex Valley. No municipal or industrial wells are known to be completed in this valley but high well yields can be expected. Some of the sand and gravel occurs as benches or terraces in these valleys. The city of Lloydminster, the towns of Marshall, Saskatchewan and Marwayne and Streamstown, Alberta and industrial wells north of Lloydminster all draw groundwater from these types of deposits.

The Judith River Formation is the youngest bedrock formation in the area. It subcrops beneath the drift in townships 46 to 50, ranges 2 and 3 (PPWB, 1985). It is an interbedded fine-grained sandstone, siltstone and shale. The sandstone members near the base of this formation are not found within the area. The Ribstone Creek tongue is a tongue of the Judith River Formation within the upper part of the Lea Park Formation. It is found in almost all areas south of township 51 except where it has been removed by erosion in the bedrock valleys. It subcrops beneath the glacial drift and ranges in depth from 15 to 50 m (Ozoray *et al.*, 1994). It is the main aquifer in the southern part of this area. Communities such as Blackfoot, Kitscoty and Paradise Valley in Alberta obtain their water supply from this aquifer and there are numerous large-scale industrial users. The Victoria tongue is another sandstone tongue of the Judith River Formation within the upper part of the Lea Park Formation. It is used where the Ribstone Creek tongue is thin, poorly developed or absent due to erosion. Yield and quality are similar to the Ribstone Creek tongue.

The Lea Park Formation is a thick sequence of dark grey marine shales. No aquifers are found in this formation. The base of groundwater exploration in this area is the Ribstone Creek or Victoria tongues where they are present, and the base of the drift where they are not present.

Approximately 2000 well and testhole records were used to prepare the AVI map. The density of the data points is fairly well distributed throughout the map except for a zone in the northern and northeastern portions of the area. In this zone the spacing of wells exceeded the maximum allowable spacing of 6 km and an area has been labelled as lacking sufficient information for vulnerability mapping. Elsewhere the lateral continuity of groundwater vulnerability is expected to be good.

The largest continuous area of high to extremely high vulnerability occurs in the central portion of the map. This area corresponds approximately with surficial ice-contact fluvial and fluvial-lacustrine sand and gravel deposits, as shown on the surficial geology map for Saskatchewan (SRC, 1987) and the Quaternary geology map for Alberta (Shetsen, 1990).

Some of the zones where aquifers are highly vulnerable probably have a thin (< 8 m) till or clay cover.

There is a significant, and fairly abrupt change in the pattern of AVI zones between the central and south-southwest portion of the map. In the south-southwest region, a thick till sequence dominates the uppermost portion of the stratigraphic column, in a glacial moraine setting (Shetsen, 1990). In this region, there are only scattered, small areas of vulnerable aquifers. The buried valley and bedrock aquifers that are important in this area are not indicated by particular patterns of high vulnerability. These aquifers are generally greater than 15 to 20 m deep and are less affected by surficial sources of contamination.

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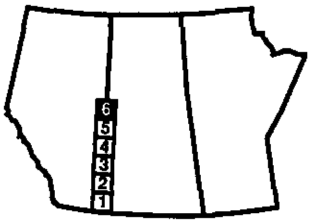

MAPS 73K & 73L

73K Waterhen River, Saskatchewan 7

73L Sand River, Alberta

Drift cover on this map ranges from about 50 m to greater than 200 m thick and attains a fairly great thickness even in areas between buried valleys. Surficial geologic mapping for Alberta (Andriashek and Fenton, 1989) and Saskatchewan (SRC, 1988) shows that much of the area is underlain by till. Surficial eskers and meltwater channels containing coarser-grained deposits are found east-northeast of Cold Lake. Glaciofluvial deposits are more common around the margins of Cold Lake but the mineral soil deposits north of the lake are generally obscured by organic materials in marshes and bogs. Alluvial deposits are found along the Beaver River and along the Cold Lake outflow channel.

South of Primrose Lake three, sand and gravel units have been identified and mapped between till sheets and at or near the base of the drift in the area. In order of increasing depth these are the Sand River Formation, the Muriel Lake Formation and units 3 and 1 of the Empress Group (Andriashek and Fenton, 1989). The Sand River Formation is a fairly extensive, interglacial, glaciolacustrine or glaciofluvial, sand and silt found near the top of the drift in townships 60 to 63. Other smaller intertill, sand and gravel lenses are also found near the top of the drift in the area. Most domestic groundwater supplies are obtained from these aquifers because they are relatively shallow. Well yields, however, may be variable and are generally low.

The Muriel Lake Formation is a thicker sand unit that is widely distributed throughout the Alberta portion of the area south of township 66. It is found within segments of the main buried valleys and channels and it is the lowermost sand and gravel unit along tributary valleys and in interfluvial areas. In Saskatchewan, Maathuis and Schreiner (1982) identified an east-west trending, basal, sand and gravel unit in the vicinity of township 60 that is probably correlative with the Muriel Lake Formation.

PPWB (1985) has identified a major bedrock valley that is most likely the Hatfield Valley (Whitaker and Pierson, 1972) passing beneath Cold Lake and connecting to the Helina Valley (Andriashek and Fenton, 1989) in Alberta. The southeasterly-trending Bronson Lake Valley (Maathuis and Schreiner, 1982; Andriashek and Fenton, 1989) and the northeasterly-trending Vermilion Valley (Andriashek and Fenton, 1989) intersect on the boundary in the southern part of township 59. Empress Group sediments are found in all the main buried valleys in the Alberta portion of the study area and are composed of preglacial (unit 1) and glacial (unit 3) sand and gravel. These sediments have also been identified in the Hatfield Valley in Saskatchewan (Maathuis and Schreiner, 1982).

Water supplies for secondary oil recovery operations have been obtained from the Muriel Lake and Empress sand aquifers in Alberta. Yields up to 260 L/s have been estimated or calculated for these aquifers (Christiansen and Whitaker; 1974; Mateyk, 1982).

A thick sequence of dark grey marine shale of the Lea Park Formation and Colorado Group forms the underlying bedrock. No aquifers are found in these formations. The base of groundwater exploration for this area is the base of the glacial drift.

Approximately 1100 well and testhole records were used to prepare the AVI map. There were insufficient data to generate contours for more than 50% of the map. Except for an area southwest of Cold Lake, the number of data points for the remainder of the area is also quite limited. Therefore, controls on the continuity of the vulnerability zones are quite general.

Groundwater vulnerability in this area predominantly ranges from moderate to extremely high. Most domestic groundwater supplies are obtained from the sand and gravel units found near the top of the drift. Vulnerability would be moderate to high where these sand and gravel units are covered by 8 m or less of till. The Muriel Lake and Empress Group aquifers that are important in this area are not indicated by particular patterns of vulnerability. These aquifers are generally covered by a thick sequence of tills and are less affected by surficial sources of contamination.

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