GROUNDWATER VULNERABILITY MAPPING ALONG THE MANITOBA-SASKATCHEWAN BOUNDARY

Prepared for the
PRAIRIE PROVINCES WATER BOARD
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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 four 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 1

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 Manitoba-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.

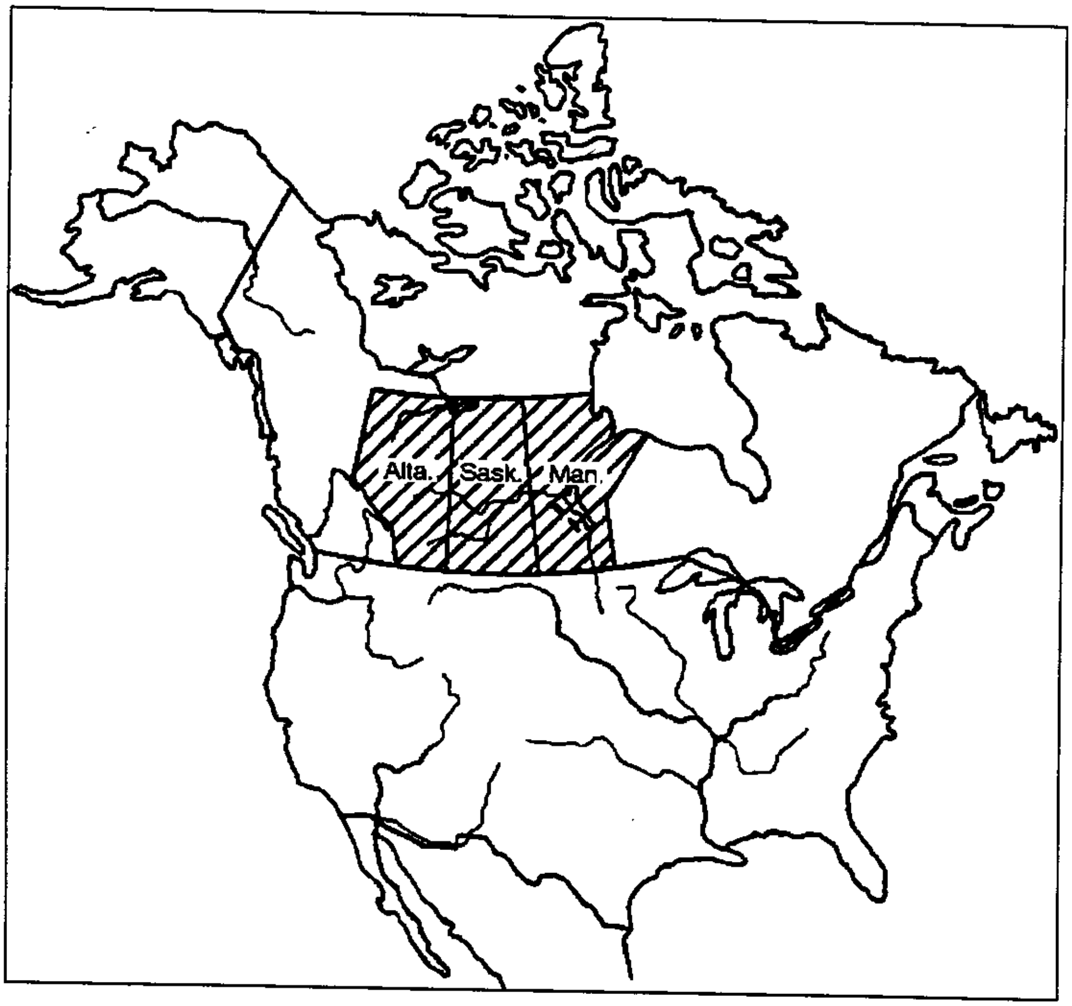

Figure 1 - Location of the Prairie Provinces

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 Manitoba-Saskatchewan Boundary

Groundwater vulnerability maps have been constructed from 49° N to 53° N latitude on the Manitoba-Saskatchewan boundary. Four 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 Manitoba-Saskatchewan boundary (PPWB, 1986). 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 62F (Virden, Manitoba/Saskatchewan)
Map No. 2: Sheet 62K (Riding Mountain, Manitoba/Saskatchewan)
Map No. 3: Sheet 62N (Duck Mountain, Manitoba/Saskatchewan)
Map No. 4: Sheet 63C (Swan Lake, Manitoba/Saskatchewan) & 63D (Hudson Bay, Saskatchewan)

Digital copies of well records from the Manitobaa 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 the Saskatchewan Research Council, the Manitoba Water Resources Branch 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 5279 points was used to construct the AVI maps along the Manitoba-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 for Saskatchewan. Up to one half of the well records were rejected for Manitoba but in most areas close to the Manitoba-Saskatchewan boundary there are more data points on the Manitoba side of the boundary. The Water Resources Branch of the Manitoba Department of Natural Resources and the Geological Survey of Canada have carried out major test drilling programs in these areas of Manitoba. 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. Along the Manitoba-Saskatchewan border, shale is considered to be an aquifer material because the Odanah shale occurs in this area, is brittle and fractured and is water-bearing. 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 four map areas along the Manitoba-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.

Acknowledgements

The AVI method was developed through a research project funded, in part, by the Prairie Provinces Water Board and undertaken by NHRI. Results of this study were reported by Van Stempvoort *et al.* (1992) to the PPWB and were published by Van Stempvoort *et al.* (1993) in the Canadian Water Resources Journal. Portions of this report are based on these previous publications and their source is generally acknowledged. Lock Gray, Manitoba Natural Resources and Nolan Shaheen, Saskatchewan Water Corporation kindly provided digital well records from their provincial databases which greatly simplified data preparation. Douglas Bingham of Alberta Environmental Protection provided a program (WELLMAP1) for conversion of Dominion Lands Survey to UTM coordinates for mapping of well locations.

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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.

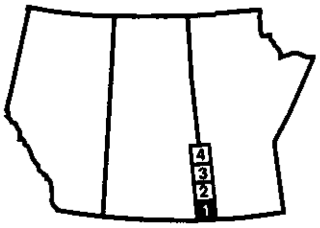
Column I is the thickness, d, based on depth ranges in column M. Till, clay or shale less than 10 m below ground surface is assumed to be affected by fracturing and weathering (see Table 2). Therefore, thick till, clay or shale layers near the surface are frequently subdivided into depth ranges of 0 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 Manitoba, the northeast corner of each section was digitized on 1:250,000 NTS map sheet and the UTM coordinates were computed for these corners by triangulation from known points on the map. For Saskatchewan, the UTM coordinates for the northeast corners were obtained from the Saskatchewan Property Management Corporation. 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



MAP 62F
62F Virden, Manitoba - Saskatchewan

2

Drift cover throughout the map area varies from less than 10 m in the extreme northeast corner to greater than 110 m in the central and southern portions of the map. Surficial geologic mapping for Manitoba (Betcher, 1983) and Saskatchewan (SRC, 1987) shows that the area in townships 1 to 4 contains the greatest amounts of glaciofluvial silt, sand and gravel at surface. The Manitoba Water Control and Conservation Branch (1968) conducted a study of groundwater availability in the Melita area that included townships 1 to 4 in Manitoba. They state, "the surficial deposits of the area consist of 25 to 350 feet of till covered by fairly extensive outwash and lacustrine deposits." They go to say that the best aquifers in the area are the outwash deposits. However, water for domestic and farm supply can also be obtained from pockets of sand and gravel in the till, lenses of sand in the lacustrine deposits and the shale bedrock.

The area north of township 4 is underlain by glacial till that is dissected by several north-south trending glacial meltwater valleys. The present-day channels and tributaries of the Antler River, Lightning Creek, Gainsborough Creek, Graham Creek, Jackson Creek, Stony Creek and Pipestone Creek follow these valleys. These long, narrow channels contain valley train deposits consisting mainly of glaciofluvial and alluvial sand and gravel up to 10 m thick (Manitoba Water Control and Conservation Branch, 1968). Studies have suggested there are few other aquifers in this region except for occasional sand lenses within the till that provide low yields to wells locally (Hydrotechnical Services Branch, 1976; Rutulis, 1980; PPWB, 1986). Intertill silt, sand and gravel deposits of the Saskatoon and Sutherland Groups are found in townships 1 and 2, ranges 32 to 34 and townships 10 and 11, ranges 31 to 33. Their depth ranges from 15 to 50 m (SRC, 1992). Rutulis (1980) outlined an area along the boundary in Manitoba from townships 5 to 9 where a satisfactory supply of groundwater is difficult or impossible to find. Groundwater possibilities for townships 10 to 12 are stated by Rutulis (1980) to be variable.

A large north-south trending buried bedrock valley, containing sand and gravel deposits, occurs just east of the village of Pierson. However, PPWB (1986) has not identified any other major bedrock valleys within the map area. The Estevan Valley has been traced to township 3, range 31 in Saskatchewan and contains Empress Group sand and locally, gravel in the map area (SRC, 1992). Empress Group sand and gravel are also found from 20 to 60 m deep in townships 10 and 11, ranges 31 to 33.

The Odanah Member of the Pierre Shale forms the underlying bedrock throughout most of this map area except for the southwest corner. In this area the Frenchman, Whitemud and Eastend Formations overlie the Pierre Shale and reach a total estimated thickness of 30 m about 20 km west of the boundary in township 1. As shown by Whitaker (1974) these formations are truncated eastwards by erosion until they become completely eroded about 5 km west of the boundary. The Tertiary Ravenscrag Formation overlies the Cretaceous Frenchman Formation in townships 1 and 2, ranges 32 and 33 in the extreme southwest corner of the map.

Hard siliceous shale makes up a portion of the Odanah Member and may be sufficiently fractured and weathered to form a good aquifer. The Manitoba Water Control and Conservation Branch (1968) states that the water-bearing beds usually occur within the upper 30 m of the shale. Nearly all of the highly fractured and weathered shale beds occur next to bedrock valleys or existing river valleys. The shale along the boundary is not fractured so it is unlikely that shale aquifers occur there. Whitaker (1974) agrees that the Pierre Shale does not form an aquifer along the boundary or farther west in Saskatchewan. He places the recommended base of groundwater exploration at the top of the Pierre Shale. Johnston (1934), however, cites several examples of wells completed in shale near the boundary. These are probably very low-yielding wells but it is important to recognize their existence. Where identifiable aquifers were not found in the overburden materials, shale at the bedrock surface was generally picked as the aquifer for this map area.

The Frenchman, Whitemud and Eastend Formations are composed of interbedded sand, silt and clay. The sand beds are potential aquifers. The Ravenscrag Formation is composed of interbedded sand, silt, clay and lignite. The sand and lignite are potential aquifers.

Approximately 1800 well logs were used to prepare the AVI map. The selection of a maximum allowable spacing of 6 km between data points meant that almost all of the map area had enough data to generate contours of iso-resistance. However, in some areas the density of data was low enough that the lateral continuity of groundwater vulnerability shown on the map may be a simplified interpretation of the actual situation.

The vulnerability mapping shows that groundwater throughout much of the map area has an extremely high degree of vulnerability. Some checking of the data was undertaken because the vulnerability rating seemed high considering the amount of till that was present in the area. The wells in townships 5, 6 and 7, range 29 along the boundary were located on the surficial geology map for the area (Betcher, 1983). Almost all of the wells are located in the narrow valley train deposits in this area where groundwater is most likely to be found. These surficial, sand and gravel deposits are, therefore, overrepresented in the dataset and the AVI map gives a higher overall groundwater vulnerability than might be expected for the area. Mapping of these narrow linear features would require a much higher density and more random distribution of data points than is available for the map area.

The pattern of groundwater vulnerability is most strongly influenced by surface and near surface sediments. The selection of shale bedrock, where no identifiable aquifers are found in the overburden material, may not be valid in all cases. Nevertheless, the selection of a deeper formation is not likely to change the vulnerability distribution because the indices for wells with shale aquifers are already low due to the thick till that overlies the shale.

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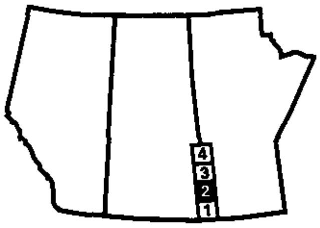

MAP 62K

62K Riding Mountain, Manitoba - Saskatchewan

3

Drift cover throughout the map area ranges from 50 m in most places to a maximum of about 100 m but is as thin as 10 m in some local areas. Surficial geologic mapping for Saskatchewan (SRC, 1986) and Manitoba (Sie, 1978) indicates that the map area is underlain predominantly by glacial till.

Fairly extensive deposits of valley-fill sands and gravels extend along the Qu'Appelle and Assiniboine Rivers. Klassen (1975) indicates that valley fill along the Qu'Appelle River is generally from 45 to 60 m thick although it is considerably thicker in some stretches. An extensive area of sand and gravel also extends north and west of the junction of the Qu'Appelle and Assiniboine Rivers in townships 17, 18 and the southern part of 19, ranges 29 and 30. This area includes the Welby aquifer described by Meneley (1972).

The Empress Group of sediments is made up of interbedded gravel, sand, silt and clay of fluvial, lacustrine and colluvial origin. These sediments, which may attain a thickness of over 150 m in some places, rest directly on bedrock and are found within the major buried valleys and on the adjacent uplands within the map area. PPWB (1986) identified two major buried valleys that cross the boundary. These valleys were named the Hatfield and Rocanville Valleys by Christiansen (1971). Major aquifers are found in and adjacent to these valleys. The Hatfield Valley aquifer crosses the boundary in townships 22 and 23 and the northern part of township 21. Within the map area it ranges from 30 m to greater than 100 m in depth and averages 70 m. The Basal aquifer, located along the south side of the Hatfield Valley, is adjacent to the boundary in township 20 and the southern part of township 21. The average depth to the Basal aquifer is about 50 m but it may range from 20 to 75 m. The Rocanville aquifer is found just west of the boundary in townships 15 to 17. Within the area it may range from 25 to 125 m in depth and averages 60 m. The Bredenbury aquifer (Potash Corporation of Saskatchewan, 1981; Schreiner and Maathuis, 1982), located on the bedrock upland north of the Hatfield Valley, is a fine- to medium-grained sand interbedded with fine-grained sand and silt.

Bedrock beneath the drift in the map area consists of the Odanah Member and undifferentiated shale of the Pierre Formation. The Odanah Member ranges from a soft to hard shale. Hard siliceous shale makes up a large part of this member and the shale is often well fractured and locally forms a low-yielding aquifer. The Odanah Member is found in the southwest and northeast portions of the area away from the valleys of the Qu'Appelle and Assiniboine Rivers where erosion has exposed the underlying undifferentiated shale. The lower part of the Pierre Formation (also called the Millwood Member) is a soft, relatively impermeable, bentonitic shale that does not form a useable aquifer.

Approximately 2500 well and testhole records have been used to prepare the AVI map. The relatively high density of data means that reasonably good control was obtained on the lateral continuity of the groundwater vulnerability ratings shown on the map.

The coarse valley-fill deposits along the Qu'Appelle and Assiniboine Rivers are indicated by an area of higher vulnerability extending in a north-south direction immediately east of the border and extending in an east-west direction west of the junction of the two rivers. The area of extremely high vulnerability in the central portion of the map area is associated with the sand and gravel of the Welby aquifer. An area of higher vulnerability in the southwest corner of the map is likely due to surficial sand that is associated with glaciofluvial deposits that have been mapped in the area (SRC, 1986).

Outside these areas, lower groundwater vulnerabilities prevail. The buried aquifers in the bedrock valleys and on the adjacent uplands are not indicated by any pattern of groundwater vulnerability for the map area. However, these sediments are covered by 20 m or more of clayey till and their vulnerability to contamination would be expected to be low.

Where identifiable aquifers were not found in the overburden materials, shale at the bedrock surface was generally picked as the aquifer for this map area. The locations of the wells with respect to the Odanah shale distribution were not checked. It is possible the undifferentiated shale below the Odanah member has been wrongly selected as an aquifer in a few cases. Since the pattern of groundwater vulnerability is most strongly influenced by surface and near surface sediments, the selection of a deeper formation is not likely to change the vulnerability distribution. The indices would already be low due to the thick till that overlies the shale.

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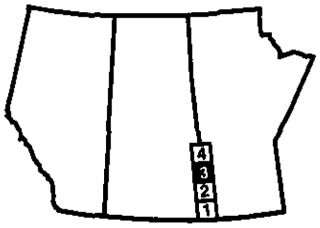

MAP 62N
62N Duck Mountain, Manitoba - Saskatchewan

4

The Duck Mountain Upland is the dominant topographic feature on this map sheet. The drift cover over the upland usually exceeds 100 m and can be up to 200 m thick. The cover is also quite thick south of Duck Mountain, although here it is less than 80 m. It becomes thin at the north end of the map area in the Swan River Lowland where it is less than 30 m thick.

Surficial geologic mapping for Saskatchewan (SRC, 1986) and Manitoba (Little and Sie, 1976) indicates that the area is underlain mainly by glacial till. The present-day valleys of the Assiniboine and Shell Rivers contain valley-fill sediments. More extensive areas of glaciofluvial silt, sand and gravel are found at surface along the Assiniboine River in townships 25 to 27, in the headwaters of the Shell River and in the Swan River Lowland.

Intertill deposits of silt, sand and gravel between the lowermost till of the Floral Formation and the uppermost till of the Sutherland Group, are found in townships 24 to 26, ranges 30 to 33.Their depth ranges from 10 to 30 m. Intertill and/or intratill granular deposits that are part of the Floral Formation or the Sutherland Group are found beneath the Duck Mountains in townships 29 to 32. The Floral Formation sediments may be quite shallow but the Sutherland Group sediments are found at depths of 100 m or greater (SRC, 1991).

Except for an area along the boundary in townships 23 to 25, ranges 30 and part of 31, interbedded fine-grained sand and silt of the Bredenbury Formation is found west of the Assiniboine River as far north as township 28. Depths range up to 50 m but can be as little as 9 m. Average depth to the Bredenbury aquifer is about 30 m (Potash Corporation of Saskatchewan, 1981; SRC, 1991). The Bredenbury Formation is believed to be preglacial in age and is differentiated from Empress Group sediments although there may be difficulty in distinguishing between the two units in some areas. Empress Group sediments are found in the same area as the Bredenbury Formation. Tertiary sand and gravel were also identified at the base of the overburden in townships 31 and 32 in Manitoba (Little and Sie, 1976).

No buried bedrock valleys have been identified in this map area (PPWB, 1986) but the Assiniboine River has eroded a valley in the bedrock along the course of the river.

The Pierre Formation forms the underlying bedrock over most of the area but the Odanah Member is not present. The underlying Niobrara Formation, Morden Shale, Favel Formation and Ashville Formation subcrop in the Swan River Lowland. These formations are mainly dark gray to black carbonaceous shales containing bentonite and useable aquifers are not found in them.

Mapping by Cherry and Whitaker (1969) and the PPWB (1986) placed the base of groundwater exploration at the top of the bedrock. However, unconsolidated quartz sand and sandstone of the Swan River Formation underlying the Ashville Formation should yield up to 5 L/s. Although water in this formation is too highly mineralized for use throughout most of the area, wells may be completed in it in the Swan River Lowland where overburden and overlying bedrock deposits are thinner.

Approximately 1900 well and testhole records were used to prepare the AVI map. Because there is very little settlement within the provincial parks particularly in Manitoba, water wells are scarce and an area has been blanked out on the AVI map where there are insufficient data. With a maximum allowable spacing of 6 km between data points the remainder of the map area has enough data to generate contours of iso-resistance. However, in some areas the density of data is low enough that the lateral continuity of groundwater vulnerability shown on the map may be a simplified interpretation of the actual situation.

An area of higher vulnerability generally follows the Assiniboine River valley from the southern edge to the northwest corner of the map area. Shallow sand and gravel in the Swan River Lowland are also reflected by higher vulnerabilities along the northern edge of the area. The area of high vulnerability on the border in townships 29 and 30 may not be indicative of conditions in the area. Surficial sand in the headwaters of the Shell River and shallow silt, sand and gravel of the Floral Formation are found in the area. However, the number of data points is quite limited in this area and control on the continuity of the vulnerability zones is quite general.

The large thickness of drift in this map area would generally give a low vulnerability rating to any sand and gravel aquifers between tills or between till and the bedrock surface.

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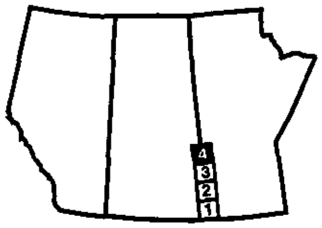

MAPS 63C & 63D

63C Swan Lake, Manitoba 5
63D Hudson Bay, Saskatchewan

The Porcupine Hills are the dominant topographic feature on this map sheet. Although data are limited, drift cover over the upland may approach 300 m in thickness (Nielson, 1988). Bedrock outcrops, however, are common along many of the deeply incised creeks flowing off the flanks of the upland.

In a report on groundwater availability in the map area, Betcher (1991) notes:

> "Overburden thickness is most variable in the Swan River Plain where the depth to bedrock varies from zero in areas where the Swan River Formation outcrops along the banks of the Roaring and Swan Rivers to as much as 88 m. The areal variation in thickness is locally extreme; thickness variations of 40 m may occur over distances of a few hundred metres or less."

Surficial geologic mapping for Saskatchewan (SRC, 1987) and Manitoba (Betcher, 1991) shows that the Porcupine Hills area is covered by glacial till. Neilson (1988) indicates that little near-surface glaciolacustrine or outwash materials are found on the upland. Almost no information is available on its subsurface Quaternary stratigraphy. However, comparison to similar physiographic regions to the south would indicate that sand and gravel aquifers should occur within the till and between the till and bedrock.

The areas surrounding the Porcupine Hills are underlain by late glaciolacustrine deposits of gravel, sand, silt and clay. Coarse sand and gravel beach deposits occur along the base of the upland. On the southern and eastern sides of the upland, blanket sands are found next to these beach deposits and grade away from its base to silt and clay. On the northern and western sides of the upland, lacustrine silt and clay are more prevalent near its base. Aquifers are most widespread in the Swan River Lowland between the Porcupine Hills and Duck Mountains.

The drift is underlain by various Cretaceous shale units on the flanks and beneath the Porcupine Hills and in the southern part of the map area. Generally, the shales are not well indurated and do not form significant aquifers. However, a sandstone unit within the Ashville Formation that has been referred to as the Newcastle sandstone member (McNeil and Caldwell, 1981) forms an aquifer on the north side of the Porcupine Hills. Small quantities of water, adequate for domestic supplies only, can be obtained from this sand unit.

The primary bedrock aquifer in the map area is the Swan River Formation. It subcrops beneath the drift in the lowland area north of the Porcupine Hills and in the southeast corner of the map in the Swan River Lowland. It consists primarily of unconsolidated, well-sorted, clean, quartzose sand that may range up to 100 m in thickness.

No major buried bedrock valleys occur in the map area. Nevertheless, the bedrock surface in the Swan River Lowland is highly eroded and dissected by major Tertiary rivers flowing out of the adjacent uplands (Betcher, 1991). Furthermore, the bedrock surface in the Red Deer River Lowland is thought to have been formed by glacial scouring (Morin and Whitaker, 1969).

Approximately 700 well and testhole records were used to prepare the AVI map. Only a portion of the area south and southeast of the Porcupine Hills and in a narrow zone along the northern edge of the Hills had enough records to map groundwater vulnerability. In much of this area, however, the density of data was low enough that the groundwater vulnerability ratings are likely a simplified interpretation of the actual situation.

Aquifer vulnerability in the Swan River Plain and in the Red Deer River Lowland exhibits a moderate to high degree of vulnerability. This is most likely due to the number of surficial and near-surface aquifers along the base of the upland and in the Swan River Plain.

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