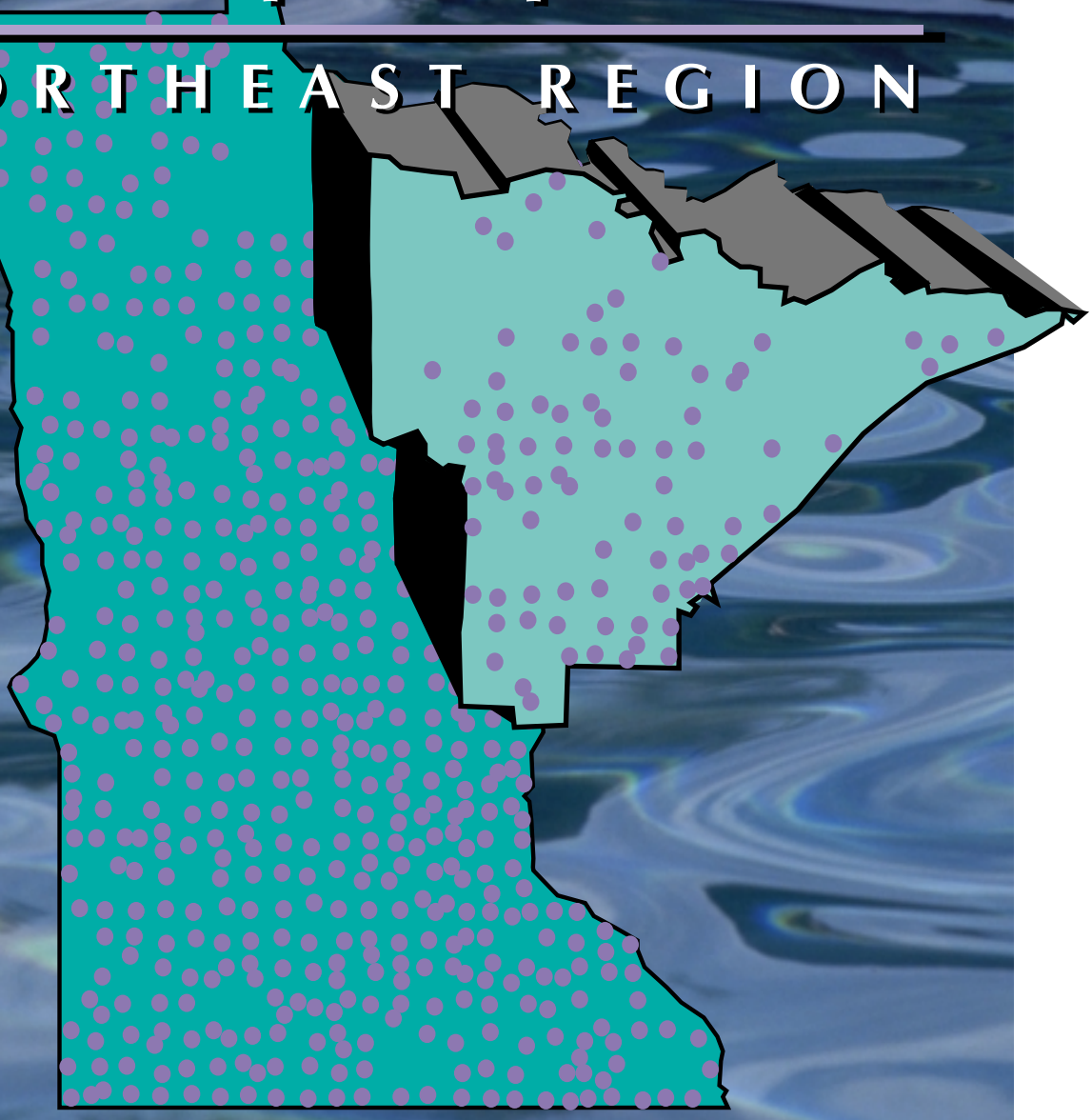
Baseline Water Quality of Minnesota's Principal Aquifers

NORTHEAST REGION



Minnesota Pollution Control Agency

Baseline Water Quality of Minnesota's Principal Aquifers - Region 1, Northeastern Minnesota

February, 1999

Published by

Minnesota Pollution Control Agency
Environmental Outcomes Division
Environmental Monitoring and Analysis Section
Ground Water and Toxics Monitoring Unit
520 Lafayette Road
St. Paul, Minnesota 55155-4194
(651) 296-6300 or (800) 657-3864

Prepared by

Ground Water Monitoring and Assessment Program (GWMAP)

Foreword

Ground Water Monitoring and Assessment Program (GWMAP) staff believe the enclosed report represents a comprehensive study of water quality in the principal aquifers of MPCA Region 1 in northeastern Minnesota. Information in this report, when used in conjunction with *Baseline Water Quality of Minnesota's Principal Aquifers* (MPCA, 1998a), can be used by water resource managers to identify baseline or background water quality conditions in areas or aquifers of concern, prioritize ground water problems, and assist in site decision-making, provided the limitations and assumptions outlined in the document are understood. Although data have been carefully analyzed, compiled, and reviewed independently, mistakes are inevitable with a data set this large. If mistakes are found in this report, please forward them to GWMAP staff. Errata sheets will be prepared as needed.

The report is divided into four parts. Part I briefly summarizes sample design and collection. Part II briefly describes analysis methods. Results and discussion are provided in Part III. Part IV includes a summary of results and recommendations.

Abbreviations

CWI - County Well Index

GWMAP - Ground Water Monitoring and Assessment Program

HBV - Health Based Value

HI - Hazard Index

HRL - Health Risk Limit

MCL - Maximum Contaminant Level

MPCA - Minnesota Pollution Control Agency

QA/QC - Quality Assurance/Quality Control

RLs - Reporting Limits

SMCL - Secondary Maximum Contaminant Level

USGS - United States Geological Survey

UTM - Universal Trans Mercator

VOC - Volatile Organic Compound

Table of Contents

Executive Summary

In 1995 and 1996, the Minnesota Pollution Control Agency's (MPCA) Ground Water Monitoring and Assessment Program (GWMAP) staff sampled 139 primarily domestic wells in MPCA Region 1, which encompasses northeastern Minnesota. This sampling effort was part of the statewide baseline assessment (baseline study). The objectives of the baseline study were to determine water quality in Minnesota's principal aquifers, identify chemicals of potential concern to humans, and identify factors affecting the distribution of chemicals. An important benefit of this study was establishment of contacts with state and local ground water groups. GWMAP efforts in 1998 and 1999 are focused on providing information from the baseline study, helping ground water groups prioritize monitoring efforts, and assisting with sampling and analysis of ground water monitoring data at the state and local levels.

Samples were collected statewide from a grid at eleven-mile grid node spacings. One well was sampled from each aquifer group located within a nine-square mile target area centered on each grid node. Sampling parameters included major cations and anions, 34 trace inorganics, total organic carbon, volatile organic compounds, and field measurement of dissolved oxygen, oxidation-reduction potential, temperature, pH, alkalinity, and electrical conductivity. Statewide, 954 wells were sampled from thirty different aquifer groups.

The hydrology of Region 1 is unique. Water infiltrating through unconsolidated material (drift) may accumulate and flow along the drift-bedrock interface because of the low permeability of the bedrock. Wells completed across this interface are considered to be Precambrian wells, although most of the water may enter the well at the interface. Despite this, there are significant differences in chemical concentrations of many chemicals, particularly trace chemicals, between the different Precambrian aquifer groups. This suggests that water accumulating at the drift-bedrock interface is in contact with bedrock for sufficient periods of time to develop a chemical signature from the bedrock. Consequently, different Precambrian groups were compared in this report.

Ground water quality in most aquifers of Region 1 is good. Concentrations of chemicals in Precambrian aquifers were similar to concentrations in similar aquifers

statewide. Concentrations of major cations and anions were lower in surficial and buried drift aquifers compared to similar aquifers statewide, while concentrations of trace metals were higher. There appears to be interaction between surficial drift, buried unconfined aquifers, and underlying bedrock. Processes occurring in the unsaturated zone appear to have less impact on water quality of these aquifers than in the remainder of the state. Water quality in Precambrian aquifers varies widely, probably due to wide variability in residence times. As residence time increases, concentrations of trace elements increase. Concentrations of most chemicals were well below drinking water criteria, but there were occasional exceedances of drinking criteria by metals such as beryllium, boron, and manganese.

The primary research needs for Region 1 include:

- a better understanding of ground water hydrology, particularly mechanisms of recharge and transport, and determining ground water residence times;
- determining impacts of mineralogy of the different bedrock units on ground water quality;
- collecting land use information to identify causes of the high occurrence of VOCs in ground water; and
- a consistent method of classifying bedrock aquifers.

Monitoring needs for Region 1 include:

- collecting additional samples from Precambrian aquifers; and
- collecting an additional 50 samples for VOCs from aquifers most likely to be impacted by VOCs.

The discussion of baseline water quality and chemistry presented in *Ground Water Quality of Minnesota's Principal Aquifers* (MPCA, 1998a) focused on statewide results. There was no attempt to explain differences in water quality between regions. Since ground water is largely managed on a regional basis, it is important to identify water quality issues at the regional level.

This report focuses on MPCA Region 1. Region 1 is located in north central Minnesota and includes the counties of Aitkin, Carlton, Cook, Itasca, Koochiching, Lake, and St. Louis (Figure B.1). The regional office is located in Duluth.

The following information needs for Region 1 were identified in Myers et al., 1992:

- determine water quality of recharge areas;
- determine water quality of surficial and buried sand aquifers in irrigated areas; and
- evaluate trends in contaminants from stock ponds, feedlots, individual sewage treatment systems, underground storage tanks, abandoned wells, landfills, historic dumps, and urban runoff.

Assistance needs were identified in the following areas:

- data interpretation;
- coordination of existing programs; and
- development of local programs.

The baseline study conducted by GWMAP may be used to partly fulfill the informational needs of determining water quality of recharge areas (provided they are mapped) and water quality of surficial and buried sand aquifers in irrigated areas. The baseline study can assist with data interpretation through analysis of the data for the region, by describing analysis methods useful in local interpretation, and by providing comparisons between information from the baseline study and other hydrologic investigations from Region 1.

The purpose of this report is to provide baseline water quality information for Region 1. Comparisons are made between water quality in the principal aquifers of Region 1 to that in the remainder of the state. Significant differences in ground water quality

between Region 1 and the statewide data were determined, factors contributing to these differences were identified, and potential health implications were investigated. **NOTE : Water quality is a relative term which may have multiple meanings. In this report, water quality typically refers to water chemistry. Specific instances occur where water quality relates to potential effects on humans consuming ground water or general quality of water. The reader should be aware of these different applications of water quality**

1. Baseline Design and Implementation

Design and implementation of the baseline study are described in Myers et al. (1991) and MPCA (1994, 1995, and 1998a). A systematic grid design was implemented, with sampling nodes spaced at eleven mile intervals. All major aquifers with a suitable domestic well located within a nine square mile area centered on each grid node were sampled. The County Well Index (CWI) (Wahl and Tipping, 1991) was used to provide information on wells within the sampling area. CWI aquifer codes are summarized in Table A.1. Wells were purged until stabilization criteria were met. Sampling parameters included field parameters (dissolved oxygen, oxidation-reduction potential, pH, temperature, electrical conductivity, and alkalinity) major cations and anions, volatile organic compounds (VOCs), total organic carbon, and 34 trace inorganic chemicals. Tritium and pesticides were sampled in selected wells. Samples were not filtered. Rigorous analysis of the data was conducted. Sampling and analysis methods are described in MPCA 1996 and 1998b, respectively. Sample locations, by aquifer, are illustrated in Figures B.2 through B.6 for Precambrian crystalline, North Shore Volcanics, Precambrian undifferentiated, surficial drift and buried drift aquifers, respectively. Sampling is summarized by aquifer in Table A.1 and for all data in Table A.2.

2. Analysis Methods

Quality assurance/quality control analysis of the data are reported in MPCA (1998a). Data analysis consisted of

- establishing descriptive statistics (mean, median, minimum, etc.) for each parameter and each aquifer group;
- conducting hypothesis tests between aquifer groups;
- conducting factor analysis related to the distribution of chemicals in the principal aquifer groups; and
- conducting an analysis of health and risk.

Methods used in conducting these analyses are described in MPCA (1998b).

3. Results and Discussion

Results are separated into

- descriptive statistics;
- group (hypothesis) tests;
- health and risk;
- discussions for individual aquifer groups; and
- discussions for individual chemicals and chemical parameters.

3.1. Descriptive Summaries

Descriptive statistics include the number of samples, number of censored samples (samples below the maximum reporting limit), the type of distribution for the data, and the mean, upper 95th percent confidence limit of the mean, median, 90th or 95th percentile, minimum, and maximum concentrations. Results are summarized in Tables A.3 through A.14 for the twelve aquifer groups sampled in Region 1. All concentrations are in ug/L (ppb) except for Eh (mV), temperature (^{o}C), pH (negative log of the hydrogen ion concentration), and specific conductivity (umhos/cm). Sample sizes for the Mount Simon-Hinckley (CMSH), Fond du Lac (PMFL), Hinckley (PMHN), Biwabik Iron Formation (PEBI), Precambrian undifferentiated (PMUU), and Duluth Complex (PMDC) aquifer groups were small and no further discussion of these is presented in this section.

Examples of how to use information from Tables A.3 through A.14 in site applications are provided in MPCA, 1998a. To use these data in site applications, the coefficients presented in Tables A.15 and A.16 will be needed. **Mean and median concentrations are considered to represent background concentrations with which site or other local water quality information can be compared.** Upper 95th percent confidence limits and 90th or 95th percentiles represent extremes in the distribution for a chemical. The distribution of a chemical indicates whether concentrations need to be log-transformed and whether concentrations below the detection limit will be encountered during subsequent sampling.

3.2. Group Tests

Group tests are statistical tests which compare concentrations of a chemical or parameter in one group with concentrations in another group or groups. A group might be month of sampling, for example, and a group test might explore potential differences in concentrations of a chemical such as nitrate between two or more months. Concentrations of sampled chemicals and chemical parameters were compared between different aquifer groups.

Concentrations of many chemicals differed between different aquifer groups. Median chemical concentrations were compared between the crystalline Precambrian (PCCR), North Shore Volcanics (PMNS), undifferentiated Precambrian (PMUD), buried confined drift (QBAA), buried unconfined drift (QBUA), and surficial drift (QWTA) aquifer groups. Results are summarized in Table A.17. P-values are included for each chemical. The p-value indicates the probability that median concentrations between aquifers are equal. Median concentrations are given in ug/L (except for Eh, redox, pH, temperature, and specific conductance). Specific aquifers which differed in concentration are not indicated in Table A.17.

Different median concentrations were observed for many chemicals. Some of these differences will be discussed in greater detail in the section for individual aquifers, but the primary conclusions are summarized below.

1. Concentrations of many trace inorganic chemicals, particularly the heavy metals, were greater in the Precambrian aquifers compared to the Quaternary aquifers. Concentrations of alkalinity, barium, calcium, silicate, and phosphorus were greater in the Quaternary aquifers compared to the Precambrian aquifers.
2. Elevated concentrations of aluminum, antimony, boron, fluoride and sodium occurred in the PMNS aquifer group. Concentrations of chloride, beryllium, zinc, sodium, and silver were also greatest in the PMNS group, but there were no statistical differences in concentrations of these chemicals compared to other groups. The chemical signature in PMNS wells indicates the importance of parent material on water quality.
3. Eh and concentrations of dissolved oxygen, strontium, lead, potassium, total organic carbon, and chloride were greatest in the PCCR aquifer group, although only dissolved oxygen and strontium showed statistically different concentrations compared to other

groups. Water quality of the PCCR group shows impacts from parent material and recharge. Many of these aquifers may be fractured and close to the land surface, resulting in elevated Eh and concentrations of dissolved oxygen and organic carbon.

4. Concentrations of most chemicals in the PMUD aquifer group were intermediate between other Precambrian aquifers and Quaternary aquifers. This makes sense, since there are potentially many different types of parent material which comprise these aquifers.
5. Concentrations of barium, alkalinity, and arsenic were greatest in the Quaternary buried, artesian aquifer group. Water quality in this group is strongly influenced by parent material and residence time. Concentrations of most chemicals in buried, unconfined Quaternary aquifers are similar to the buried artesian aquifers, as would be expected since both aquifer groups are found in similar parent material. Residence time, however, appears to have an impact on water quality in these aquifers, since concentrations of calcium are lower, while concentrations of potassium, sodium, chloride, and sulfate are greater in the buried artesian aquifers. Residence times in buried artesian aquifers should be significantly greater compared to buried unconfined aquifers.
6. Water quality of water table aquifers (QWTA) is not typical of statewide water quality in these aquifers. Concentrations of aluminum, iron, and sulfate are greater than the buried Quaternary aquifers, while Eh is lower. These data suggest interactions with parent material, but also suggest that aquifers classified as QWTA in this region of the state are not as responsive to processes occurring in the vadose zone as QWTA aquifers in other parts of the state.

The hydrology of Region 1 is unique because Precambrian bedrock underlies the entire region, it is often close to the land surface, and it is relatively impermeable. Consequently, water moving through the unsaturated zone may only slowly penetrate underlying bedrock. Water may accumulate and move along the interface between the unconsolidated (drift) deposits and bedrock. Wells drilled across the interface intercept this water. If water within these wells reflects inputs from the unsaturated zone, there should be no differences in water quality of buried Quaternary and Precambrian bedrock

aquifers. Table A.18 compares concentrations in buried Quaternary and Precambrian bedrock aquifers. It is apparent that water quality differs for many chemicals. Concentrations of magnesium, bicarbonate (alkalinity), calcium, and potassium were lower in Precambrian aquifers, while concentrations of aluminum, antimony, beryllium, boron, cesium, copper, and lead were greater in Precambrian aquifers. Consequently, water is in contact with bedrock for sufficient lengths of time to develop a chemical signature from the bedrock. Ground water from Precambrian bedrock is dominated by calcium, magnesium, and bicarbonate, which is reflective of inputs from the unsaturated zone. The results support the hypothesis that water percolates through the unsaturated zone, accumulates at the bedrock-drift interface, and moves sufficiently slow along this interface to develop a chemical signature from ground water.

3.3. Health and Risk

Drinking water criteria for individual chemicals are summarized in Table A.19. The Health Risk Limit (HRL) and Health-Based Value (HBV) are health-based criteria. HRLs are defined in the following manner: *HRLs are promulgated concentrations of a ground water contaminant, in ug/L, which estimates the long-term exposure level which is unlikely to result in deleterious effects to humans. HRLs strictly incorporate factors related to human health* (Minn. R., Pts. 4717.7100 to 4717.7800). HBVs have a similar definition, with the exception that they are not promulgated and have not undergone rigorous external peer review. Drinking water criteria are calculated based on a standard adult (70 kg) ingestion rate of two liters of water per day. Uncertainty and other exposure pathways, such as showering, cooking, and inhalation of water vapor, are addressed through the use of safety factors. Lifetime exposure is assumed to apply to baseline data, since the sampled wells are used for domestic supply. Maximum Contaminant Levels (MCLs) and Secondary Maximum Contaminant Levels (SMCLs) are not strictly health-based and may include factors such as treatability.

The number and percent of samples exceeding health-based ground water drinking criteria are summarized in Tables A.20 and A.21, respectively. **In anticipation of a change in the HRL for manganese from 100 ug/L to a value of 1000 ug/L or greater,**

the drinking criteria for manganese used in this report is modified from the HRL (MDH, 1997). Sample size was not sufficient for the Mt. Simon-Hickley (CMSH) and several of the Precambrian aquifer groups (PCUU, PEBI, PMDC, PMFL, and PMHN) to provide meaningful results. No chemical appeared to represent a significant potential risk in any aquifer, although the single sample for the Duluth Complex group exceeded the HRL for beryllium. Boron and beryllium showed a relatively high frequency of exceeding drinking criteria in Precambrian aquifers, particularly the North Shore Volcanic group. Two percent of samples exceeded the HRL for boron in buried artesian drift aquifers, but this is less than half the statewide exceedance rate of 7.7 percent. Arsenic, manganese, and selenium are other chemicals which exceeded their HRL one time in Precambrian aquifers.

The number and percent of samples exceeding non-health-based ground water drinking criteria are summarized in Tables A.22 and A.23, respectively. Non-health-based drinking criteria include chemicals with a Maximum Contaminant Level (MCL) or Secondary Maximum Contaminant Level (SMCL). Iron exceeded its SMCL in 38, 42, 50, 52, 58, and 62 percent of the sampled wells in the PCCR, PMNS, PMUD, QBAA, QBUA, and QWTA aquifer groups, respectively. Aluminum exceeded its SMCL in 31, 50, 10, 15, 0, and 24 percent of wells sampled in the PCCR, PMNS, PMUD, QBAA, QBUA, and QWTA aquifer groups, respectively. The incidence of other exceedances was low.

Some chemicals have the same toxic endpoint. For example, Table A.18 indicates that barium and nitrate both affect the cardiovascular/blood system. A useful calculation is to estimate the probability that chemicals with the same endpoint will exceed drinking water criteria. To make this calculation, a hazard index (HI) is used to add the contribution of each chemical with similar endpoints

$$[HI_{endpoint} = C_{chemical\ 1}/HRL_{chemcial1} + C_{chemical\ 2}/HRL_{chemcial2} + ... + C_{chemical\ n}/HRL_{chemcialn}]$$

where C represents the concentration (ug/L) of a chemical. If the HI exceeds 1.0 in an individual well, further investigation is recommended to evaluate the potential factors controlling chemical concentrations and the validity of the exposure assumptions. These

calculations were not made for this report, primarily because there are a limited number of samples for all aquifers except the buried drift. The calculations would therefore be potentially misleading. These calculations were made for statewide data and are reported in MPCA, 1998a.

3.4. Aquifers

The hydrology and geology of Region 1 is described in numerous reports, although there is no specific report which encompasses the entire area. The Hydrologic Investigations Reports for the Big Fork River (Lindholm et al., 1976), Little Fork River (Helgesen et al., 1976), St. Louis River (Lindholm et al., 1979), Rainy Lake (Ericson et al., 1976), and Lake Superior (Olcott et al., 1978) watersheds provide information about climate, the water budget, surface water, and ground water. Precipitation across the region varies from about 30 inches in the east to 24 inches in the west. Annual runoff to surface rivers (ground water recharge) varies from more than 11 inches in the east to less than 6.5 inches in the west. Annual recharge to surficial aquifers may be greater than these amounts and but will vary widely with annual precipitation. Most of the major rivers in the region are gaining streams in that they have a baseflow component (ground water discharges to them).

The hydrogeology of Region 1 is dominated by Precambrian bedrock geology in two ways. First, Precambrian rocks form an impermeable surface which water does not penetrate, except in locations where there are fractures. Consequently, water infiltrating through the soil zone reaches this impermeable surface and then travels laterally along the interface between the bedrock and the unconsolidated Quaternary deposits. Wells are often drilled across this interface and into the underlying Precambrian bedrock. The portion of the well completed in the bedrock acts primarily as a storage basin, while water enters a well at the interface. Some aquifers may occur within the numerous and irregular fractured flow zones of the North Shore Volcanic Group and, to a lesser extent, other crystalline rocks. These flow systems are independent of each other. Second, the mineralogy of the different bedrock formations is highly variable. Consequently, if ground water is in contact with bedrock for a sufficient length of time, the ground water will have

a chemical signature reflective of the bedrock. This was observed and discussed in Section 3.2. Consequently, a discussion of ground water quality from different bedrock units is appropriate, even if water entering a well is moving along the bedrock-drift interface. Ground water with long residence times will vary considerably in response to mineralogical differences.

Sedimentary bedrock deposits are relatively unimportant, constituting aquifers only in the extreme western and southern portions of the region. Glacial and lacustrine deposits vary widely in thickness. These deposits are absent in the eastern portion of the region but may be over 100 feet thick in the western and southern portions. Most surficial deposits consist of fine-grained lake sediments, peat, and ground moraine. Sand and gravel deposits occur in bedrock valleys, as beach ridges, at the interface between tills, and in the extreme southern part of the region, as outwash. Cretaceous bedrock deposits are unimportant hydrologically within the region.

Ground water originates as precipitation which percolates through the soil and vadose zone and into the saturated zone (ground water). Most recharge originates in spring following snowmelt and prior to plant growth, but locations where bedrock is close to the land surface and near-surface fractured bedrock systems are likely to be responsive to larger precipitation events during the summer and autumn. There is little information indicating rates of recharge to the different aquifers in the study area. In areas with sufficient thickness of overlying glacial deposits, the water table reflects, in a subdued way, surface topography. Ground water flow is controlled by local factors such as topography, extent of fracturing, and permeability of glacial deposits. Most flow systems are local, with discharge occurring to the numerous lakes, streams, and rivers in the region.

Because ground water systems are generally local, research has focused on specific geographic areas. There has been no attempt to describe regional ground water resources, but because of the variability in aquifer parent material and limited demand on ground water as a source of water for industrial and municipal use, the value of regional analysis may be questionable. Objectives of regional analysis may therefore focus on differences in water quality within aquifers from the same parent material and identification of potential

ground water quality problems. The aquifers considered in this report include those associated with Precambrian crystalline, Precambrian undifferentiated, North Shore Volcanic, buried Quaternary, and surficial Quaternary deposits.

3.4.1. Surficial and Buried Drift Aquifers

Well-sorted sand and gravel were deposited as beach ridges in glacial lakes, in bedrock valleys, and as outwash plains by advancing and retreating glaciers. Outwash is limited to the southern portion of the study area, while beach ridge deposits are most common in the western part of the study area. Deposits located in bedrock valleys are scattered throughout the region, except in the northeastern third where bedrock is near the land surface. Sand and gravel deposits are typically less than 30 feet thick and have limited potential supply for high capacity uses, but they yield sufficient quantities for domestic use. Beach ridge deposits are generally less than 10 feet thick, while alluvial deposits may be as much as 100 feet thick. The scattered distribution of surficial aquifers is evident in Figure B.6, which illustrates the distribution of wells sampled in Region 1. These aquifers are vulnerable to contamination from human activity at the land surface. Hydrologic information, including climatic data and both surface and ground water data, can be found in the USGS watershed reports for the area (Lindholm et al., 1976; Helgesen et al., 1976; Lindholm et al., 1979; Ericson et al., 1976; and Olcott et al., 1978).

Using the County Well Index (CWI) nomenclature, the surficial drift group is comprised of water-table wells (QWTA) while the buried drift group is comprised of both artesian (QBAA) and unconfined (QBUA) aquifers. QWTA aquifers have less than 10 feet of confining material between the land surface and well screen. There was no attempt to identify the extent of confinement, depths of well screen, and depth to the water table in the wells sampled as part of the baseline analysis.

Water quality information for buried and surficial drift aquifer groups of Region 1 is illustrated in Tables A.12 through A.14. These groups have similar concentrations of dissolved oxygen and similar redox potentials (Eh). Concentrations of total dissolved solids are lower in the surficial aquifer group than in the buried group, as would be expected, but concentrations of iron and manganese were greater in the surficial group.

The water quality of surficial drift aquifers in Region 1 differs dramatically compared to similar aquifers in other areas of the state. The greatest differences were for alkalinity, antimony, barium, calcium, chloride, magnesium, manganese, specific conductance, total dissolved solids, and total phosphorus, which were less in Region 1, and for aluminum and sulfate, which were greater. Water quality of buried aquifers also differs dramatically with buried aquifers in the remainder of the state. Concentrations of most chemicals were lower in buried aquifers in Region 1 compared to similar aquifers statewide. Concentrations of most chemicals were similar between surficial and buried sand and gravel aquifers within Region 1. In addition, concentrations of alkalinity, boron, dissolved oxygen, potassium, and sodium were correlated with well depth. The results suggest confining deposits may be leaky or buried aquifers have short residence times which results in minimal dissolution of parent material.

Water quality information for surficial and buried drift aquifers in Region 1 is illustrated in Table A.24 for several different studies. The data indicate GWMAP data falls within the range of data for most chemicals, but concentrations of boron and sulfate were lower and iron higher for the GWMAP data. The greatest concentrations of dissolved solids were observed in the studies by Lindholm et al. (1976) and Helgeson et al. (1978), which corresponds with the western portion of the study area. Concentrations of calcium, magnesium, and bicarbonate increase to the west. These results suggest parent materials comprising the aquifers differs between the eastern and western portions of the study area. This may be a cause of the large variability in chemical concentrations within individual CWI aquifer groups for Quaternary deposits.

Water quality of drift aquifers in Region 1 is generally very good. Drinking water criteria for beryllium, boron, manganese, aluminum, iron, and lead were exceeded in at least one sample from drift aquifers. Each of these chemicals is discussed below.

Beryllium

The HRL of 0.08 ug/L was exceeded in five Quaternary wells. However, median concentrations were below the reporting limit of 0.01 ug/L. The 95th percentile and 95th percent upper confidence limit concentrations exceeded the HRL for both the water-table

(QWTA) and buried unconfined (QBUA) aquifer groups, but not for the buried artesian (QBAA) ground.

Beryllium concentrations were most strongly correlated with other trace metals such as cadmium and silver, but were also negatively correlated with calcium, magnesium, and silica. Beryllium is a divalent metal which can substitute for calcium, magnesium, and silica in igneous rocks. Consequently, the areas in which beryllium concentrations are greatest in Quaternary deposits occur where crystalline Precambrian and North Shore Volcanic deposits are present. While most forms of beryllium have a low solubility, the HRL is so low it will be exceeded in aquifers with parent material enriched in beryllium. Beryllium is therefore a potential health concern.

Boron

There was just one exceedance of the HRL for boron (600 ug/L) in Quaternary wells. The median concentrations were less than 50 ug/L in all three aquifer classes. Boron was most strongly correlated with total dissolved solids and well depth, indicating the role of residence time on boron concentrations. Concentrations of boron were positively correlated with all major cations and anions. Boron does not appear to represent a potential health concern in Quaternary aquifers of Region 1.

Iron

There were 47 exceedances of the Secondary Maximum Contaminant Limit (SMCL) of 300 ug/L for iron. This represents about 57 percent of the sampled wells. Median concentrations of iron exceeded the SMCL in all three Quaternary aquifer groups. Iron was most strongly correlated with organic carbon and total suspended solids, but in general, correlations between other chemicals and iron were weak. This contrasts with results from other regions in the state, where iron was often correlated with the distribution of several chemicals. Similarly, the correlation between iron and total suspended solids was not as strong as for other regions of the state. The concentration of iron in underlying bedrock aquifers is low and this may be responsible for the lack of

correlations between iron and other chemicals. The primary effect of iron is staining of plumbing fixtures.

Manganese

There were four exceedances of the drinking criteria of 1000 ug/L used for manganese. This value is an order of magnitude above the current HRL, which is expected to be modified in the near future. The median concentration of manganese in the drift aquifers was about 100 ug/L, with concentrations being greatest in the buried unconfined aquifers (median = 157 ug/L). Either the 95th percentile or the upper 95th percent confidence limit concentration exceeded the drinking water criteria for each of the three aquifer groups.

The strongest correlation for manganese was with iron (0.40), but manganese was also correlated with some trace elements such as arsenic and barium. The greatest concentrations of manganese occurred in areas underlain by crystalline bedrock aquifers (PCCR). These bedrock aquifers also had elevated concentrations of manganese but not of arsenic and barium. The source of manganese in the Quaternary aquifers appears to be underlying Precambrian bedrock. Manganese will be a potential health concern in about five percent of wells completed in Quaternary aquifers, with the greatest potential risk being in areas underlain by crystalline Precambrian bedrock.

Aluminum

Aluminum exceeded the SMCL of 50 ug/L in 13 Quaternary wells, which represents about 15 percent of the sampled wells. The median concentration was less than 5.3 ug/L in all three Quaternary aquifer groups, but the 95th percentile and 95th percent upper confidence limits were greater than 200 ug/L for the QWTA and QBAA groups. The strongest correlations were with other trace metals such as chromium, cobalt, copper, and lead (all positive), and with total suspended solids. Underlying Precambrian bedrock was enriched in aluminum but there was no apparent correlation between high aluminum concentrations in Precambrian bedrock aquifers and high concentrations in Quaternary aquifers.

Lead

Lead exceeded the Action Level of 15 ug/L in one Quaternary well. The median concentrations of lead in QBAA, QBUA, and QWTA wells were 0.21, 0.14, and 0.17 ug/L, respectively. Lead concentrations were most strongly correlated with other trace metals such as cobalt, aluminum, chromium, and particularly copper. Concentrations appeared to be greatest in areas underlain by Precambrian crystalline or North Shore Volcanic aquifers. In general, however, lead does not represent a health concern in QWTA wells of Region 1.

3.4.2. Precambrian aquifers

Precambrian deposits underlie the entire region. These units do not behave as typical aquifers, however. Wells completed in bedrock units may actually intercept water moving along the interface between drift and bedrock. There appears to be sufficient residence time for this water to develop a water quality signature from the bedrock unit. The different Precambrian units are therefore considered different aquifers in this report because water quality differs between the different units. The objective of this discussion is to identify potential water quality concerns and identify differences between the major Precambrian aquifer groups.

The geology and mineralogy of a wide variety of Precambrian deposits are described in the literature (Minnesota Geological Survey, 1970; Cotter et al., 1964; Southwick, 1993; Sims, 1970; Minnesota Geological Survey, 1979; Minnesota Geological Survey, 1982; Wright et al., 1970; Morey et al., 1970; Morey, 1967; Green, 1992; Jirsa et al., 1991). It is beyond the scope of this paper to discuss these. Crystalline, North Shore Volcanic, and undifferentiated Precambrian aquifers are discussed below.

3.4.2.1. Crystalline aquifers

Aquifers classified as crystalline (PCCR) encompass a wide range of bedrock but consist primarily of metamorphosed igneous and sedimentary rocks. Water quality varies

with the formation in which a well is completed. The PCCR aquifers sampled during this study cannot therefore be treated as a single aquifer system.

Comparison of GWMAP data with data from other literature sources is summarized in Table A.25. Concentrations of most chemicals were relatively low in the GWMAP data but were within the range reported in the literature. Concentrations of fluoride and phosphorus were greater in the GWMAP data.

Ground water within the crystalline bedrock aquifers was, on average, oxygenated and had a median Eh value of 266 mV. Concentrations of most chemical parameters were low. Bicarbonate accounted for more than 90 percent of the total anion concentration, while calcium and magnesium accounted for about 78 percent of the cation concentration. There was large variability in concentrations of chemicals, with mean and median concentrations differing by about 13 percent. This compares to 7.5 and 8.3 percent for the water-table and North Shore Volcanic aquifer groups.

The importance of bicarbonate, calcium, and magnesium, and the presence of oxygen reflect an impact from the unsaturated zone. This makes sense, since ground water primarily occurs at the interface of the drift and bedrock. In addition to these chemicals, there are elevated concentrations of arsenic, beryllium, manganese, selenium, and fluoride, all of which may be related to mineralogy of the bedrock. The large variability in water quality is reflected by comparing concentrations with drinking water criteria. Concentrations of arsenic, beryllium, manganese, selenium, aluminum, fluoride, iron, and sulfate exceeded drinking water criteria in at least one well from the PCCR group. Each of these chemicals is discussed below.

Arsenic

The Maximum Contaminant Level (MCL) of 50 ug/L for arsenic was exceeded in one well (157 ug/L). The median concentration of arsenic was 0.64 ug/L, but the 90th percentile and upper 95th percent confidence limit concentrations were 49 and 28 ug/L. There is general agreement that a health-based concentration for arsenic would be 10 ug/L or lower. The observed concentrations of arsenic in crystalline bedrock aquifers thus represent a potential health concern in at least five and probably more than 10 percent of

wells completed in these aquifers. Arsenic was negatively correlated with other trace metals such as barium, vanadium, and zinc, and positively correlated with sodium and boron. Arsenic is present in many wells at concentrations which are likely to represent potential health concerns if a health-based drinking criteria is developed.

Beryllium

There were 3 exceedances of the HRL for beryllium (0.08 ug/L), although the highest concentration was 0.51 ug/L. The median concentration of beryllium in sampled PCCR wells was 0.020 ug/L. The strongest correlation for beryllium was with silica. Beryllium can substitute for silica in minerals, thus supporting this correlation. The 90th percentile and 95th percent upper confidence limit concentrations were both well above the HRL (0.23 and 0.39 ug/L, respectively). Beryllium may represent a significant potential health concern in Precambrian crystalline aquifers.

Manganese

The drinking criteria for manganese (1000 ug/L) was exceeded in one well (2087 ug/L). The current HRL for manganese is 100 ug/L and this value was exceeded in eight wells. The 90th percentile concentration was 1191 ug/L, but the upper 95th percent confidence limit concentration was only 399 ug/L. Manganese was not well correlated with either the redox parameters (dissolved oxygen, Eh, iron) or with most trace elements. The strongest correlations were with cobalt and selenium. The occurrence of elevated manganese concentrations in ground water are difficult to understand with the existing data, but if the HRL is amended to a concentration of 1000 ug/L or more, manganese will not be a significant potential health concern in PCCR aquifers.

Selenium

The HRL for selenium (30 ug/L) was exceeded in one well (307.7). The next highest concentration was 4.3 ug/L. The 90th percentile and 95th percent upper confidence limit concentrations both exceeded the HRL (95 and 80 ug/L, respectively).

Selenium was correlated with manganese concentrations but not with most other chemicals. Selenium is mobile in soil, but the lack of correlation with the redox parameters suggest that dissolution of parent material may be a more important mechanism for introducing selenium into ground water than leaching through the soil zone. The single well in which selenium exceeded the HRL had a dissolved oxygen concentration of 7340 ug/L, an Eh of 299 mV, and elevated concentrations of chromium and beryllium. These suggest a potential leaching source in this well. In general, selenium does not represent a potential health concern in wells completed in Precambrian crystalline bedrock.

Aluminum

Aluminum exceeded the Secondary Maximum Contaminant Level of 50 ug/L in five wells. The 90th percentile and 95th percent upper limit concentrations were 272 and 117 ug/L, respectively. Aluminum was well correlated with several trace metals, including cobalt, chromium, lead, copper, and vanadium, but the strongest correlation was with total suspended solids (0.80). The source of aluminum is dissolution of parent rock, but once released from the bedrock, aluminum becomes associated with suspended material. This material is most likely oxides and sesquioxides of iron, manganese, and other metals, since aluminum was negatively correlated with organic matter concentrations. Aluminum can have deleterious effects on aquatic life at low concentrations, but, despite the relatively high concentrations, it does not appear to represent a significant concern for humans.

Fluoride

Fluoride exceeded the Maximum Contaminant Level of 4000 ug/L in one sample, with the next highest concentration being 1450 ug/L. The median, 90th percentile, and upper 95th percent confidence limit concentrations of fluoride were 490, 3258, and 1020 ug/L, respectively. Fluoride was not well coordinated with other chemical parameters, with the greatest correlation being with sodium ($R^2 = 0.54$). Fluoride has no specific health effects but causes mottling of teeth. Concentrations of fluoride appear to be highly variable in the PCCR aquifer, but in general do not appear to represent a concern.

Iron

The SMCL of 300 ug/L for iron was exceeded in six samples. The median concentration of iron was 145 ug/L, which is low compared to most other aquifers in Minnesota. There was considerable variability in the data, however, since the mean concentration was 445 ug/L and the 90th percentile concentration was 20875 ug/L. Iron was not well correlated with the redox parameters (Eh and dissolved oxygen), but was significantly correlated with most trace elements. This may reflect the association of these trace elements with iron as suspended materials. The primary effect of iron is on staining of plumbing fixtures. Ground water with high concentrations of suspended material will have iron concentrations exceeding the drinking water criteria. Filtering may be an option for reducing iron content of ground water pumped from these aquifers.

Sulfate

Sulfate exceeded the SMCL of 250000 ug/L in one well, with the next highest concentration being 55230 ug/L. The single well with the high sulfate concentration also had very high concentrations of total dissolved and suspended solids, calcium, magnesium, sodium, bicarbonate, arsenic, and aluminum. There was no apparent distribution to the sulfate concentrations in sampled wells, but this may be due to the excessive concentration in the one well. Sulfate does not represent a drinking water concern in Region 1.

3.4.2.2. North Shore Volcanics

The structure, stratigraphy, and geochemistry of the North Shore Volcanic Group are discussed in Green, 1992. A limited discussion of the hydrology of aquifers occurring within the North Shore Volcanic deposits is presented in Olcott et al. (1978). Aquifers occur within fractures and may vary widely in age depending on individual flow paths within the fractured bedrock. Despite this, the variability in concentrations of different chemical parameters was not as great as for the other Precambrian groups. This may be

due to bedrock consisting primarily of olivine-rich material throughout the North Shore Volcanic Group.

GWMAP data is compared to data from other literature sources in Table A.26. Although the data available for comparison is limited, concentrations of bicarbonate and iron were greater while chloride, sulfate, sodium, and total dissolved solid concentrations were lower in the GWMAP data compared to the remainder of the data. The data from Olcott et al. (1978) and from this study may be used to define a range of ground water quality in the North Shore Volcanic Group.

Aquifers from the North Shore Volcanic group have low concentrations of dissolved solids and occasional high concentrations of some trace metals, particularly aluminum, boron, and beryllium. The high concentrations of aluminum and iron reflect dissolution of parent material, which is rich in iron and aluminum. Sodium accounts for a relatively high percentage of the concentration of total cations, but sodium concentrations are well below drinking water criteria. The water quality comparisons indicate parent material has a much larger effect on water quality of the North Shore Volcanic group than for other Precambrian aquifers. This may be due to increased importance of fractures in ground water hydrology compared to other aquifers. There were exceedances of drinking water criteria for aluminum, beryllium, boron, iron, and lead in at least one well sampled from the North Shore Volcanic Group. These chemicals are discussed below.

Aluminum

Aluminum exceeded the Secondary Maximum Contaminant Level (SMCL) of 50 ug/L in six samples. The overall mean and median concentrations of aluminum in the PMNS aquifer group were 45 and 49 ug/L, meaning nearly 50 percent of wells completed in this formation exceed the drinking criteria. Aluminum concentrations were strongly correlated with concentrations of other trace metals, including copper, chromium, cobalt, zinc, and antimony. Aluminum was also strongly correlated with concentrations of total suspended solids. Since aluminum was negatively correlated with organic carbon, it appears to be associated with other metal complexes in ground water. Filtering may thus be an option for removing some aluminum from ground water.

Aluminum is toxic to aquatic life at low concentrations. Because aquifers occur within fractures, rapid transport systems may pose potential risk to ecological receptors. Information on aluminum concentrations from surface waters is limited for the North Shore Region of Lake Superior, where North Shore Volcanic deposits occur. However, ground water is likely to be a small contributor to the water budget of most lakes and streams because of the low permeability of surficial deposits.

Beryllium

The HRL for beryllium (0.08 ug/L) was exceeded in two samples. The overall mean and median concentrations were 0.018 and 0.025 ug/L. The 90th percentile and 95th percent upper confidence limit concentrations were 1.8 and 2.1 ug/L, respectively, which exceed the HRL. Beryllium was strongly correlated with other metals such as zinc, iron, lead, antimony, and copper. It was also positively correlated with dissolved oxygen, despite the strong positive correlation with iron. These conflicting results indicate dissolution of parent material is the dominant process affecting the concentration of beryllium in ground water, but redox reactions may also be important in some aquifers. Beryllium is a potential drinking water concern in wells completed within the North Shore Volcanic Group.

Boron

The HRL for boron (600 ug/L) was exceeded in 2 wells. The overall mean and median concentrations were 182 and 219 ug/L. The 90th percentile and 95th percent upper limit concentrations of 1795 and 3980 ug/L, respectively, are above the HRL. Boron was positively correlated with trace metals such as aluminum, cobalt, and copper, but was most strongly correlated with chloride, sulfate, sodium, selenium, and total dissolved solids. These results reflect the higher solubility of boron compared to most trace metals. Boron represents a potential health risk in wells completed in deposits from the North Shore Volcanic Group.

Iron

Iron exceeded the SMCL (300 ug/L) in 5 samples. Mean and median concentrations were 266 and 204 ug/L, respectively. The upper 95th percent confidence limit concentration was 1100 ug/L. Iron was strongly correlated with other trace metals such as lead, copper, chromium, and antimony. Iron was also well correlated with silicate, reflecting the dissolution of parent material (olivine-rich bedrock). Iron was correlated with total suspended solid concentrations but not with organic carbon concentrations. Filtering may reduce concentrations of iron in ground water. The primary concern with high iron concentrations is staining of plumbing fixtures.

Lead

The Action Level for lead of 15 ug/L was exceeded in one well (16.08 ug/L). The next highest concentrations of lead were 6.38 and 1.26 ug/L. The 95th percent upper limit concentration was 1.4 ug/L. Lead was most strongly correlated with other trace metals such as beryllium, chromium, copper, and aluminum. As with the other trace metals, lead was strongly associated with concentrations of suspended solids. The well with the single exceedance of the drinking water criteria also had a suspended solid concentration of 192000 ug/L, well above the median concentration of 4500 ug/L. Lead does not appear to represent a drinking water concern in Region 1.

3.4.2.3. Undifferentiated Precambrian Aquifers

Because of the complex nature of bedrock deposits in Region 1, the type of geologic material comprising many aquifers cannot be identified clearly from well logs. These include a wide variety of metamorphosed igneous and sedimentary rocks. If all undifferentiated aquifers are combined into a single group, the mineralogy of this group will be highly variable. Consequently, the overall average difference in mean and median concentration for sampled chemical parameters from the undifferentiated group (PMUD) was greater than 20 percent.

Aquifers occur both along the drift-bedrock interface and within bedrock fractures. Ground water may thus be part of a rapid response system with high conductivity, or may become entrapped in dead-end fractures and therefore have a very long residence time.

The concentrations of chemical parameters reported in other studies are comparable to the concentrations found in this study (Table A.24). Water quality is, in general, good, although concentrations of iron are high. Water is primarily of the calcium-magnesium-bicarbonate type, but concentrations of dissolved solids are relatively low and sodium may account for a significant portion of the total concentration of cations in some wells.

Exceedances of drinking water criteria were found for beryllium, boron, manganese, selenium, aluminum, chloride, and iron in at least one sampled well. These chemicals are discussed below.

Beryllium

The HRL of 0.08 ug/L for beryllium was exceeded in one well. Overall mean and median concentrations were 0.0059 and 0.0075 ug/L, respectively. The 95th percentile (0.35) and upper 95th percent confidence limit (0.17) concentrations exceeded the drinking criteria.

The strongest correlations were with aluminum, chromium, iron, lead, and total suspended solids. Beryllium appears to represent a slight potential health concern in these aquifers.

Boron

The HRL of 600 ug/L for boron was exceeded in one well (635.4 ug/L) and there were four additional wells in which the concentration exceeded 100 ug/L. However, the mean and median concentrations were 45 and 37 ug/L, well below the drinking criteria. Both the upper 95th percentile (626 ug/L) and upper 95th percent confidence limit (662 ug/L) concentrations were slightly greater than the HRL. The only significant correlations were with pH and sodium. Boron does not represent a significant potential health risk in PMUD aquifers in Region 1, although about 5 percent of sampled wells will exceed the drinking water criteria.

Manganese

The drinking criteria for manganese (1000 ug/L) was exceeded in one well (2507.5 ug/L). The next highest concentration was 621.5 ug/L. Mean and median concentrations

were 45 and 70 ug/L, and the upper 95th percent confidence limit concentration of 123 ug/L is well below the drinking criteria. Manganese does not represent a potential health concern in Region 1.

Selenium

The HRL for selenium (30 ug/L) was exceeded in one well (92.5 ug/L). The mean and median concentrations were both 2.0 ug/L. The 95th percentile and upper 95th percent confidence limit concentrations were 89 and 36 ug/L, respectively. Selenium was not well correlated with any chemical parameter. There was a positive correlation with Eh which may reflect the tendency for higher selenium concentrations in oxygenated ground water, but it is unclear if the source of the selenium is the soil or aquifer material. Selenium represents a potential health concern in just over 5 percent of wells completed in the PMUD aquifer.

Aluminum

Aluminum exceeded the Secondary Maximum Contaminant Level of 50 ug/L in two wells. The mean and median concentrations were 4.2 and 6.5 ug/L, while the upper 95th percent confidence limit concentration was 197 ug/L. The greatest correlations were with beryllium, iron, chromium, lead, vanadium, and suspended solids. As with other Precambrian aquifers, aluminum concentrations in ground water are a function of parent material, and aluminum primarily forms complexes with other metals in ground water.

Chloride

The SMCL of 250000 ug/L for chloride was exceeded in one well. This well had a concentration of 5029000 ug/L, or about 0.5%. There were no other chemical concentrations which exceeded a drinking criteria in this well. The sample appears to have been contaminated, either by recent chlorination of the well or by addition of hydrochloric acid to the sample bottle. The median concentration of 2275 ug/L is well below the SMCL. Chloride does not represent a drinking water concern in Region 1.

Iron

The SMCL for iron (300 ug/L) was exceeded in 10 of the 20 wells sampled. The mean and median concentrations were 297 and 298 ug/L. The upper 95th percent confidence limit concentration was 680 ug/L. As with other Precambrian aquifers, iron concentrations were most strongly correlated with other trace metals and suspended solids. Because of the association with suspended solids, it is difficult to determine if iron represents a concern in ground water, but concentrations of iron are high compared to most other aquifers of Region 1.

3.5. Volatile Organic Compounds (VOCs)

VOC results are summarized in Table A.27. The distribution of VOC samples and detections are illustrated in Figure B.7. There were 28 wells in which a VOC was detected. This represents 20 percent of the sampled wells, which is greater than the overall statewide rate of 11 percent. There were two wells in which more than one VOC was detected. Eleven of the 30 total detections were chloroform. Chloroform may represent a by-product of well disinfection, but chloroform and other trihalomethane compounds may also be naturally occurring. Nine of the detections were compounds which may be associated with fuel oil leaks or spills, although all but one of these was toluene and the concentrations were less than 0.5 ug/L. Eight of the detections were fluorocarbon compounds, which accounts for 27 percent of the VOC detections. This was well above the statewide rate of 7 percent. Fluorocarbons may be the result of atmospheric fallout. Only one compound was a chlorinated solvent, which are generally associated with industrial uses.

Eight of the VOC detections were in the QBAA aquifer group, seven were in the PCCR aquifer group, and there were three each in the PMNS, PMUD, QBUA, and QWTA groups. The occurrence of VOCs was not associated with any chemical. Median concentrations of dissolved oxygen were below the detection limit for samples with and without detectable VOCs, and the Eh of these two groups were equal. The frequency of detecting tritium in samples with a detected VOC was 83 percent, while the frequency was

71 percent in wells with no detectable VOC. There was no significant difference in well depth or static water elevation in samples with and without a detectable VOC. The occurrence of VOCs in ground water appears to be somewhat random, being dependent on a source for the VOC.

There were no exceedances of drinking criteria. Overall, VOCs do not represent a drinking water concern in Region 1.

4. Summary and Recommendations

This chapter is divided into a section providing a summary of the results, a section providing recommendations for additional research, and a section providing monitoring recommendations.

4.1. Summary

1. Summary statistics (median, minimum, maximum, mean, 95th confidence limit, and 90th or 95th percentile concentrations) for a wide range of chemical parameters have been calculated for 12 aquifer groups sampled in MPCA Region 1 in northeast Minnesota. Sample size was sufficient for the Precambrian crystalline (PCCR), North Shore Volcanic (PMNS), undifferentiated Precambrian (PMUD), buried artesian drift (QBAA), buried unconfined drift (QBUA), and surficial drift (QWTA) aquifer groups for these values to serve as background concentrations for the aquifers in Region 1.
2. There were differences in concentrations of many chemicals between different aquifer groups. Buried and surficial drift aquifers had very similar water quality, including higher concentrations of arsenic, iron, phosphorus, and silicate, and lower concentrations of aluminum, beryllium, lead, sodium, and zinc compared to the Precambrian aquifers. The Precambrian aquifers had a wide variability in concentrations of chemicals. Concentrations of boron, beryllium, fluoride, and sodium were greatest in the PMNS aquifer group, while arsenic concentrations were greatest in the PMUD group. Concentrations of many chemicals were lower in the PMNS group compared to other Precambrian groups, including alkalinity, potassium, organic

carbon, magnesium, barium, calcium, and manganese. Water quality of aquifers was most affected by parent material, particularly for the Precambrian aquifers.

3. Ground water quality of Precambrian aquifers reflects impacts from both the unsaturated zone and bedrock units. Ground water in Precambrian aquifers is of the calcium-magnesium-bicarbonate type, similar to that of the buried drift aquifers. Concentrations of many trace chemicals, such as boron, beryllium, and copper, are greater in Precambrian aquifers, reflecting mineralogy of the different bedrock units.
4. Health-based drinking standards (HRL or HBV) were exceeded for the following compounds:
    - manganese - 6 exceedances, primarily in drift aquifers;
    - boron - 5 exceedances, primarily in Precambrian aquifers;
    - beryllium - 12 exceedances in Precambrian and drift aquifers;
    - selenium - 1 exceedance in a PCCR aquifer; and
    - arsenic - 1 exceedance in a PCCR aquifer.
5. Non-health based standards (MCL or SMCL) were exceeded for the following compounds:
    - iron - 70 exceedances, scattered among all aquifers;
    - aluminum - 28 exceedances in Precambrian and drift aquifers;
    - sulfate - 1 exceedance in a PCCR aquifer;
    - chloride - 1 exceedance in a PMUD aquifer;
    - lead - 4 exceedances of the action level of 15 ug/L, primarily in Precambrian aquifers; and
    - fluoride - 1 exceedance in a PCCR aquifer.
6. Median concentrations of many chemicals in all aquifers of Region 1 varied in comparison with statewide median concentrations for similar aquifers. Median concentrations of chemicals which reflect leaching, such as bicarbonate, selenium, antimony, vanadium, calcium, and nitrate, were lower in Region 1 aquifers compared to similar aquifers statewide. Concentrations of trace elements were higher. The primary trace elements of concern include beryllium, boron, aluminum, and lead. Beryllium and boron have health-based drinking water criteria, while the drinking

criteria for iron and aluminum is not health-based. Iron and aluminum concentrations exceeded or were near the drinking criteria in a high percentage of wells in all aquifers, while the high rates of exceedance for boron and beryllium were primarily in the Precambrian aquifers. The primary control on concentrations of boron, aluminum, iron, and beryllium appears to be parent material.

7. Volatile organic compounds were detected in 28 wells or 20 percent of the samples. Trihalomethane compounds, primarily chloroform, were the most common VOC found. Fuel oil compounds were detected next most frequently. No drinking water criteria for VOCs was exceeded.

4.2. Research Recommendations

The objective of research is to provide information relating physical processes to water quality. Although research is typically conducted at small scales, results should have widespread application. GWMAP conducts research related to impacts of human activity on ground water quality. Research recommendations for Region 1 are discussed below.

1. A better understanding of ground water hydrology is required before water quality can be related to hydrologic processes. In particular, the following questions should be addressed:
    - What are residence times of ground water accumulating and moving along the bedrock-drift interface?
    - How important are fracture systems in ground water hydrology?
    - What are the mechanisms of chemical dissolution of bedrock and how do these relate to potential health impacts for drinking water receptors?
2. Land use information needs to be collected to determine if there is a relationship between the high frequency of VOC detection and human activity.
3. Bedrock aquifers need to be classified so that water quality can be related to hydrologic and geochemical conditions. In particular, individual well logs should be examined when considering water quality, since wells classified as being completed in Precambrian aquifers may be completed across the bedrock-drift interface.

4.3. Monitoring Needs

The objective of ground water monitoring is to provide information which can serve as a point of reference for ground water quality. Baseline monitoring is used to provide data which can be compared with site-specific or regional data. Ambient monitoring includes a time component and is intended to provide information regarding long-term trends in water quality of an aquifer. Monitoring needs for Region 1 are discussed below.

1. Baseline data : the baseline data for the buried confined drift (QBAA), and surficial drift (QWTA) aquifers is sufficient to be considered representative of background. These data can simply be updated over time. Data bases for the Precambrian aquifers should be expanded and the data reanalyzed to establish baseline conditions. Information in this report provides an initial estimate of background water quality in these aquifers, but the values may change as additional data is incorporated. The following specific recommendations are made for baseline enhancement.
    - Expand the database for PCCR, PMNS, and PMUD aquifers by about 20 wells each. Wells selected for sampling should have well logs and would preferably be grouted. The wells do not need to be located within GWMAP grid cells. The parameter list includes major cations and anions and the inorganic trace elements. In addition to using the 4-letter CWI code, additional effort should be made to determine specific formations the PCCR and PMUD aquifers are completed in. This may reduce some of the variability in the water quality data for these two aquifers.
    - Sample for VOCs in approximately 50 additional wells across Region 1. Sampling would primarily be done in Precambrian aquifers, particularly aquifers classified as PCCR. The data would be used to verify the distribution of VOCs found in the current study. When developing an ambient network for VOC analysis, it is important to verify where wells are completed in the geologic formations.

- Analysis of the data should be conducted at approximately five to ten year intervals, provided data have been collected during this period. Analysis methods similar to those employed by GWMAP should be used.
- Data from other studies can be incorporated into the baseline data base. Field sampling methods must be documented and meet standard QA/QC protocol.

2. Ambient monitoring : ambient monitoring is needed in aquifers impacted by humans. At this time, VOCs are the only potential chemical of concern related to human activity in Region 1, particularly in Precambrian aquifers. It is unclear, however, if the high incidence of VOC detections is related to human activity and what the potential health implications of VOCs are. An ambient network should not be established, therefore, until the link between human activity and incidence of VOC detections has been proven.
3. Sampling, data management, and data analysis protocol should be established and documented. Protocol developed by other agencies or ground water groups can be utilized.

References

Cotter, R.D., H.L. Young, and T.C. Winter. 1964. *Preliminary Surficial Geologic Map of the Mesabi-Vermilion Iron Range Area, Northeastern Minnesota*. Misc. Map Series I-403. United States Geological Survey. 1 plate.

Ericson, D.W., G.F. Lindholm, and J.O. Helgeson. 1976. *Water Resources of the Rainy Lake Watershed, Northeastern Minnesota*. Hydrologic Investigations Atlas HA-556. United States Geological Survey. 2 plates.

Green, J.C. 1992. *Geologic Map of the North Shore of Lake Superior, Lake and Cook Counties, Minnesota: Part 1. Little Marais to Tofte.* Misc. Map Series M-71. University of Minnesota. St. Paul, MN. 1 plate.

Helgeson, J.O., G.F. Lindholm, and D.W. Ericson. 1976. *Water Resources of the Little Fork River Watershed, Northeastern Minnesota.* Hydrologic Investigations Atlas HA-551. United States Geological Survey. 2 plates.

Jirsa, M.A., T.J. Boerboom, V.W. Chandler, and P.L. McSwiggen. 1991. *Bedrock Geologic Map of the Cook to Side Lake Area, St. Louis and Itasca Counties, Minnesota*. Misc. Map Series. Map M-75. University of Minnesota. St. Paul, MN. 1 plate.

Lindholm, G.F., D.W. Ericson, W.L. Broussard, and M.F. Hult. 1979. *Water Resources of the St. Louis River Watershed, Northeastern Minnesota*. Hydrologic Investigations Atlas HA-586. United States Geological Survey. 3 plates.

Lindholm, G.F., J.O. Helgeson, and D.W. Ericson. 1974. *Water Resources of the Big Fork River Watershed, North-Central Minnesota*. Hydrologic Investigations Atlas HA-549. United States Geological Survey. 2 plates.

Minnesota Department of Health. 1997. *Health Based Value for Manganese.* Office Memorandum by Larry Gust, Supervisor, Health Risk Assessment Unit. St. Paul, MN. 1 p.

Minnesota Geological Survey. 1982. *Geologic Map of Minnesota - Two Harbors Sheet*. University of Minnesota. St. Paul, MN. 1 plate.

Minnesota Geological Survey. 1979. *Geologic Map of Minnesota - International Falls Sheet. University of Minnesota*. St. Paul, MN. 1 plate.

Minnesota Geological Survey. 1970. *Geologic Map of Minnesota - Hibbing Sheet. University of Minnesota*. St. Paul, MN. 1 plate.

Minnesota Pollution Control Agency. 1994. *Ground Water Monitoring and Assessment Program (GWMAP) Annual Report.* St. Paul, MN. 182 p.

Minnesota Pollution Control Agency. 1995. *Ground Water Monitoring and Assessment Program (GWMAP) Annual Report.* St. Paul, MN. 116 p.

Minnesota Pollution Control Agency. 1996. *GWMAP Field Guidance Manual*. St. Paul, MN. 42p.

Minnesota Pollution Control Agency. 1998a. *Baseline Water Quality of Minnesota's Principal Aquifers.* St. Paul, MN. 145p. and appendices.

Minnesota Pollution Control Agency. 1998b. *Data Analysis Protocol for the Ground Water Monitoring and Assessment Program (GWMAP)*. Draft in review.

Morey, G.B. 1967. *Stratigraphy and Petrology of the Type Fond du Lac Formation, Dultuth, Minnesota*. Report of Investigations 7. University of Minnesota. Minneapolis, MN. 35 pp.

Morey, G.B., J.C. Green, R.W. Ojakangas, and P.K. Sims. 1970. *Stratigraphy of the Lower Precambrian Rocks in the Vermilion District, Northeastern Minnesota*. Report of Investigations 14. University of Minnesota. Minneapolis, MN. 33 pp.

Myers, Georgianna, S. Magdalene, D. Jakes, E. Porcher. 1992. *The Redesign of the Ambient Ground Water Monitoring Program*. Minnesota Pollution Control Agency. St. Paul, MN. 151 p.

Olcott, P.G., D.W. Ericson, P.E. Felsheim, and W.L. Broussard. 1978. *Water Resources of the Lake Superior Watershed, Northeastern Minnesota*. Hydrologic Investigations Atlas HA-582. United States Geological Survey. 2 plates.

Sims, P.K. 1970. *Geologic Map of Minnesota*. Misc. Map Series M-14. Minnesota Geological Survey - University of Minnesota. Minneapolis, MN. 1 plate.

Southwick, D.L. 1993. *Geologic Map of Archean Bedrock, Soudan-Bigfork Area, Northern Minnesota*. Misc. Map Series M-79. University of Minnesota. St. Paul, MN. 1 plate.

Wahl, T. E., and R. G. Tipping. 1991. *Ground-water Data Management - The County Well Index*. Minnesota Geological Survey. Minneapolis, MN. 38 p.

Wright, H.E. Jr., L.A. Mattson, and J.A. Thomas. 1970. *Geology of the Cloquet Quadrangle*. Geologic Map Series GM-3. University of Minnesota-Minnesota Geological Survey. Minneapolis, MN. 30 pp. and 1 plate.

Appendix A - Tables

1. Distribution of samples, by aquifer.
2. Summary information for all chemical parameters. Censoring values were established just below the maximum reporting limit.
3. Descriptive statistics for the Mount Simon-Hinckley Formation (CMSH).
4. Descriptive statistics for undifferentiated Precambrian formations (PCCR).
5. Descriptive statistics for undifferentiated Precambrian crystalline formations (PCUU).
6. Descriptive statistics for the Biwabik Iron Formation (PEBI).
7. Descriptive statistics for the Duluth Complex (PMDC).
8. Descriptive statistics for the Mount Simon-Fond du Lac Formation (PMFL).
9. Descriptive statistics for the Hinckley Formation (PMHN).
10. Descriptive statistics for the North Shore Volcanics Group (PMNS).
11. Descriptive statistics for undifferentiated Proterozoic Metasedimentary units (PMUD).
12. Descriptive statistics for buried Quaternary artesian aquifers (QBAA).
13. Descriptive statistics for unconfined buried Quaternary aquifers (QBUA).
14. Descriptive statistics for Quaternary water table aquifers (QWTA).
15. Coefficients for log-censored data from analysis of descriptive statistics, for each aquifer and chemical. See MPCA, 1998a, for application of these coefficients.
16. Coefficients for log-normal data from analysis of descriptive statistics, for each aquifer and chemical. See MPCA, 1998a, for application of these coefficients.
17. Median concentrations, in ug/L, of sampled chemicals for each of the major aquifers. The p-value indicates the probability that aquifers have equal concentrations.
18. Median concentrations of chemicals in buried Quaternary and Precambrian bedrock aquifers. An asterisk indicates chemicals for which concentrations differed between the two aquifer groups. Concentrations are in ug/L except for pH, temperature (^{o}F), specific conductance (umhos/cm), and Eh (mV).
19. Summary of water quality criteria, basis of criteria, and endpoints, by chemical parameter.
20. Number of samples exceeding health-based water quality criteria, by aquifer.
21. Percentage of samples exceeding health-based water quality criteria, by aquifer.
22. Number of samples exceeding non-health-based water quality criteria, by aquifer.
23. Percentage of samples exceeding non-health-based water quality criteria, by aquifer.
24. Comparison of water quality data for Quaternary glacial drift aquifers from different literature sources for Northeast Minnesota. Concentrations represent median values, in ug/L (ppb)[1].
25. Comparison of water quality data for Precambrian bedrock aquifers from different literature sources for Northeastern Minnesota. Concentrations represent median values, in ug/L (ppb)[1].
26. Comparison of water quality data for North Shore Volcanic aquifers from different literature sources for Northeast Minnesota. Concentrations represent median values, in ug/L (ppb)[1].
27. Summary of VOC detections for Region 1.

Table A.1 : Distribution of samples, by aquifer.

Aquifer	Number of Samples
Mount Simon-Hinckley (CMSH)	1
Precambrian Crystalline (PCCR)	16
Precambrian undifferentiated (PCUU)	1
Biwabik Iron Formation (PEBI)	1
Duluth Complex (PMDC)	1
Fond du Lac Formation (PMFL)	1
Hinckley (PMHN)	1
North Shore Volcanics (PMNS)	12
Precambrian undifferentiated (PMUD)	20
Quaternary buried artesian aquifer (QBAA)	52
Quaternary buried unconfined aquifer (QBUA)	12
Quaternary water table aquifer (QWTA)	21

Table A.2 : Summary information for all chemical parameters. Censoring values were established just below the maximum reporting limit.

Chemical	Number of samples	Number of missing	Maximum reporting limit (ug/L)	Number of detections above censoring value	Number censored values
Alkalinity	137	2	nnd[1]	137	0
Aluminum	139	0	0.060	132	7
Antimony	139	0	0.0080	79	60
Arsenic	139	0	0.060	124	15
Barium	139	0	1.4	134	5
Beryllium	139	0	0.010	75	64
Bismuth	76	63	0.040	1	75
Boron	139	0	13	120	19
Bromide	139	0	0.20	1	138
Cadmium	139	0	0.020	56	83
Calcium	139	0	nnd	139	0
Cesium	76	63	0.010	40	36
Chloride	139	0	200	139	0
Chromium	139	0	0.050	132	31
Cobalt	139	0	0.0020	138	1
Copper	139	0	5.5	70	69
Dissolved oxygen	139	0	nnd	32	107

Table A.2 continued.

			Maximum	Number of	Number

Chemical	Number of samples	Number missing	reporting limit (ug/L)	detections above censoring value	censored values
Eh	139	0	nnd	139	0
Fluoride	109	30	[2]	109	0
Iron	139	0	3.2	138	1
Lead	139	0	0.030	130	9
Lithium	139	0	4.5	79	60
Magnesium	139	0	nnd	139	0
Manganese	139	0	0.90	136	3
Molybdenum	139	0	4.2	41	98
Nickel	139	0	6.0	41	98
Nitrate-N	139	0	500	14	125
pH	137	2	nnd	137	0
Phosphorus	139	0	14.9	113	26
Potassium	139	0	118.5	136	3
Rubidium	139	0	555.3	8	130
Selenium	139	0	1.0	95	44
Silicate	139	0	nnd	139	0
Silver	139	0	0.0090	64	75
Sodium	139	0	nnd	139	0
Specific Conductance	137	2	nnd	137	0
Strontium	139	0	nnd	139	0
Sulfate	139	0	300	125	14
Sulfur	139	0	21.8	138	1
Temperature	137	2	nnd	137	0
Thallium	139	0	0.0050	38	101
Tin	76	63	0.040	54	22
Titanium	139	0	0.0035	40	90
Total dissolved solids	139	0	nnd	139	0
Total organic carbon	139	0	500	134	5
Total suspended solids	139	0	nnd	139	0
Vanadium	139	0	4.7	66	73
Zinc	139	0	2.7	126	13
Zirconium	76	63	0.030	54	22

Table A.2 continued

Chemical	Number of samples	Number missing	Maximum reporting limit (ug/L)	Number of detections above censoring value	Number censored values
1,1-Dichloroethane	139	-	0.2	-	-
1,1-Dichloroethene	139	-	0.5	-	-
1,1-Dichloropropene	139	-	0.2	-	-
1,1,1-Trichloroethane	139	-	0.2	-	-
1,1,1,2-Tetrachloroethane	139	-	0.2	-	-
1,1,2-Trichloroethane	139	-	0.2	-	-
1,1,2,2-Tetrachloroethane	139	-	0.2	-	-
1,1,2-Trichlorotrifluoroethane	139	-	0.2	-	-
1,2-Dichlorobenzene	139	-	0.2	-	-
1,2-Dichloroethane	139	-	0.2	-	-
1,2-Dichloropropane	139	-	0.2	-	-
1,2,3-Trichlorobenzene	139	-	0.5	-	-
1,2,3-Trichloropropane	139	-	0.5	-	-
1,2,4-Trichlorobenzene	139	-	0.5	-	-
1,2,4-Trimethylbenzene	139	-	0.5	-	-
1,3-Dichlorobenzene	139	-	0.2	-	-
1,3-Dichloropropane	139	-	0.2	-	-
1,3,5-Trimethylbenzene	139	-	0.5	-	-
1,4-Dichlorobenzene	139	-	0.2	-	-
2,2-Dichloropropane	139	-	0.5	-	-
2-Chlorotoluene	139	-	0.5	-	-
4-Chlorotoluene	139	-	0.5	-	-
Acetone	139	-	20	-	-
Allyl chloride	139	-	0.5	-	-
Bromochloromethane	139	-	0.5	-	-
Bromodichloromethane	139	-	0.2	-	-
Benzene	139	-	0.2	-	-
Bromobenzene	139	-	0.2	-	-
Bromoform	139	-	0.5	-	-
Bromomethane	139	-	0.5	-	-
cis-1,2-Dichloroethene	139	-	0.2	-	-
cis-1,3-Dichloropropene	139	-	0.2	-	-
Carbon tetrachloride	139	-	0.2	-	-
Chlorodibromomethane	139	-	0.5	-	-
Chlorobenzene	139	-	0.2	-	-
Chloroethane	139	-	0.5	-	-
Chloroform	139	-	0.1	-	-

Table A.2 continued.

Chemical	Number of samples	Number of missing	Maximum reporting limit (ug/L)	Number of detections above censoring value	Number of censored values
Chloromethane	139	-	0.5	-	-
1,2-Dibromo-3-chloropropane	139	-	0.5	-	-
Dibromomethane	139	-	0.5	-	-
Dichlorodifluoromethane	139	-	0.5	-	-
Dichlorofluoromethane	139	-	0.5	-	-
1,2-Dibromoethane	139	-	0.5	-	-
Ethylbenzene	139	-	0.2	-	-
Ethyl ether	139	-	2	-	-
Hexachlorobutadiene	139	-	0.5	-	-
Isopropylbenzene	139	-	0.5	-	-
Methylene chloride	139	-	0.5	-	-
Methyl ethyl ketone	139	-	10	-	-
Methyl isobutyl ketone	139	-	5	-	-
Methyl tertiary butyl ether	139	-	2	-	-
n-Butylbenzene	139	-	0.5	-	-
Naphthalene	139	-	0.5	-	-
n-Propylbenzene	139	-	0.5	-	-
o-Xylene	139	-	0.2	-	-
p&m-Xylene	139	-	0.2	-	-
p-Isopropyltoluene	139	-	0.5	-	-
sec-Butylbenzene	139	-	0.5	-	-
Styrene	139	-	0.5	-	-
tert-Butylbenzene	139	-	0.5	-	-
trans-1,2-Dichloroethene	139	-	0.1	-	-
trans-1,3-Dichloropropene	139	-	0.2	-	-
Trichloroethene	139	-	0.1	-	-
Trichlorofluoromethane	139	-	0.5	-	-
Tetrachloroethene	139	-	0.2	-	-
Tetrahydrofuran	139	-	10	-	-
Toluene	139	-	0.2	-	-
Vinyl chloride	139	-	0.5	-	-

[1] nnd = no samples were below the maximum reporting limit

[2] Fluoride was censored at several detection limits. Censoring at the highest detection limit would result in only a few values above the censoring limit. Consequently, all non-detections were treated as missing data and removed from the data set.

Table A.3 : Descriptive statistics for the Mount Simon-Hinckley Formation (CMSH).

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95th percentile	Min	Max	State Median
						ug/L				ug/L
Alkalinity	1	0	ins	ins	ins	139000	ins	-	-	132500
Aluminum	1	0	ins	ins	ins	< 0.060	ins	-	-	1.2
Antimony	1	0	ins	ins	ins	0.010	ins	-	-	0.010
Arsenic	1	0	ins	ins	ins	1.2	ins	-	-	0.86
Barium	1	0	ins	ins	ins	80	ins	-	-	57
Beryllium	1	0	ins	ins	ins	0.010	ins	-	-	< 0.010
Boron	1	0	ins	ins	ins	300	ins	-	-	23
Bromide	1	1	ins	ins	ins	< 0.20	ins	-	-	< 0.20
Cadmium	1	0	ins	ins	ins	0.080	ins	-	-	< 0.020
Calcium	1	0	ins	ins	ins	16692	ins	-	-	43648
Chloride	1	0	ins	ins	ins	36070	ins	-	-	2135
Chromium	1	0	ins	ins	ins	0.55	ins	-	-	0.25
Cobalt	1	0	ins	ins	ins	0.11	ins	-	-	0.41
Copper	1	1	ins	ins	ins	< 5.5	ins	-	-	5.7
Dissolved oxygen	1	1	ins	ins	ins	< 300	ins	-	-	630
Eh	1	0	ins	ins	ins	75	ins	-	-	212
Fluoride	1	0	ins	ins	ins	580	ins	-	-	225
Iron	1	0	ins	ins	ins	164	ins	-	-	387
Lead	1	0	ins	ins	ins	0.070	ins	-	-	0.17
Lithium	1	0	ins	ins	ins	6.0	ins	-	-	7.0
Magnesium	1	0	ins	ins	ins	5591	ins	-	-	13269
Manganese	1	0	ins	ins	ins	28	ins	-	-	44
Molybdenum	1	1	ins	ins	ins	< 4.2	ins	-	-	< 4.2
Nickel	1	1	ins	ins	ins	< 6.0	ins	-	-	< 6.0
Nitrate-N	1	1	ins	ins	ins	< 500	ins	-	-	< 500
pH	1	0	ins	ins	ins	8.1	ins	-	-	7.3
Phosphorus	1	0	ins	ins	ins	33	ins	-	-	34
Potassium	1	0	ins	ins	ins	2478	ins	-	-	1292
Redox	1	0	ins	ins	ins	-145	ins	-	-	-3.0
Rubidium	1	1	ins	ins	ins	< 555	ins	-	-	< 555
Selenium	1	1	ins	ins	ins	< 1.0	ins	-	-	1.6
Silicate	1	0	ins	ins	ins	4313	ins	-	-	10894
Silver	1	0	ins	ins	ins	0.020	ins	-	-	< 0.0090
Sodium	1	0	ins	ins	ins	66103	ins	-	-	3823
Specific Conductance	1	0	ins	ins	ins	87	ins	-	-	304
Strontium	1	0	ins	ins	ins	189	ins	-	-	109
Sulfate	1	0	ins	ins	ins	17040	ins	-	-	1735
Sulfur	1	0	ins	ins	ins	6050	ins	-	-	1948
Temperature	1	0	ins	ins	ins	8.9	ins	-	-	8.7
Thallium	1	0	ins	ins	ins	0.010	ins	-	-	< 0.0050
Titanium	1	1	ins	ins	ins	< 0.0035	ins	-	-	< 0.0035
Total dissolved solids	1	0	ins	ins	ins	238000	ins	-	-	218000

Table A.3 continued.

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95th percentile	Min	Max	State Median
Total organic carbon	1	0	ins	ins	ins	1500	ins	-	-	1850
Total phosphate-P	1	1	ins	ins	ins	< 20	ins	-	-	20
Total suspended solids	1	0	ins	ins	ins	2000	ins	-	-	5000
Vanadium	1	1	ins	ins	ins	< 4.7	ins	-	-	4.9
Zinc	1	1	ins	ins	ins	< 2.7	ins	-	-	12

Table A.4 : Descriptive statistics for undifferentiated Precambrian formations (PCCR).

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	90th percentile	Min	Max	State Median
				ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
Alkalinity	16	0	log-normal	188018	270334	135500	443000	54000	541000	211000
Aluminum	16	0	log-normal	16	45	13	272	1.4	467	9.4
Antimony	16	5	log-censored	0.017	0.13	0.018	0.062	< 0.0080	0.090	0.014
Arsenic	16	3	log-censored	0.70	28	0.64	49	< 0.060	157	0.64
Barium	16	0	log-normal	43	69	38	139	10	173	39
Beryllium	16	6	log-censored	0.019	0.39	0.020	0.23	< 0.010	0.51	0.020
Boron	16	1	log-censored	49	603	49	395	< 13	592	55
Bromide	16	16	ins	ins	ins	< 0.20	ins	< 0.20	0.10	< 0.20
Cadmium	16	8	log-censored	0.026	0.81	0.020	0.35	< 0.020	0.47	0.020
Calcium	16	0	log-normal	46505	77144	31747	190363	11585	309399	38909
Chloride	16	0	log-normal	3506	7997	3220	22999	360	28830	2680
Chromium	16	4	log-censored	0.45	4.1	0.49	2.8	< 0.050	4.3	0.61
Cobalt	16	0	normal	0.83	1.3	0.37	2.0	0.12	2.3	0.37
Copper	16	6	log-censored	7.3	64	7.5	35	< 5.5	37	7.3
Dissolved oxygen	16	7	log-censored	744	47253	810	18932	< 300	45700	735
Eh	16	0	normal	233	288	266	332	-18	354	217
Fluoride	10	0	log-normal	595	1020	490	3258	220	4090	490
Iron	16	0	log-normal	445	2102	145	20875	20	39594	205
Lead	16	0	log-normal	0.67	1.2	0.50	4.2	0.26	11	0.50
Lithium	16	4	log-censored	6.0	74	5.9	76	< 4.5	215	6.5
Magnesium	16	0	log-normal	16018	27970	11780	77945	4206	147192	13501
Manganese	16	0	log-normal	116	399	103	1191	2.8	2087	102
Molybdenum	16	12	log-censored	1.3	39	< 4.2	17	< 4.2	29	< 4.2
Nickel	16	10	log-censored	4.4	24	< 6.0	15	< 6.0	23	< 6.0
Nitrate-N	16	13	ins	ins	ins	< 500	500	< 500	500	< 500
pH	16	0	normal	7.4	7.9	7.1	8.6	6.3	9.0	7.4
Phosphorus	16	6	log-censored	25	237	24	131	< 15	249	31
Potassium	16	0	normal	3087	4702	2007	7475	360	9766	2792

Table A. 4 continued.

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	90th percentile	Min	Max	State Median
Redox	16	0	normal	12	66	45	109	-237	131	3
Rubidium	16	15	ins	ins	ins	< 555	608	< 555	732	< 555
Selenium	16	7	log-censored	0.70	80	1.1	95	< 1.0	308	2.0
Silicate	16	0	normal	8830	10471	8733	14667	5083	16249	8567
Silver	16	9	log-censored	0.0068	0.061	< 0.0090	0.036	< 0.0090	0.050	0.0090
Sodium	16	0	log-normal	14928	28054	8453	107935	3338	144848	9821
Specific Conductance	16	0	log-normal	200	440	240	680	5.0	1000	300
Strontium	16	0	log-normal	256	421	192	957	59	2077	197
Sulfate	16	0	no distribution	-	-	9765	400875	2340	1207380	3410
Sulfur	16	0	no distribution	-	-	3583	142756	1067	429506	3721
Temperature	16	0	normal	7.9	8.5	7.7	9.7	6.2	10	8.5
Thallium	16	11	log-censored	0.0073	0.011	< 0.0050	0.010	< 0.0050	0.010	< 0.0050
Titanium	16	10	log-censored	0.0018	0.058	< 0.0035	0.024	< 0.0035	0.049	< 0.0035
Total dissolved solids	16	0	log-normal	302831	500726	194000	1209400	64000	2594000	257000
Total organic carbon	16	1	log-censored	2757	19157	3450	9340	< 500	14100	2100
Total phosphate-P	16	11	log-censored	12	128	< 20	69	< 20	90	< 20
Total suspended solids	16	0	log-normal	5171	12850	4000	59000	1000	108000	4000
Vanadium	16	7	log-censored	4.9	30	5.5	19	4.7	35	5.1
Zinc	16	0	no distribution	-	-	8.9	380	3.1	517	15

Table A.5 : Descriptive statistics for undifferentiated Precambrian crystalline formations (PCUU).

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95h percentile	Min	Max	State Median
						ug/L				ug/L
Alkalinity	1	0	ins	ins	ins	72000	ins	-	-	333000
Aluminum	1	0	ins	ins	ins	1.5	ins	-	-	< 0.060
Antimony	1	1	ins	ins	ins	< 0.0080	ins	-	-	< 0.0080
Arsenic	1	0	ins	ins	ins	0.19	ins	-	-	1.4
Barium	1	0	ins	ins	ins	1.7	ins	-	-	12
Beryllium	1	1	ins	ins	ins	< 0.010	ins	-	-	< 0.010
Boron	1	1	ins	ins	ins	< 13	ins	-	-	271
Bromide	1	1	ins	ins	ins	< 0.20	ins	-	-	< 0.20
Cadmium	1	1	ins	ins	ins	< 0.020	ins	-	-	< 0.020
Calcium	1	0	ins	ins	ins	22568	ins	-	-	102262
Chloride	1	0	ins	ins	ins	420	ins	-	-	2120
Chromium	1	0	ins	ins	ins	1.1	ins	-	-	1.1
Cobalt	1	0	ins	ins	ins	0.14	ins	-	-	0.54

Table A.5 continued.

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95h percentile	Min	Max	State Median
Copper	1	0	ins	ins	ins	5.9	ins	-	-	5.9

Dissolved oxygen	1	0	ins	ins	ins	9110	ins	-	-	1640
Eh	1	0	ins	ins	ins	225	ins	-	-	159
Fluoride	1	0	ins	ins	ins	200	ins	-	-	410
Iron	1	0	ins	ins	ins	16	ins	-	-	1650
Lead	1	0	ins	ins	ins	0.11	ins	-	-	0.11
Lithium	1	0	ins	ins	ins	4.7	ins	-	-	20
Magnesium	1	0	ins	ins	ins	5178	ins	-	-	46382
Manganese	1	1	ins	ins	ins	< 0.90	ins	-	-	241
Molybdenum	1	1	ins	ins	ins	< 4.2	ins	-	-	<4.2
Nickel	1	1	ins	ins	ins	< 6.0	ins	-	-	<6.0
Nitrate-N	1	1	ins	ins	ins	< 500	ins	-	-	<500
pH	1	0	ins	ins	ins	7.2	ins	-	-	7.2
Phosphorus	1	1	ins	ins	ins	< 15	ins	-	-	70
Potassium	1	0	ins	ins	ins	400	ins	-	-	5629
Redox	1	0	ins	ins	ins	2.0	ins	-	-	-53
Rubidium	1	1	ins	ins	ins	< 555	ins	-	-	<555
Selenium	1	0	ins	ins	ins	2.0	ins	-	-	2.0
Silicate	1	0	ins	ins	ins	8975	ins	-	-	8621
Silver	1	1	ins	ins	ins	< 0.0090	ins	-	-	<0.0090
Sodium	1	0	ins	ins	ins	2961	ins	-	-	63903
Specific Conductance	1	0	ins	ins	ins	160	ins	-	-	162
Strontium	1	0	ins	ins	ins	31	ins	-	-	743
Sulfate	1	0	ins	ins	ins	5910	ins	-	-	58010
Sulfur	1	0	ins	ins	ins	2200	ins	-	-	60092
Temperature	1	0	ins	ins	ins	6.8	ins	-	-	9.6
Thallium	1	1	ins	ins	ins	< 0.0050	ins	-	-	<0.0050
Titanium	1	1	ins	ins	ins	< 0.0035	ins	-	-	<0.0035
Total dissolved solids	1	0	ins	ins	ins	136000	ins	-	-	666000
Total organic carbon	1	0	ins	ins	ins	700	ins	-	-	3000
Total phosphate-P	1	1	ins	ins	ins	< 20	ins	-	-	ins
Total suspended solids	1	0	ins	ins	ins	2000	ins	-	-	4000
Vanadium	1	0	ins	ins	ins	5.5	ins	-	-	5.5
Zinc	1	0	ins	ins	ins	5.1	ins	-	-	8.0

Table A.6 : Descriptive statistics for the Biwabik Iron Formation (PEBI).

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95th percentile	Min	Max	State Median
						ug/L				ug/L
Alkalinity	1	0	ins	ins	ins	78000	ins	-	-	78000
Aluminum	1	0	ins	ins	ins	0.89	ins	-	-	0.89
Antimony	1	0	ins	ins	ins	0.14	ins	-	-	0.14
Arsenic	1	0	ins	ins	ins	5.0	ins	-	-	5.0
Barium	1	0	ins	ins	ins	34	ins	-	-	34
Beryllium	1	0	ins	ins	ins	0.010	ins	-	-	0.010
Boron	1	0	ins	ins	ins	46	ins	-	-	46
Bromide	1	1	ins	ins	ins	< 0.20	ins	-	-	< 0.20
Cadmium	1	1	ins	ins	ins	< 0.020	ins	-	-	< 0.020
Calcium	1	0	ins	ins	ins	30801	ins	-	-	30801
Chloride	1	0	ins	ins	ins	1270	ins	-	-	1270
Chromium	1	1	ins	ins	ins	< 0.050	ins	-	-	< 0.050
Cobalt	1	0	ins	ins	ins	0.17	ins	-	-	0.17
Copper	1	1	ins	ins	ins	< 5.5	ins	-	-	< 5.5
Dissolved oxygen	1	1	ins	ins	ins	< 300	ins	-	-	< 300
Eh	1	0	ins	ins	ins	184	ins	-	-	178
Fluoride	1	0	ins	ins	ins	300	ins	-	-	300
Iron	1	0	ins	ins	ins	155	ins	-	-	155
Lead	1	0	ins	ins	ins	0.17	ins	-	-	0.17
Lithium	1	0	ins	ins	ins	7.0	ins	-	-	7.0
Magnesium	1	0	ins	ins	ins	13310	ins	-	-	13310
Manganese	1	0	ins	ins	ins	290	ins	-	-	290
Molybdenum	1	1	ins	ins	ins	< 4.2	ins	-	-	< 4.2
Nickel	1	1	ins	ins	ins	< 6.0	ins	-	-	< 6.0
Nitrate-N	1	1	ins	ins	ins	< 500	ins	-	-	< 500
pH	1	0	ins	ins	ins	7.8	ins	-	-	7.8
Phosphorus	1	0	ins	ins	ins	17	ins	-	-	17
Potassium	1	0	ins	ins	ins	1727	ins	-	-	1727
Redox	1	0	ins	ins	ins	-36	ins	-	-	-36
Rubidium	1	1	ins	ins	ins	< 555	ins	-	-	< 555
Selenium	1	0	ins	ins	ins	4.5	ins	-	-	4.5
Silicate	1	0	ins	ins	ins	7921	ins	-	-	7921
Silver	1	1	ins	ins	ins	< 0.0090	ins	-	-	< 0.0090
Sodium	1	0	ins	ins	ins	4671	ins	-	-	4671
Specific Conductance	1	0	ins	ins	ins	290	ins	-	-	285
Strontium	1	0	ins	ins	ins	96	ins	-	-	96
Sulfate	1	0	ins	ins	ins	65940	ins	-	-	21980
Sulfur	1	0	ins	ins	ins	21499	ins	-	-	21499
Temperature	1	0	ins	ins	ins	9.0	ins	-	-	9.0
Thallium	1	1	ins	ins	ins	< 0.0050	ins	-	-	< 0.0050
Titanium	1	1	ins	ins	ins	< 0.0035	ins	-	-	< 0.0035
Total dissolved solids	1	0	ins	ins	ins	202000	ins	-	-	202000

Table A.6 continued.

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95th percentile	Min	Max	State Median
Total organic carbon	1	1	ins	ins	ins	< 500	ins	-	-	< 500
Total phosphate-P	1	1	ins	ins	ins	20	ins	-	-	< 20
Total suspended solids	1	0	ins	ins	ins	2000	ins	-	-	2000
Vanadium	1	1	ins	ins	ins	< 4.7	ins	-	-	< 4.7
Zinc	1	0	ins	ins	ins	151	ins	-	-	151

Table A.7 : Descriptive statistics for Duluth Complex (PMDC).

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95th percentile	Min	Max	State Median
						ug/L				ug/L
Alkalinity	1	0	ins	ins	ins	177000	ins	-	-	177000
Aluminum	1	0	ins	ins	ins	771	ins	-	-	771
Antimony	1	0	ins	ins	ins	0.11	ins	-	-	0.11
Arsenic	1	0	ins	ins	ins	1.2	ins	-	-	1.2
Barium	1	0	ins	ins	ins	2.0	ins	-	-	2.0
Beryllium	1	0	ins	ins	ins	0.39	ins	-	-	0.39
Boron	1	0	ins	ins	ins	748	ins	-	-	748
Bromide	1	1	ins	ins	ins	< 0.20	ins	-	-	< 0.20
Cadmium	1	1	ins	ins	ins	< 0.020	ins	-	-	< 0.020
Calcium	1	0	ins	ins	ins	4781	ins	-	-	4781
Chloride	1	0	ins	ins	ins	5900	ins	-	-	5900
Chromium	1	0	ins	ins	ins	2.1	ins	-	-	2.1
Cobalt	1	0	ins	ins	ins	0.83	ins	-	-	0.83
Copper	1	0	ins	ins	ins	79	ins	-	-	79
Dissolved oxygen	1	0	ins	ins	ins	9100	ins	-	-	9100
Eh	1	0	ins	ins	ins	175	ins	-	-	175
Fluoride	1	0	ins	ins	ins	1210	ins	-	-	1210
Iron	1	0	ins	ins	ins	1953	ins	-	-	1953
Lead	1	0	ins	ins	ins	26	ins	-	-	26
Lithium	1	1	ins	ins	ins	< 4.5	ins	-	-	< 4.5
Magnesium	1	0	ins	ins	ins	1807	ins	-	-	1807
Manganese	1	0	ins	ins	ins	120	ins	-	-	120
Molybdenum	1	0	ins	ins	ins	8.1	ins	-	-	8.1
Nickel	1	1	ins	ins	ins	< 6.0	ins	-	-	< 6.0
Nitrate-N	1	1	ins	ins	ins	< 500	ins	-	-	< 500
pH	1	0	ins	ins	ins	8.5	ins	-	-	8.5
Phosphorus	1	0	ins	ins	ins	66	ins	-	-	66
Potassium	1	0	ins	ins	ins	749	ins	-	-	749
Redox	1	0	ins	ins	ins	-46	ins	-	-	-46

Table A.7 continued.

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95th percentile	Min	Max	State Median

Rubidium	1	1	ins	ins	ins	< 555	ins	-	-	< 555
Selenium	1	0	ins	ins	ins	14	ins	-	-	14
Silicate	1	0	ins	ins	ins	8442	ins	-	-	8442
Silver	1	0	ins	ins	ins	0.050	ins	-	-	0.050
Sodium	1	0	ins	ins	ins	74622	ins	-	-	74622
Specific Conductance	1	0	ins	ins	ins	320	ins	-	-	320
Strontium	1	0	ins	ins	ins	20	ins	-	-	20
Sulfate	1	0	ins	ins	ins	9720	ins	-	-	9720
Sulfur	1	0	ins	ins	ins	3468	ins	-	-	3468
Temperature	1	0	ins	ins	ins	8.1	ins	-	-	8.1
Thallium	1	1	ins	ins	ins	< 0.0050	ins	-	-	< 0.0050
Titanium	1	0	ins	ins	ins	0.064	ins	-	-	0.064
Total dissolved solids	1	0	ins	ins	ins	186000	ins	-	-	186000
Total organic carbon	1	0	ins	ins	ins	900	ins	-	-	900
Total phosphate-P	1	0	ins	ins	ins	60	ins	-	-	60
Total suspended solids	1	0	ins	ins	ins	86000	ins	-	-	86000
Vanadium	1	1	ins	ins	ins	< 4.7	ins	-	-	< 4.7
Zinc	1	0	ins	ins	ins	168	ins	-	-	168

Table A.8 : Descriptive statistics for the Mount Simon-Fond du Lac Formation (PMFL).

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95th percentile	Min	Max	State Median
						ug/L				ug/L
Alkalinity	1	0	ins	ins	ins	223000	ins	-	-	ins
Aluminum	1	0	ins	ins	ins	174	ins	-	-	ins
Antimony	1	0	ins	ins	ins	0.050	ins	-	-	ins
Arsenic	1	0	ins	ins	ins	1.1	ins	-	-	ins
Barium	1	0	ins	ins	ins	104	ins	-	-	ins
Beryllium	1	0	ins	ins	ins	0.020	ins	-	-	ins
Boron	1	0	ins	ins	ins	30	ins	-	-	ins
Bromide	1	1	ins	ins	ins	< 0.20	ins	-	-	ins
Cadmium	1	0	ins	ins	ins	0.41	ins	-	-	ins
Calcium	1	0	ins	ins	ins	58420	ins	-	-	ins
Chloride	1	0	ins	ins	ins	1020	ins	-	-	ins
Chromium	1	0	ins	ins	ins	5.0	ins	-	-	ins
Cobalt	1	0	ins	ins	ins	0.31	ins	-	-	ins
Copper	1	0	ins	ins	ins	48	ins	-	-	ins

Table A.8 continued.

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95th percentile	Min	Max	State Median
Dissolved oxygen	1	1	ins	ins	ins	< 300	ins	-	-	ins
Eh	1	0	ins	ins	ins	222	ins	-	-	ins

Fluoride	1	0	ins	ins	ins	300	ins	-	-	300
Iron	1	0	ins	ins	ins	631	ins	-	-	ins
Lead	1	0	ins	ins	ins	15	ins	-	-	ins
Lithium	1	1	ins	ins	ins	< 4.5	ins	-	-	ins
Magnesium	1	0	ins	ins	ins	19695	ins	-	-	ins
Manganese	1	0	ins	ins	ins	4.5	ins	-	-	ins
Molybdenum	1	1	ins	ins	ins	< 4.2	ins	-	-	ins
Nickel	1	1	ins	ins	ins	< 6.0	ins	-	-	ins
Nitrate-N	1	1	ins	ins	ins	< 500	ins	-	-	ins
pH	1	0	ins	ins	ins	7.5	ins	-	-	ins
Phosphorus	1	1	ins	ins	ins	< 15	ins	-	-	ins
Potassium	1	0	ins	ins	ins	1390	ins	-	-	ins
Redox	1	0	ins	ins	ins	0	ins	-	-	ins
Rubidium	1	1	ins	ins	ins	< 555	ins	-	-	ins
Selenium	1	0	ins	ins	ins	5.9	ins	-	-	ins
Silicate	1	0	ins	ins	ins	11069	ins	-	-	ins
Silver	1	0	ins	ins	ins	0.12	ins	-	-	ins
Sodium	1	0	ins	ins	ins	5884	ins	-	-	ins
Specific Conductance	1	0	ins	ins	ins	430	ins	-	-	ins
Strontium	1	0	ins	ins	ins	60	ins	-	-	ins
Sulfate	1	0	ins	ins	ins	14700	ins	-	-	ins
Sulfur	1	0	ins	ins	ins	5232	ins	-	-	ins
Temperature	1	0	ins	ins	ins	7.5	ins	-	-	ins
Thallium	1	0	ins	ins	ins	0.010	ins	-	-	ins
Titanium	1	0	ins	ins	ins	0.014	ins	-	-	ins
Total dissolved solids	1	0	ins	ins	ins	254000	ins	-	-	ins
Total organic carbon	1	0	ins	ins	ins	900	ins	-	-	ins
Total phosphate-P	1	1	ins	ins	ins	< 20	ins	-	-	ins
Total suspended solids	1	0	ins	ins	ins	12000	ins	-	-	ins
Vanadium	1	0	ins	ins	ins	5.1	ins	-	-	ins
Zinc	1	0	ins	ins	ins	196	ins	-	-	ins

Table A.9 : Descriptive statistics for the Mount Simon-Hinckley Formation (PMHN).

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95th percentile	Min	Max	State Median
						ug/L				ug/L
Alkalinity	1	0	ins	ins	ins	127000	ins	-	-	110000
Aluminum	1	0	ins	ins	ins	7.0	ins	-	-	3.2
Antimony	1	0	ins	ins	ins	0.030	ins	-	-	0.030
Arsenic	1	0	ins	ins	ins	2.7	ins	-	-	2.7
Barium	1	0	ins	ins	ins	111	ins	-	-	33
Beryllium	1	1	ins	ins	ins	< 0.010	ins	-	-	<0.010
Boron	1	0	ins	ins	ins	51	ins	-	-	<13
Bromide	1	1	ins	ins	ins	< 0.20	ins	-	-	<0.20
Cadmium	1	1	ins	ins	ins	< 0.020	ins	-	-	<0.020
Calcium	1	0	ins	ins	ins	32651	ins	-	-	26173
Chloride	1	0	ins	ins	ins	490	ins	-	-	1660
Chromium	1	0	ins	ins	ins	0.15	ins	-	-	0.15
Cobalt	1	0	ins	ins	ins	0.41	ins	-	-	0.99
Copper	1	0	ins	ins	ins	13	ins	-	-	<5.5
Dissolved oxygen	1	1	ins	ins	ins	< 300	ins	-	-	<300
Eh	1	0	ins	ins	ins	164	ins	-	-	160
Iron	1	0	ins	ins	ins	121	ins	-	-	1634
Lead	1	0	ins	ins	ins	0.45	ins	-	-	0.45
Lithium	1	0	ins	ins	ins	12	ins	-	-	<4.5
Magnesium	1	0	ins	ins	ins	8202	ins	-	-	8925
Manganese	1	0	ins	ins	ins	42	ins	-	-	139
Molybdenum	1	0	ins	ins	ins	4.4	ins	-	-	<4.2
Nickel	1	0	ins	ins	ins	9.2	ins	-	-	<6.0
Nitrate-N	1	1	ins	ins	ins	< 500	ins	-	-	<500
pH	1	0	ins	ins	ins	8.2	ins	-	-	6.8
Phosphorus	1	0	ins	ins	ins	43	ins	-	-	43
Potassium	1	0	ins	ins	ins	1436	ins	-	-	677
Redox	1	0	ins	ins	ins	-57	ins	-	-	-55
Rubidium	1	0	ins	ins	ins	713	ins	-	-	<555
Selenium	1	1	ins	ins	ins	< 1.0	ins	-	-	<1.0
Silicate	1	0	ins	ins	ins	5742	ins	-	-	11996
Silver	1	0	ins	ins	ins	0.020	ins	-	-	<0.0090
Sodium	1	0	ins	ins	ins	9340	ins	-	-	4096
Specific Conductance	1	0	ins	ins	ins	250	ins	-	-	248
Strontium	1	0	ins	ins	ins	186	ins	-	-	45
Sulfate	1	0	ins	ins	ins	930	ins	-	-	2040
Sulfur	1	0	ins	ins	ins	390	ins	-	-	2200
Temperature	1	0	ins	ins	ins	7.8	ins	-	-	7.8
Thallium	1	0	ins	ins	ins	0.040	ins	-	-	<0.0050
Titanium	1	0	ins	ins	ins	0.0054	ins	-	-	<0.0035
Total dissolved solids	1	0	ins	ins	ins	152000	ins	-	-	150000

Table A.9 continued.

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95th percentile	Min	Max	State Median
Total organic carbon	1	0	ins	ins	ins	2700	ins	-	-	2700
Total phosphate-P	1	0	ins	ins	ins	20	ins	-	-	20
Total suspended solids	1	0	ins	ins	ins	3000	ins	-	-	4000
Vanadium	1	0	ins	ins	ins	12	ins	-	-	6.1
Zinc	1	0	ins	ins	ins	23	ins	-	-	16

Table A.10 : Descriptive statistics for the North Shore Volcanics group (PMNS).

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	90th percentile	Min	Max	State Median
				ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
Alkalinity	12	0	normal	135500	174249	119500	210700	66000	217000	125500
Aluminum	12	0	log-normal	45	216	49	1414	1.1	1448	37
Antimony	12	2	log-censored	0.031	0.28	0.040	0.20	< 0.0080	0.26	0.040
Arsenic	12	1	log-censored	0.75	13	0.97	11	< 0.060	15	0.98
Barium	12	3	log-censored	5.2	62	5.6	34	< 1.4	41	7.0
Beryllium	12	4	log-censored	0.018	2.1	0.025	1.8	< 0.010	2.5	0.020
Boron	12	1	log-censored	182	3980	219	1795	< 13	2114	129
Bromide	12	11	ins	ins	ins	< 0.20	0.50	< 0.20	0.67	< 0.20
Cadmium	12	6	log-censored	0.041	0.19	0.020	0.12	< 0.020	0.13	0.030
Calcium	12	0	normal	27843	38162	23723	50769	1801	55204	26763
Chloride	12	0	log-normal	2524	7929	2445	72428	280	97340	1880
Chromium	12	3	log-censored	0.57	11	0.63	5.6	< 0.050	5.9	0.66
Cobalt	12	0	no distribution	-	-	0.27	3.5	0.10	4.0	0.29
Copper	12	4	log-censored	9.5	151	8.0	73	< 5.5	79	12
Dissolved oxygen	12	7	log-censored	480	43736	< 300	10390	< 300	10690	< 300
Eh	12	0	normal	158	223	184	267	13	269	173
Fluoride	8	0	normal	805	1174	715	1596	270	1600	430
Iron	12	0	log-normal	266	1100	204	19929	9.6	26320	238
Lead	12	0	log-normal	0.50	1.4	0.39	13	0.060	16	0.38
Lithium	12	5	log-censored	6.1	50	5.8	35	< 4.5	44	11
Magnesium	12	0	normal	11654	17226	9555	21840	793	22091	11528
Manganese	12	0	log-normal	25	61	35	173	1.5	199	28
Molybdenum	12	7	log-censored	5.6	20	< 4.2	14	< 4.2	15	< 4.2
Nickel	12	8	log-censored	3.2	36	< 6.0	21	< 6.0	26	< 6.0
Nitrate-N	12	11	ins	ins	ins	< 500	497	< 500	500	< 500
pH	12	0	normal	8.3	8.7	8.0	9.2	7.0	9.3	8.0
Phosphorus	12	4	log-censored	19	403	21	278	< 15	299	23
Potassium	12	2	log-censored	686	3651	674	2881	< 119	3540	776
Redox	12	0	normal	-64	0.62	-38	43	-209	46	-42
Rubidium	12	11	ins	ins	ins	< 555	567	< 555	573	< 555
Selenium	12	5	log-censored	1.3	19	1.4	10	< 1.0	11	1.7

Table A.10 continued.

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	90th percentile	Min	Max	State Median
Silicate	12	0	normal	8678	11642	8296	16192	4637	16766	9039
Silver	12	3	log-censored	0.017	0.27	0.018	0.19	< 0.0090	0.24	0.013
Sodium	12	0	log-normal	19893	38681	18686	144433	4187	177736	17890
Specific Conductance	12	0	log-normal	300	420	270	840	160	950	339
Strontium	12	0	log-normal	112	206	111	493	11	611	121
Sulfate	12	0	log-normal	11174	251134	9150	188817	1800	247290	2930
Sulfur	12	0	log-normal	4142	9014	3258	67289	898	88252	3390
Temperature	12	0	normal	7.3	7.8	7.2	8.4	6.0	8.6	7.8
Thallium	12	8	log-censored	0.0061	0.012	< 0.0050	0.010	< 0.0050	0.010	< 0.0050
Titanium	12	5	log-censored	0.0035	0.28	0.0039	0.17	< 0.0035	0.23	0.0050
Total dissolved solids	12	0	normal	245400	351507	172000	528200	108000	614000	238000
Total organic carbon	12	0	no distribution	-	-	1000	5700	900	5700	1300
Total phosphate-P	12	7	log-censored	7.5	728	< 20	256	< 20	280	< 20
Total suspended solids	12	0	no distribution	-	-	4500	218600	2000	230000	4000
Vanadium	12	4	log-censored	6.1	27	6.4	22	< 4.7	23	6.5
Zinc	12	1	log-censored	11	214	11	271	< 2.7	370	13

Table A.11 : Descriptive statistics for undifferentiated Proterozoic Metasedimentary units (PMUD).

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95th percentile	Min	Max	State Median
				ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
Alkalinity	19	0	normal	171421	209259	160000	ins	47000	330000	159500
Aluminum	20	1	log-censored	6.5	197	4.2	2217	< 0.060	2330	3.9
Antimony	20	6	log-censored	0.019	0.15	0.020	0.090	< 0.0080	0.090	0.010
Arsenic	20	4	log-censored	1.0	16	1.6	8.2	< 0.060	8.3	1.1
Barium	20	2	log-censored	30	348	37	207	< 1.4	209	42
Beryllium	20	10	log-censored	0.0059	0.17	< 0.010	0.35	< 0.010	0.37	< 0.010
Boron	20	2	log-censored	45	662	37	626	< 13	635	36
Bromide	20	20	ins	ins	ins	< 0.20	ins	< 0.20	0.10	< 0.20
Cadmium	20	12	log-censored	0.025	0.33	< 0.020	0.25	< 0.020	0.25	< 0.020
Calcium	20	0	normal	35392	46722	31662	82000	539	82499	31704
Chloride	20	0	no distribution	-	-	2275	4779162	470	5029000	1850
Chromium	20	8	log-censored	0.22	4.6	0.26	5.2	< 0.050	5.4	0.28
Cobalt	20	1	log-censored	0.27	4.6	0.21	5.0	< 0.0020	5.1	0.22
Copper	20	9	log-censored	9.2	62	7.2	39	< 5.5	39	6.8
Eh	20	0	normal	183	238	224	333	-57	333	216
Fluoride	14	0	normal	448	569	400	ins	200	890	350
Iron	20	0	log-normal	297	680	298	11407	12	11763	209

Table A.11 continued.

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95th percentile	Min	Max	State Median
Lead	20	0	log-normal	0.41	0.80	0.42	8.4	0.050	8.7	0.47
Lithium	20	8	log-censored	4.9	53	5.2	49	< 4.5	50	5.0
Magnesium	20	0	normal	12975	17904	12797	31520	201	31558	13317
Manganese	20	0	log-normal	45	123	70	2413	1.3	2508	65
Molybdenum	20	14	log-censored	3.7	11	< 4.2	9.9	< 4.2	10	< 4.2
Nickel	20	13	log-censored	6.0	19	< 6.0	16	< 6.0	16	< 6.0
Nitrate-N	20	18	log-censored	16	2534	< 500	1930	< 500	2000	< 500
pH	19	0	normal	7.7	8.0	7.6	ins	6.1	9.1	7.6
Phosphorus	20	4	log-censored	33	231	32	286	< 15	292	35
Potassium	20	0	normal	1747	2410	1489	5660	146	5761	1540
Redox	19	0	normal	-39	16	0	ins	-279	112	-1.0
Rubidium	20	20	ins	ins	ins	< 555	ins	< 555	555	< 555
Selenium	20	4	log-censored	2.0	36	2.0	89	< 1.0	93	2.1
Silicate	20	0	normal	8624	9898	8757	13650	2921	13669	8688
Silver	20	10	log-censored	0.011	0.14	0.0090	0.12	< 0.0090	0.12	< 0.0090
Sodium	20	0	log-normal	12850	20602	10163	107579	3305	108875	10241
Specific Conductance	19	0	normal	330	410	320	ins	56	690	330
Strontium	20	0	normal	217	320	124	850	1.0	872	125
Sulfate	20	2	log-censored	5034	73806	5805	50201	< 300	50220	1950
Sulfur	20	1	log-censored	1830	28677	2195	16777	< 22	16781	2374
Temperature	19	0	normal	7.6	7.9	7.6	ins	6.7	8.7	7.7
Thallium	20	15	log-censored	0.0041	0.042	< 0.0050	0.030	< 0.0050	0.030	< 0.0050
Titanium	20	14	log-censored	0.00074	0.039	< 0.0035	0.064	< 0.0035	0.067	< 0.0035
Total dissolved solids	20	0	normal	224211	266489	216000	432700	90000	438000	222000
Total organic carbon	20	2	log-censored	2004	7525	2000	5480	< 500	5500	1700
Total phosphate-P	20	11	log-censored	15	288	< 20	263	< 20	270	20
Total suspended solids	20	0	no distribution	-	-	4000	141200	1000	148000	4000
Vanadium	20	13	log-censored	3.8	21	< 4.7	20	< 4.7	20	< 4.7
Zinc	20	1	log-censored	13	134	12	271	< 2.7	278	11

Table A.12 : Descriptive statistics for buried Quaternary artesian aquifers (QBAA).

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95th percentile	Min	Max	State Median
				ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
Alkalinity	51	0	normal	200333	226364	198000	378200	49000	394000	328000
Aluminum	52	3	log-censored	4.0	220	2.8	450	< 0.060	870	0.88
Antimony	52	27	log-censored	0.012	0.093	< 0.0080	0.067	< 0.0080	0.091	0.011
Arsenic	52	3	log-censored	2.0	27	2.3	15	< 0.060	42	2.6
Barium	52	0	normal	62	73	57	131	2.7	189	61
Beryllium	52	29	log-censored	0.0068	0.070	< 0.010	0.047	< 0.010	0.14	< 0.010
Boron	52	6	log-censored	38	435	43	359	< 13	709	98
Bromide	52	52	ins	ins	ins	< 0.20	.	< 0.20	0.1	< 0.20
Cadmium	52	34	log-censored	0.016	0.22	< 0.020	0.14	< 0.020	0.24	< 0.020
Calcium	52	0	log-normal	38177	47152	34432	97273	222	108918	79537
Chloride	52	0	log-normal	2780	5045	1630	23509	300	89250	2320
Chromium	52	12	log-censored	0.24	6.4	0.28	3.7	< 0.050	7.1	0.49
Cobalt	52	0	log-normal	0.33	0.45	0.32	1.7	0.020	2.6	0.46
Copper	52	33	log-censored	2.0	99	< 5.5	55	< 5.5	530	< 5.5
Dissolved oxygen	52	46	log-censored	42	11563	< 300	5496	< 300	28300	< 300
Eh	52	0	log-normal	277	287	197	312	-28	318	158
Fluoride	32	0	normal	432	495	400	759	200	1110	380
Iron	52	1	log-censored	344	11731	502	4227	< 3.2	20207	1179
Lead	52	4	log-censored	0.24	5.3	0.21	4.9	< 0.030	25	0.18
Lithium	52	26	log-censored	4.8	33	4.5	27	< 4.5	51	14
Magnesium	52	0	log-normal	17426	22553	13773	43987	180	64521	30515
Manganese	52	1	log-censored	84	1385	89	750	< 0.90	1462	131
Molybdenum	52	36	log-censored	3.6	13	< 4.2	9.8	< 4.2	18	< 4.2
Nickel	52	40	log-censored	3.6	14	< 6.0	12	< 6.0	20	< 6.0
Nitrate-N	52	47	log-censored	173	792	< 500	700	< 500	1000	< 500
pH	51	0	normal	7.7	7.8	7.8	8.5	6.2	8.5	7.3
Phosphorus	52	7	log-censored	49	312	51	203	< 15	342	102
Potassium	52	0	log-normal	1982	2569	1889	5500	274	7542	3068
Redox	51	0	log-normal	52	64	-26	92	-248	96	-56
Rubidium	52	49	log-censored	361	670	< 555	622	< 555	746	< 555
Selenium	52	13	log-censored	1.8	11	1.9	9.3	< 1.0	11	2.4
Silicate	52	0	normal	8836	9545	8803	13424	4935	13612	11914
Silver	52	30	log-censored	0.0096	0.088	< 0.0090	0.080	< 0.0090	0.11	< 0.0090
Sodium	52	0	log-normal	10399	15940	9638	83962	2308	187823	18812
Specific Conductance	51	0	normal	340	390	300	700	2	770	619
Strontium	52	0	log-normal	144	205	135	728	1.5	1000	304
Sulfate	52	3	log-censored	6836	85013	7290	82166	< 300	376800	7300
Sulfur	52	0	log-normal	3032	4683	2849	31182	113	130743	8110
Temperature	51	0	normal	8.0	8.2	7.8	9.6	6.4	11	8.9
Thallium	52	38	log-censored	0.0052	0.031	< 0.0050	0.030	< 0.0050	0.032	< 0.0050
Titanium	52	38	log-censored	0.0018	0.017	< 0.0035	0.013	< 0.0035	0.028	< 0.0035
Total dissolved solids	52	0	normal	266980	309180	240000	497600	96000	1010000	430000
Total organic carbon	52	0	log-normal	1782	2314	2000	7645	700	12000	2600

Table A. 12 continued.

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95th percentile	Min	Max	State Median
Total phosphate-P	52	12	log-censored	39	342	35	221	< 20	320	60
Total suspended solids	52	0	log-normal	4557	7186	4000	34900	1000	112000	5000
Vanadium	52	29	log-censored	5.2	13	< 4.7	11	< 4.7	13	< 4.7
Zinc	52	5	log-censored	10	160	8.3	329	< 2.7	1102	13

Table A.13 : Descriptive statistics for unconfined buried Quaternary aquifers (QBUA).

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	90th percentile	Min	Max	State Median
				ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
Alkalinity	12	0	normal	199919	266274	189000	402100	30000	427000	281000
Aluminum	12	1	log-censored	1.7	38	1.3	28	< 0.060	30	0.91
Antimony	12	9	log-censored	0.013	0.057	< 0.0080	0.040	< 0.0080	0.040	0.016
Arsenic	12	1	log-censored	1.5	22	2.2	8.6	< 0.060	9.1	1.9
Barium	12	0	normal	74	108	54	177	1.6	191	71
Beryllium	12	7	log-censored	0.0059	1.0	< 0.010	0.32	< 0.010	0.41	< 0.010
Boron	12	4	log-censored	19	54	18	41	< 13	41	23
Bromide	12	12	ins	ins	ins	< 0.20	ins	< 0.20	0.10	< 0.20
Cadmium	12	7	log-censored	0.021	0.24	< 0.020	0.15	< 0.020	0.18	< 0.020
Calcium	12	0	normal	46120	65663	46994	100875	155	115508	78821
Chloride	12	0	log-normal	1001	2066	660	14423	390	18950	3625
Chromium	12	0	log-normal	0.45	1.0	0.49	4.3	0.090	4.7	0.69
Cobalt	12	0	normal	0.28	0.39	0.32	0.56	0.050	0.63	0.46
Copper	12	7	log-censored	6.3	29	< 5.5	20	< 5.5	22	< 5.5
Dissolved oxygen	12	10	log-censored	42	26955	< 300	6956	< 300	9230	< 500
Eh	12	0	normal	186	238	214	290	71	295	220
Fluoride	4	0	normal	320	424	290	ins	200	570	305
Iron	12	0	log-normal	448	1905	464	7390	7	7816	367
Lead	12	2	log-censored	0.17	1.4	0.14	1.5	< 0.030	2.0	0.19
Lithium	12	8	log-censored	5.6	15	< 4.5	12	< 4.5	13	7.1
Magnesium	12	0	normal	11858	17392	10502	28034	112	32641	26539
Manganese	12	0	normal	282	512	157	1038	0.90	1248	152
Molybdenum	12	8	log-censored	2.1	13	< 4.2	9.4	< 4.2	12	< 4.2
Nickel	12	9	log-censored	6.0	20	< 6.0	15	< 6.0	16	< 6.0
Nitrate-N	12	11	ins	ins	ins	< 500	1127	< 500	1400	< 500
pH	12	0	normal	7.4	7.8	7.4	70	6.0	8.4	7.2
Phosphorus	12	2	log-censored	61	414	86	8.3	< 15	202	57
Potassium	12	0	normal	1410	1785	1430	193	475	2884	1796
Redox	12	0	normal	-34	18	-5.5	2555	-149	74	5
Rubidium	12	11	ins	ins	ins	< 555	701	< 555	764	< 555
Selenium	12	2	log-censored	2.3	5.8	2.4	4.4	< 1.0	4.7	3.2
Silicate	12	0	normal	10198	12794	10130	18051	3331	20396	10867

Table A.13 continued.

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	90th percentile	Min	Max	State Median
Silver	12	8	log-censored	0.011	0.065	< 0.0090	0.044	< 0.0090	0.050	< 0.0090
Sodium	12	0	no distribution	-	-	4525	120410	1688	168649	5906
Specific Conductance	12	0	normal	350	500	360	750	38	780	533
Strontium	12	0	normal	81	110	85	139	0.90	139	112
Sulfate	12	4	log-censored	1899	39772	2655	13185	< 300	14220	5280
Sulfur	12	0	normal	1732	2862	1501	4951	401	5364	5406
Temperature	12	0	no distribution	-	-	8.2	11	7.4	12	8.8
Thallium	12	11	ins	ins	ins	< 0.0050	0.0080	< 0.0050	0.010	< 0.0050
Titanium	12	9	log-censored	0.0044	0.011	< 0.0035	0.0090	< 0.0035	0.0096	< 0.0035
Total dissolved solids	12	0	normal	245000	326715	223000	471200	28000	482000	350000
Total organic carbon	12	1	log-censored	2684	23591	2500	18850	< 500	21700	1900
Total phosphate-P	12	4	log-censored	57	390	60	201	< 20	210	40
Total suspended solids	12	0	log-normal	3631	6817	3000	16000	1000	16000	2000
Vanadium	12	8	log-censored	5.1	16	< 4.7	12	< 4.7	13	< 4.7
Zinc	12	2	log-censored	9.0	133	8.0	106	< 2.7	138	12

Table A.14 : Descriptive statistics for Quaternary water table aquifers (QWTA).

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95th percentile	Min	Max	State Median
				ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
Alkalinity	21	0	normal	143238	172460	128000	287300	31000	290000	237500
Aluminum	21	1	log-censored	8.4	745	5.3	750	< 0.060	756	1.2
Antimony	21	10	log-censored	0.011	0.065	0.010	0.075	< 0.0080	0.080	0.017
Arsenic	21	3	log-censored	1.0	20	1.8	17	< 0.060	19	1.3
Barium	21	0	normal	55	73	38	143	2.9	145	85
Beryllium	21	6	log-censored	0.015	0.19	0.010	0.12	< 0.010	0.12	< 0.010
Boron	21	4	log-censored	21	96	18	80	< 13	82	24
Bromide	21	21	ins	ins	ins	< 0.20	ins	< 0.20	0.10	< 0.20
Cadmium	21	12	log-censored	0.040	0.21	< 0.020	0.18	< 0.020	0.19	< 0.020
Calcium	21	0	normal	35569	43709	32346	65444	99	65513	74237
Chloride	21	0	log-normal	1537	2744	1160	19679	330	20050	5810
Chromium	21	3	log-censored	0.28	6.3	0.25	4.8	< 0.050	5.0	0.55
Cobalt	21	0	log-normal	0.34	0.55	0.34	2.4	0.020	2.5	0.48
Copper	21	8	log-censored	6.2	71	6.6	128	< 5.5	140	6.3
Dissolved oxygen	21	18	log-censored	24	11886	< 300	6525	< 300	6590	< 500
Eh	21	0	normal	178	221	186	298	-34	298	187
Fluoride	7	0	normal	338	416	310	ins	200	620	300
Iron	21	0	log-normal	728	1779	726	13515	41	13774	811
Lead	21	3	log-censored	0.21	18	0.17	10	< 0.030	11	0.18
Lithium	21	7	log-censored	5.6	18	5.3	16	< 4.5	17	5.7
Magnesium	21	0	normal	12160	15969	10147	36349	121	37601	22224
Manganese	21	1	log-censored	89	3101	90	994	< 0.90	1011	176
Molybdenum	21	17	log-censored	1.9	14	< 4.2	12	< 4.2	12	< 4.2
Nickel	21	13	log-censored	6.8	18	< 6.0	18	< 6.0	18	< 6.0
Nitrate-N	21	19	log-censored	1.5	5497	< 500	3750	< 500	4100	< 500
pH	21	0	normal	7.5	7.8	7.6	8.4	6.1	8.4	7.2
Phosphorus	21	1	log-censored	49	403	38	427	< 15	441	56
Potassium	21	1	log-censored	1333	6040	1301	5179	< 119	5288	1766
Redox	21	0	normal	-43	-0.49	-35	77	-251	77	-24
Rubidium	21	19	log-censored	227	857	< 555	795	< 555	817	< 555
Selenium	21	11	log-censored	1.1	10	< 1.0	8.6	< 1.0	9.0	2.1
Silicate	21	0	log-normal	10069	11572	9449	22295	6611	23012	10819
Silver	21	13	log-censored	0.016	0.040	< 0.0090	0.039	< 0.0090	0.040	< 0.0090
Sodium	21	0	log-normal	5358	7681	4275	75862	2324	83019	4986
Specific Conductance	21	0	normal	250	310	240	530	2.0	540	465
Strontium	21	0	log-normal	68	112	78	414	1.3	436	105
Sulfate	21	5	log-censored	7066	38424	10440	20256	< 300	20520	4250
Sulfur	21	0	normal	3303	4446	3845	7357	100	7427	4603
Temperature	21	0	normal	8.1	8.6	8.1	11	5.8	11	8.8
Thallium	21	15	log-censored	0.0073	0.011	< 0.0050	0.010	< 0.0050	0.010	< 0.0050
Titanium	21	11	log-censored	0.0031	0.051	< 0.0035	0.045	< 0.0035	0.047	< 0.0035
Total dissolved solids	21	0	normal	196476	233155	168000	354800	68000	356000	340000
Total organic carbon	21	0	log-normal	2211	3356	2000	14550	600	15100	2400

Table A.14 continued.

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95th percentile	Min	Max	State Median
Total phosphate-P	21	9	log-censored	21	909	20	942	< 20	1020	40
Total suspended solids	21	0	log-normal	4982	8221	4000	29600	1000	30000	4000
Vanadium	21	9	log-censored	6.0	15	5.8	12	< 4.7	12	5.4
Zinc	21	3	log-censored	7.7	50	8.0	71	< 2.7	76	12

Table A.15 : Coefficients for log-censored data from analysis of descriptive statistics, for each aquifer and chemical. See MPCA, 1998a, for application of these coefficients.

Chemical Parameter	PCCR		PMNS		PMUD		QBAA		QBUA		QWTA	
	a	b	a	b	a	b	a	b	a	b	a	b
Aluminum	-	-	-	-	1.865	1.743	1.376	2.049	0.512	1.596	2.125	2.29
Antimony	-4.082	1.038	-3.46	1.119	-3.977	1.068	-4.434	1.048	-4.327	0.743	-4.535	0.916
Arsenic	-0.35	1.877	-0.289	1.454	0.046	1.403	0.687	1.328	0.426	1.369	-0.004	1.521
Barium	-	-	1.644	1.27	3.403	1.25	-	-	-	-	-	-
Beryllium	-3.988	1.549	-4.039	2.435	-5.129	1.713	-4.991	1.187	-5.133	2.631	-4.214	1.314
Boron	3.891	1.281	5.206	1.573	3.801	1.375	3.64	1.243	2.924	0.54	3.037	0.779
Cadmium	-3.667	1.764	-3.201	0.782	-3.693	1.321	-4.122	1.334	-3.868	1.246	-3.213	0.834
Chromium	-0.795	1.122	-0.557	1.512	-1.504	1.544	-1.408	1.666	-	-	-1.281	1.591
Cobalt	-	-	-	-	-1.317	1.454	-	-	-	-	-	-
Copper	1.99	1.105	2.253	1.409	2.22	0.97	0.71	1.98	1.836	0.776	1.827	1.245
Dissolved oxygen	6.612	2.118	6.174	2.302	6.09	1.062	3.748	2.861	3.73	3.302	3.164	3.173
Iron	-	-	-	-	-	-	5.842	1.8	-	-	-	-
Lead	-	-	-	-	-	-	-1.427	1.579	-1.793	1.079	-1.56	2.262
Lithium	1.787	1.281	1.812	1.068	1.59	1.216	1.577	0.987	1.718	0.509	1.715	0.611
Manganese	-	-	-	-	-	-	4.431	1.43	-	-	4.494	1.809
Molybdenum	0.298	1.715	1.724	0.639	1.312	0.554	1.274	0.666	0.762	0.927	0.659	1.023
Nickel	1.479	0.864	1.176	1.232	1.796	0.594	1.28	0.709	1.797	0.601	1.91	0.492
Nitrate-N	-	-	-	-	2.763	2.589	5.153	0.776	-	-	0.431	4.174
Phosphorus	3.22	1.147	2.941	1.56	3.489	0.997	3.901	0.94	4.118	0.974	3.889	1.077
Potassium	-	-	6.531	0.853	-	-	-	-	-	-	7.195	0.771
Rubidium	-	-	-	-	-	-	5.89	0.315	-	-	5.425	0.678
Selenium	-0.355	2.419	0.242	1.379	0.69	1.481	0.604	0.895	0.818	0.481	0.075	1.138
Silver	-4.985	1.119	-4.087	1.426	-4.531	1.326	-4.65	1.132	-4.493	0.894	-4.141	0.476
Sulfate	-	-	-	-	8.524	1.37	8.83	1.286	7.549	1.552	8.863	0.864
Sulfur	-	-	-	-	7.512	1.404	-	-	-	-	-	-
Thallium	-4.915	0.206	-5.106	0.366	-5.498	1.187	-5.255	0.915	-	-	-4.916	0.205

Table A.15 continued.

Chemical Parameter	PCCR		PMNS		PMUD		QBAA		QBUA		QWTA	
	a	b	a	b	a	b	a	b	a	b	a	b
Titanium	-6.312	1.77	-5.66	2.241	-7.204	2.021	-6.334	1.152	-5.426	0.462	-5.781	1.428
Total organic carbon	7.922	0.989	-	-	7.603	0.675	-	-	7.895	1.109	-	-
Total phosphate-P	2.486	1.206	2.016	2.334	2.723	1.5	3.67	1.104	4.048	0.979	3.033	1.928
Vanadium	1.589	0.932	1.814	0.752	1.342	0.871	1.645	0.478	1.631	0.593	1.793	0.463
Zinc	-	-	2.369	1.529	2.573	1.186	2.346	1.39	2.193	1.375	2.041	0.954

Table A.16 : Coefficients for log-normal data from analysis of descriptive statistics, for eachaquifer and chemical. See MPCA, 1998a, for application of these coefficients.

Chemical Parameter	PCCR		PMNS		PMUD		QBAA		QBUA		QWTA	
	std. dev.	n	std. dev.	n	std. dev.	n	std. dev.	n	std. dev.	n	std. dev.	n
Alkalinity	0.2940	16	-	-	-	-	-	-	-	-	-	-
Aluminum	0.7351	16	1.079	12	-	-	-	-	-	-	-	-
Barium	0.3698	16	-	-	-	-	-	-	-	-	-	-
Calcium	0.3776	16	-	-	-	-	0.3791	52	-	-	-	-
Chloride	0.5901	16	0.7824	12	-	-	0.6234	52	0.4951	12	0.5532	21
Chromium	-	-	-	-	-	-	-	-	0.5472	12	-	-
Cobalt	-	-	-	-	-	-	0.3796	52	-	-	0.4789	21
Eh	-	-	-	-	-	-	0.4660	52	-	-	-	-
Fluoride	0.3869	13	-	-	-	-	-	-	-	-	-	-
Iron	1.079	16	0.9710	12	0.7679	20	-	-	0.9888	12	0.8524	21
Lead	0.3869	16	0.7153	12	0.6073	20	-	-	-	-	-	-
Magnesium	0.3916	16	-	-	-	-	0.3684	52	-	-	-	-
Manganese	0.8942	16	0.5963	12	0.9338	20	-	-	-	-	-	-
Potassium	-	-	-	-	-	-	0.2839	52	-	-	-	-
Redox	-	-	-	-	-	-	0.4280	51	-	-	-	-
Silicate	-	-	-	-	-	-	-	-	-	-	0.1327	21
Sodium	0.5022	16	0.4546	12	0.4380	20	0.4684	52	-	-	0.3434	21
Specific Conductance	0.5062	16	0.2293	12	-	-	-	-	-	-	-	-
Strontium	0.3719	16	0.4200	12	-	-	0.4252	52	-	-	0.4784	21
Sulfate	-	-	0.5536	12	-	-	-	-	-	-	-	-
Sulfur	-	-	0.5315	12	-	-	0.5443	52	-	-	-	-
Total dissolved solids	0.3797	16	-	-	-	-	-	-	-	-	-	-

Table A.16 continued.

Chemical Parameter	PCCR		PMNS		PMUD		QBAA		QBUA		QWTA	
	std. dev.	n	std. dev.	n	std. dev.	n	std. dev.	n	std. dev.	n	std. dev.	n
Total organic carbon	-	-	-	-	-	-	0.3142	52	-	-	0.3981	21
Total suspended solids	0.6134	16	-	-	-	-	0.4468	52	0.4307	12	0.4779	21

Table A.17 : Median concentrations, in ug/L, of sampled chemicals for each of the major aquifers. The p-value indicates the probability that aquifers have equal concentrations.

Chemical	p-value	PCCR	PMNS	PMUD	QBAA	QBUA	QWTA
	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
Alkalinity	0.051	135500	119500	160000	198000	189000	128000
Aluminum	0.002	13	49	4.2	2.8	1.3	5.3
Antimony	0.011	0.018	0.040	0.020	< 0.0080	< 0.0080	0.010
Arsenic	0.028	0.64	0.97	1.6	2.3	2.2	1.8
Barium	< 0.001	38	5.6	37	57	54	38
Beryllium	0.062	0.020	0.025	0.0075	< 0.010	< 0.010	0.010
Boron	< 0.001	49	219	37	43	18	18
Bromide	0.073	< 0.20	< 0.20	< 0.20	< 0.20	< 0.20	< 0.20
Cadmium	0.794	0.020	0.020	< 0.020	< 0.020	< 0.020	< 0.020
Calcium	0.167	31747	23723	31662	34432	46994	32346
Chloride	0.169	3220	2445	2275	1630	660	1160
Chromium	0.587	0.49	0.63	0.26	0.28	0.49	0.25
Cobalt	0.639	0.37	0.27	0.21	0.32	0.32	0.34
Copper	0.137	7.5	8.0	7.2	< 5.5	< 5.5	6.6
Dissolved oxygen	0.005	810	< 300	< 300	< 300	< 300	< 300
Eh	0.438	266	184	224	197	214	186
Fluoride	0.021	490	715	400	400	290	310
Iron	0.697	145	204	298	502	464	726
Lead	0.025	0.50	0.39	0.42	0.21	0.14	0.17
Lithium	0.646	5.9	5.8	5.2	4.5	< 4.5	5.3
Magnesium	0.154	11780	9555	12797	13773	10502	10147
Manganese	0.228	103	35	70	89	157	90
Molybdenum	0.747	< 4.2	< 4.2	< 4.2	< 4.2	< 4.2	< 4.2
Nickel	0.633	< 6.0	< 6.0	< 6.0	< 6.0	< 6.0	< 6.0
Nitrate-N	0.961	< 500	< 500	< 500	< 500	< 500	< 500
pH	0.440	7.1	8.0	7.6	7.8	7.4	7.6
Phosphorus	0.117	24	21	32	51	86	38
Potassium	0.058	2007	674	1489	1889	1430	1301
Redox	0.005	45	-38	0	-26	-5.5	-35
Rubidium	0.853	< 555	< 555	< 555	< 555	< 555	< 555
Selenium	0.213	1.1	1.4	2.0	1.9	2.4	< 1.0

Table A.17 continued.

Chemical	p-value	PCCR	PMNS	PMUD	QBAA	QBUA	QWTA
Silicate	0.298	8733	8296	8757	8803	10130	9449
Silver	0.369	< 0.0090	0.018	0.0090	< 0.0090	< 0.0090	< 0.0090
Sodium	0.001	8453	18686	10163	9638	4525	4275
Specific Conductance	0.524	0.24	0.27	0.32	0.30	0.36	0.24
Strontium	0.002	192	111	124	135	85	78
Sulfate	0.076	9765	9150	5805	7290	2655	10440
Sulfur	0.108	3583	3258	2195	2849	1501	3845
Temperature	0.009	7.7	7.2	7.6	7.8	8.2	8.1
Thallium	0.801	< 0.0050	< 0.0050	< 0.0050	< 0.0050	< 0.0050	< 0.0050
Titanium	0.161	< 0.0035	0.0039	< 0.0035	< 0.0035	< 0.0035	< 0.0035
Total dissolved solids	0.405	194000	172000	216000	240000	223000	168000
Total organic carbon	0.199	3450	1000	2000	2000	2500	2000
Total phosphate-P	0.011	< 20	< 20	< 20	35	60	20
Total suspended solids	0.848	4000	4500	4000	4000	3000	4000
Vanadium	0.531	5.5	6.4	< 4.7	< 4.7	< 4.7	5.8
Zinc	0.791	8.9	11	12	8.3	8.0	8.0

Table A.18 : Median concentrations of chemicals in buried Quaternary and Precambrian bedrock aquifers. An asterisk indicates chemicals for which concentrations differed between the two aquifer groups. Concentrations are in ug/L except for pH, temperature (^{o}F), specific conductance (umhos/cm), and Eh (mV).

Chemical	Precambrian	Buried Quaternary
Alkalinity	141000 *	198000
Aluminum	7.0 *	2.6
Antimony	0.03 *	< 0.0080
Arsenic	0.99 *	2.3
Barium	23 *	56
Beryllium	0.010 *	< 0.010
Boron	52 *	26
Cadmium	< 0.020	< 0.020
Calcium	30801 *	37074
Cesium	0.040 *	< 0.010
Chloride	2190	975
Chromium	0.43	0.28
Cobalt	0.26	0.32
Copper	7.5 *	5.4
Dissolved oxygen	< 300 *	< 300

Table A.18 continued.

Chemical	Precambrian	Buried Quaternary
Eh	223	201
Fluoride	425	370
Iron	206	484
Lead	0.47 *	0.20
Lithium	5.7	4.4
Magnesium	11466 *	13520
Manganese	55	89
Molybdenum	< 4.2	< 4.2
Nickel	< 6.0	< 6.0
Nitrate-N	< 500	< 500
pH	7.80	7.70
Phosphorus	24 *	53
Potassium	1390 *	1743
Rubidium	< 555.5	< 555.5
Selenium	1.9	2.1
Silicate	8460	9237
Silver	0.01	< 0.0090
Sodium	10085	7341
Specific Conductance	272	303
Strontium	136	123
Sulfate-S	2610	2125
Sulfur	2773	2526
Temperature	7.55 *	7.9
Thallium	< 0.0050	< 0.0050
Tin	< 0.080	< 0.080
Titanium	< 0.0035	< 0.0035
Total dissolved solids	200000	235000
Total organic carbon	1700	2050
Total phosphate-P	10 *	40
Total suspended solids	4000	4000
Vanadium	5.1	4.6
Zinc	13	8.3
Zirconium	0.090	0.050

Table A.19 : Summary of water quality criteria, basis of criteria, and endpoints, by chemical parameter.

Chemical	Criteria (ug/L)	Basis of criteria	Endpoint
Alkalinity	-	-	-
Aluminum (Al)	50	MCL	-
Antimony (Sb)	6	HRL	-
Arsenic (As)	50	MCL	Cancer
Barium (Ba)	2000	HRL	Cardiovascular/blood
Beryllium (Be)	0.08	HRL	Cancer
Boron (B)	600	HRL	Reproductive
Bromide (Br)	-	-	-
Cadmium (Cd)	4	HRL	Kidney
Calcium (Ca)	-	-	-
Chloride (Cl)	250000	SMCL	-
Chromium (Cr)	20000[1]	HRL	-
Cobalt (Co)	30	HBV	-
Copper (Cu)	1000	HBV	-
Dissolved Oxygen	-	-	-
Fluoride (F)	4000	MCL	-
Iron (Fe)	300	SMCL	-
Lead (Pb)	15	Action level at tap	-
Lithium (Li)	-	-	-
Magnesium (Mg)	-	-	-
Manganese (Mn)	100 (1000)[2]	HRL	Central nervous system
Mercury (Hg)	2	MCL	-
Molybdenum (Mo)	30	HBV	Kidney
Nickel (Ni)	100	HRL	-
Nitrate-N (NO_3-N)	10000	HRL	Cardiovascular/blood
Ortho-phosphate	-	-	-
pH	-	-	-
$Phosphorus_{total}$	-	-	-
Potassium (K)	-	-	-
Redox/Eh	-	-	-
Rubidium (Rb)	-	-	-
Selenium (Se)	30	HRL	-
Silicate (Si)	-	-	-
Silver (Ag)	30	HRL	-
Sodium (Na)	250000	SMCL	-
Specific Conductivity	-	-	-
Strontium (Sr)	4000	HRL	Bone
Sulfate (SO_4)	500000	MCL	-
Sulfur (S)	-	-	-
Temperature	-	-	-
Thallium (Tl)	0.6	HRL	Gastrointestinal/liver
Titanium (Ti)	-	-	-
Total dissolved solids	-	-	-
Total organic carbon	-	-	-
Total phosphate	-	-	-

Table A.19 continued.

Chemical	Criteria (ug/L)	Basis of criteria	Endpoint
Total suspended solids	-	-	-
Vanadium (V)	50	HRL	-
Zinc (Zn)	2000	HRL	-
1,1,1-trichloroethane	600	HRL	Gastrointestinal/liver
1,1-dichloroethane	70	HRL	kidney
1,1-dichloroethene	6	HRL	Gastrointestinal/liver
1,2-dichloroethane	4	HRL	cancer
1,2-dichloropropane	5	HRL	cancer
acetone	700	HRL	cardiovascular/blood; liver
benzene	10	HRL	cancer
bromodichloromethane	6	HRL	cancer
chlorodibromomethane	-	-	-
chloroform	60	HRL	cancer
dichlorodifluoromethane	1000	HRL	body weight
dichlorofluoromethane	-	-	-
ethyl ether	1000	HRL	body weight
isopropylbenzene	-	-	-
xylene	10000	HRL	nervous system
methyl ethyl ketone	4000	HRL	reproductive
methylene chloride	50	HRL	cancer
naphthalene	300	HRL	cardiovascular/blood
tetrachloroethene	7	HRL	cancer
tetrahydrofuran	100	HRL	Gastrointestinal/liver
toluene	1000	HRL	kidney; gastrointestinal/liver
trichloroethene	30	HRL	cancer
1,2,4-trimethylbenzene	-	-	-
1,3,5-trimethylbenzene	-	-	-
cis-1,2 dichloroethene	70	HRL	cardiovascular/blood
ethyl benzene	700	HRL	kidney; gastrointestinal/liver
n-butylbenzene	-	-	-
n-propyl benzene	-	-	-
p-isopropyltoluene	-	-	-
styrene	-	-	-
trichlorofluoromethane	-	-	-

[1] Trivalent chromium

[2] The current HRL for manganese is 100, but calculations were made using a value of 1000 ug/L (MDH, 1997)

Table A.20 : Number of samples exceeding health-based water quality criteria, by aquifer.

Chemical	Number exceedances of criteria							
	PCCR	PMDC	PMFL	PMNS	PMUD	QBAA	QBUA	QWTA
Arsenic (As)	1	-	-	-	-	-	-	-
Beryllium (Be)	3	1		2	1	1	2	2
Boron (B)	-	-	-	2	1	1	-	-
Manganese (Mn)	1	-	-	-	1	2	1	1
Selenium (Se)	1	-	-	-	1	-	-	-

Table A.21 : Percentage of samples exceeding health-based water quality criteria, by aquifer.

Chemical	% exceedances of criteria						
	PCCR	PMDC	PMNS	PMUD	QBAA	QBUA	QWTA
Arsenic (As)	6	-	-	-	-	-	-
Beryllium (Be)	19	100	17	5	2	2	10
Boron (B)	6	-	17	5	2	-	-
Manganese (Mn)	6	-	-	5	4	8	5
Selenium (Se)	6	-	-	5	-	-	-

Table A.22 : Number of samples exceeding non-health-based water quality criteria, by aquifer.

Chemical	No. exceedances of criteria							
	PCCR	PMDC	PMFL	PMNS	PMUD	QBAA	QBUA	QWTA
Aluminum (Al)	5	1	1	6	2	8	-	5
Chloride (Cl)	-	-	-	-	1	-	-	-
Fluoride (F)	1	-	-	-	-	-	-	-
Iron (Fe)	6	1	1	5	10	27	7	13
Lead (Pb)	-	1	1	1	-	1	-	-
Sulfate (SO4)	1	-	-	-	-	-	-	-

Table A.23 : Percentage of samples exceeding non-health-based water quality criteria, by aquifer.

	% exceedances of criteria							
Chemical	**PCCR**	**PMDC**	**PMFL**	**PMNS**	**PMUD**	**QBAA**	**QBUA**	**QWTA**
Aluminum (Al)	31	100	100	50	10	15	-	24
Chloride (Cl)	-	-	-	-	5	-	-	-
Fluoride (F)	10	-	-	-	-	-	-	-
Iron (Fe)	38	100	100	42	50	52	58	62
Lead (Pb)	-	100	100	8	-	2	-	-
Sulfate (SO4)	6	-	-	-	-	-	-	-

Table A.24 : Comparison of water quality data for Quaternary glacial drift aquifers from different literature sources for Northeast Minnesota. Concentrations represent median values, in ug/L (ppb)1.

Chemical	**USGS Atlas HA-582**	**USGS Atlas HA-549**	**USGS Atlas HA-586**	**USGS Atlas HA-556**	**USGS Atlas HA-551**	**GWMAP**
No. Samples	2	23	18	16	19	85
Bicarbonate	141500	390000	159000	110000	277000	189000
Boron	30	20	60	40	60	18.25
Calcium	29000	83000	38000	24000	58000	34432
Chloride	900	4.9	2450	4800	3100	1160
Fluoride	1000	300	200	200	300	310
Iron	270	550	190	460	280	501.65
Magnesium	12500	25000	13000	7100	17000	10502
Manganese	15	140	80	170	240	90
Nitrate	150	-	1200	-	-	490
pH	8	7.3	7.65	6.7	7.3	7.6
Potassium	1100	3600	2000	3500	3400	1430
Silica	-	21000	-	18000	20000	9449
Sodium	4950	15000	6350	4600	23000	4525
Sulfate	9650	14000	15500	10000	14000	7290
Temperature	-	10	-	10.5	12	8.1
Total dissolved solids	142000	387000	179000	141000	354000	223000
Total phosphorus	10	-	40	-	-	51

1 Temperature in degrees Celcius, and pH in pH units

Table A.25 : Comparison of water quality data for Precambrian bedrock aquifers from different literature sources for Northeastern Minnesota. Concentrations represent median values, in ug/L (ppb)1.

Chemical	EPA Report 86-4033	USGS Atlas HA-549	USGS Atlas HA-586	USGS Atlas HA-556	USGS Atlas HA-551	GWMAP
No. of Samples	29	3	14	9	5	16
Bicarbonate	185000	433000	153500	150000	532000	135500
Boron		100	195	40	250	49
Calcium	41000	78000	30500	51000	110000	31747
Chloride	2500	2000	5500	8100	48000	3220
Fluoride		300	300	400	300	490
Iron		200	175	60	240	145
Manganese		80	45	80	380	103
Nitrate			1350			<500
Magnesium	10000	30000	9750	10000	39000	11780
pH		7.6	7.4	7.2	7.3	7.1
Potassium	1800	4700	1950	2800	5400	2007
Silica		22000		15000	19000	8733
Sodium	16000	16000	12500	9800	64000	8453
Sulfate	11000	7800	8150	13000	97000	9765
Temperature		9		10	14	7.7
Total dissolved solids	237000	379000	191500	235000	580000	194000
Total phosphorus			10			24

1 Temperature in degrees Celsius, and pH in pH units

Table A.26 : Comparison of water quality data for North Shore Volcanic aquifers from different literature sources for Northeast Minnesota. Concentrations represent median values, in ug/L (ppb)[1].

Chemical	USGS Report 94-4199	EPA Report 86-4033	USGS Report HA-582	GWMAP
No. samples	4	21	-	12
Bicarbonate	48000	150	48000	119500
Boron	-	-	730	219
Calcium	23500	45000	70000	23723
Chloride	86800	47000	370000	2445
Conductivity	770.5	-	-	270
Fluoride	550	-	1200	715
Iron	33.5	-	90	204
Magnesium	1950	9800	400	9555
Manganese	17.5	-	30	35
Nitrate	-	-	600	<500
pH	8.2	-	8.2	8.0

Table A.26 continued.

Chemical	USGS Report 94-4199	EPA Report 86-4033	USGS Report HA-582	GWMAP
Potassium	450	1300	950	674
Sodium	65500	56000	200000	18686
Sulfate	12200	14000	29000	9150
Temperature	8	-	-	7.2
Total dissolved solids	250500	351000	353000	172000

1 Specific Conductance in mmhos/cm, Temperature in degrees C, and pH in pH units.

Table A.27 : Summary of VOC detections for Region 1.

Unique No.	Chemical	Concentration	Chemical class
1	toluene	0.3	BTEX[1]
2	toluene	0.2	BTEX
3	chloroform	0.1	Trihalomethane
4	toluene	0.2	BTEX
5	dichlorodifluoromethane	1.3	Chlorofluorocarbon
6	chloroform	0.7	Trihalomethane
7	dichlorodifluoromethane	4.2	Chlorofluorocarbon
8	dichlorodifluoromethane	13	Chlorofluorocarbon
9	chloroform	0.8	Trihalomethane
10	dichlorodifluoromethane	0.6	Chlorofluorocarbon
11	dichlorodifluoromethane	18	Chlorofluorocarbon
12	toluene	0.3	BTEX
13	chloroform	0.4	Trihalomethane
14	toluene	0.3	BTEX
15	chloroform	0.1	Trihalomethane
15	dichlorodifluoromethane	0.9	Chlorofluorocarbon
16	chloroform	3.5	Trihalomethane
17	toluene	0.2	BTEX
18	tetrachloroethene	0.3	Halogenated aliphatic
19	chloroform	0.4	Trihalomethane
20	toluene	0.3	BTEX
20	chloroform	0.2	Trihalomethane
21	toluene	0.2	BTEX
22	benzene	0.2	BTEX
23	tetrahydrofuran	10	Ether
24	chloroform	0.7	Trihalomethane
25	chloroform	0.3	Trihalomethane
26	chloroform	0.7	Trihalomethane

[1] BTEX refers to a class of VOCs which are aromatic, nonhalogenated, and frequently associated with gasoline and fuel oils. Benzene (B), toluene (T), ethylbenzene (E), and xylene (X) are the most common of the BTEX compounds.

Appendix B - Figures

Figure 1 : Location of Region 1.

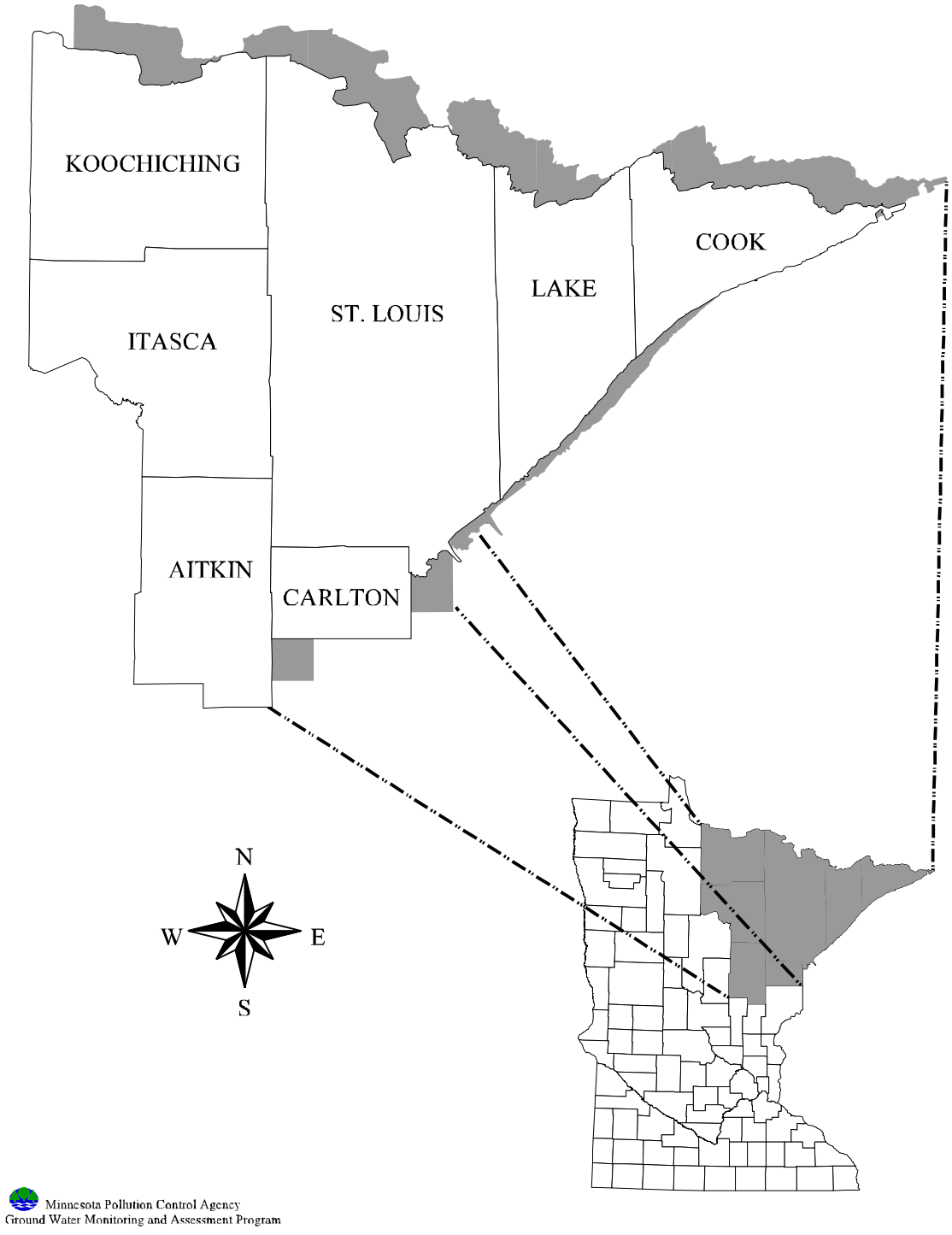


Figure 2 : Sample locations for the crystalline Precambrian aquifers.

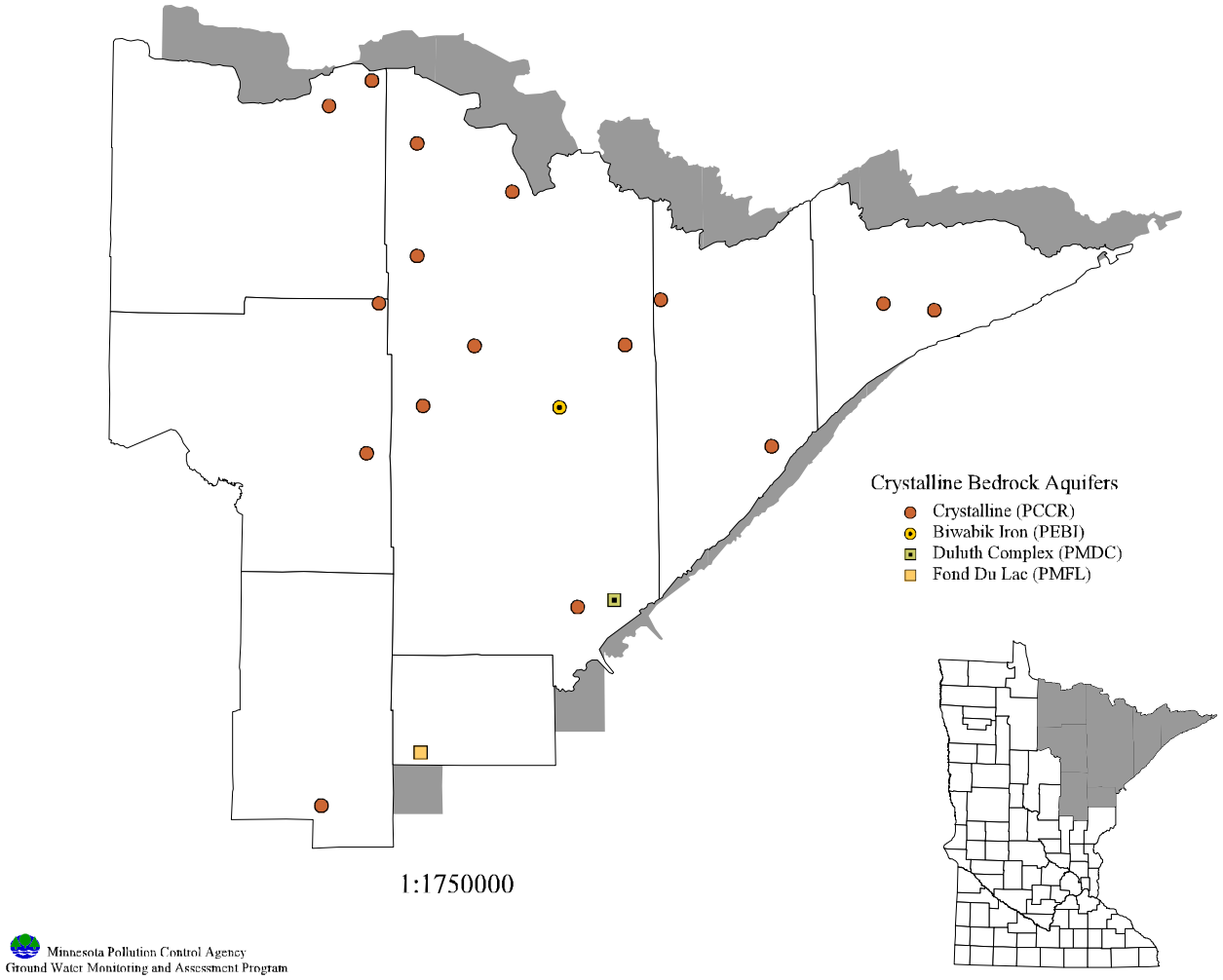


Figure 3 : Sample locations for the North Shore Volcanic aquifers.

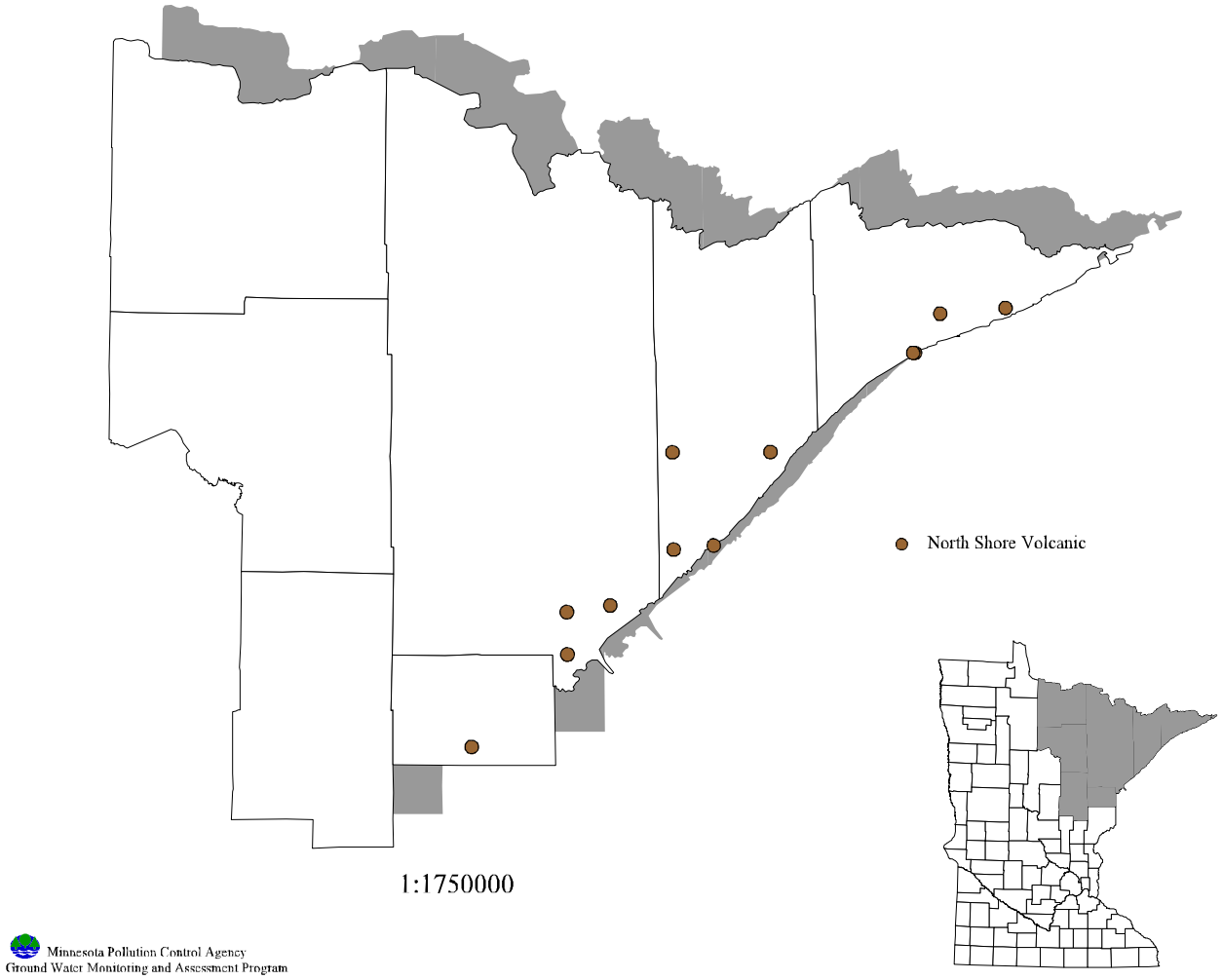


Figure 4 : Sample location for the undifferentiated Precambrian aquifers.

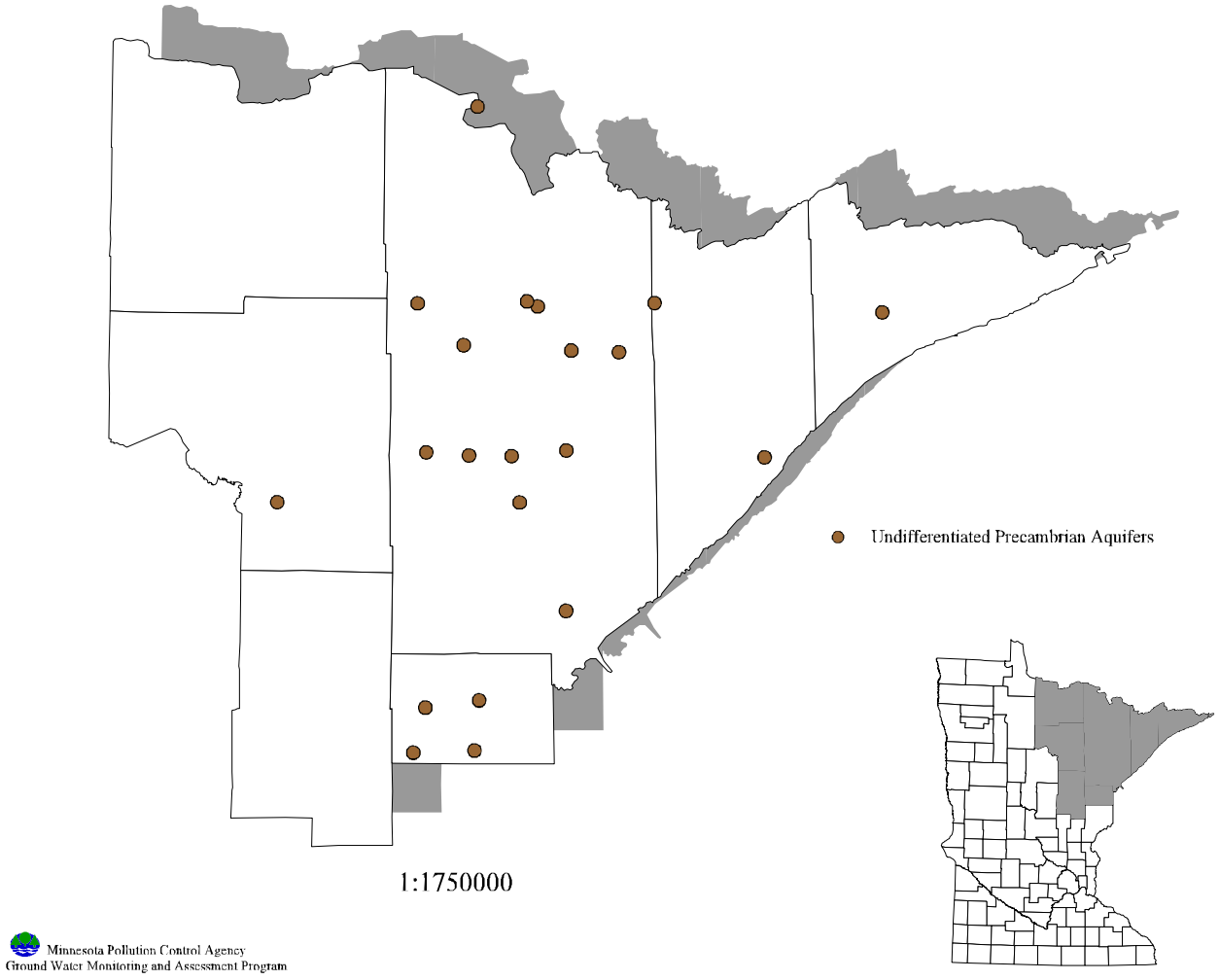


Figure 5 : Sample locations for the surficial drift aquifers.

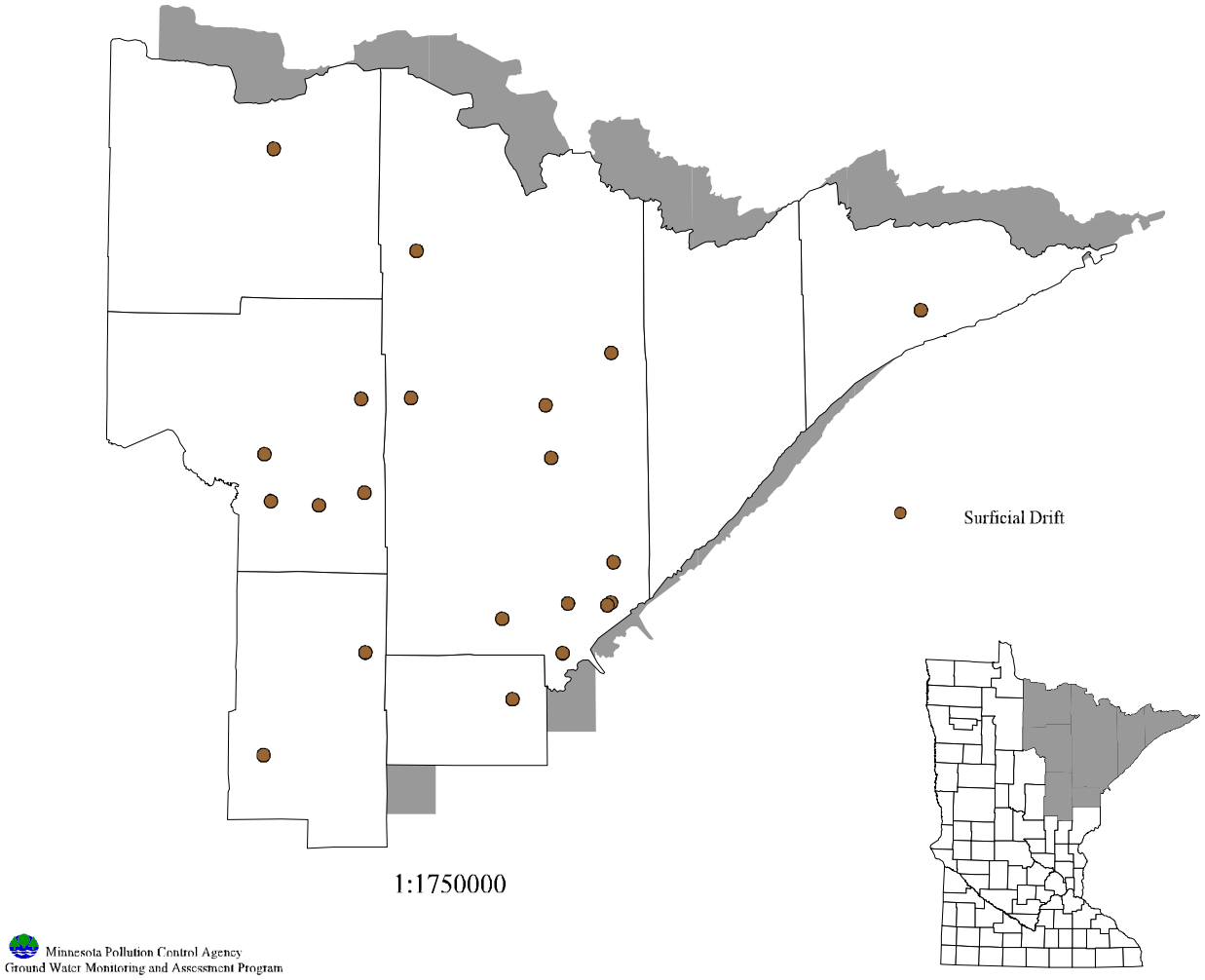


Figure 6 : Sample locations for the buried drift aquifers.

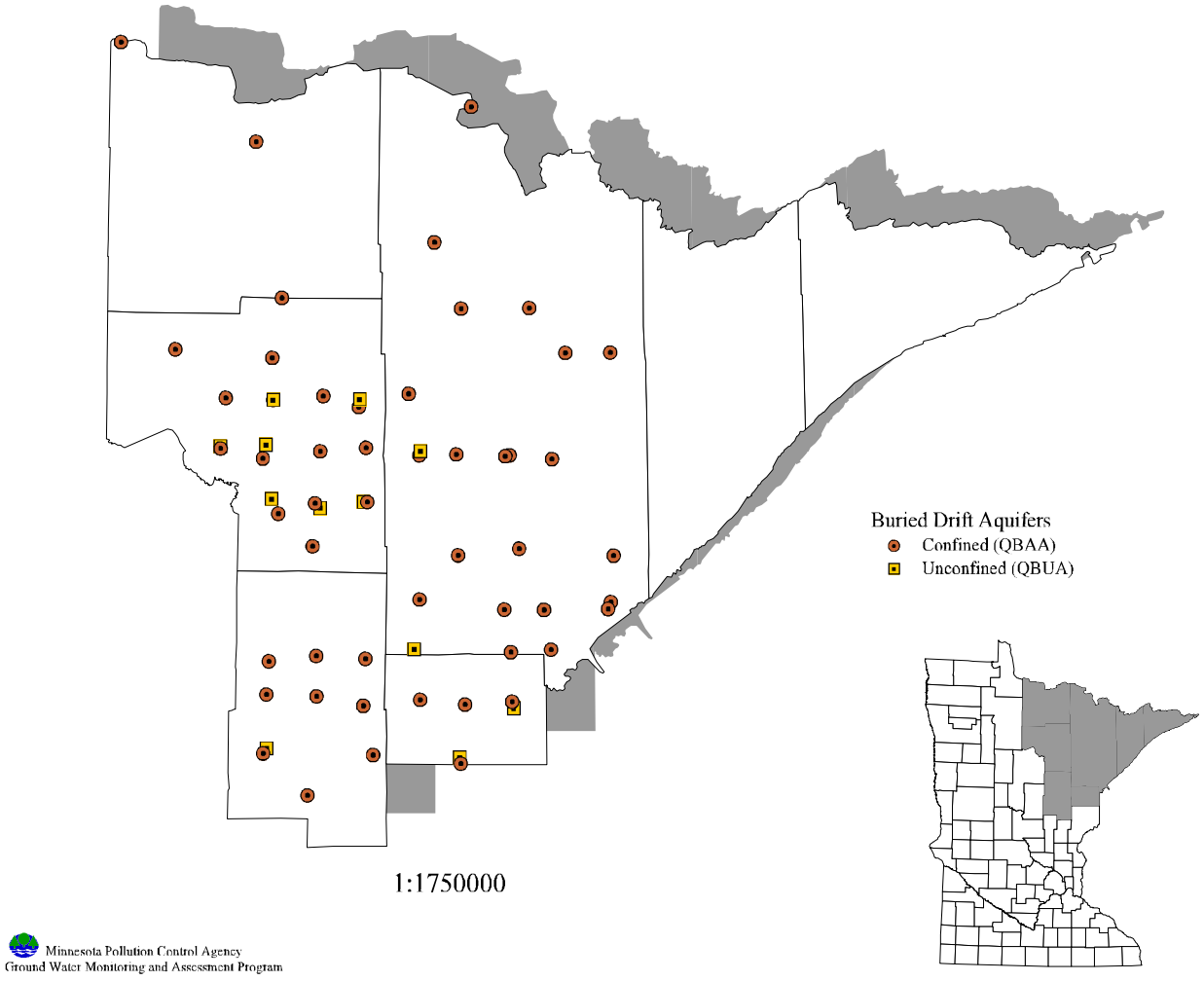


Figure 7 : Locations of VOC detections in Region 1.