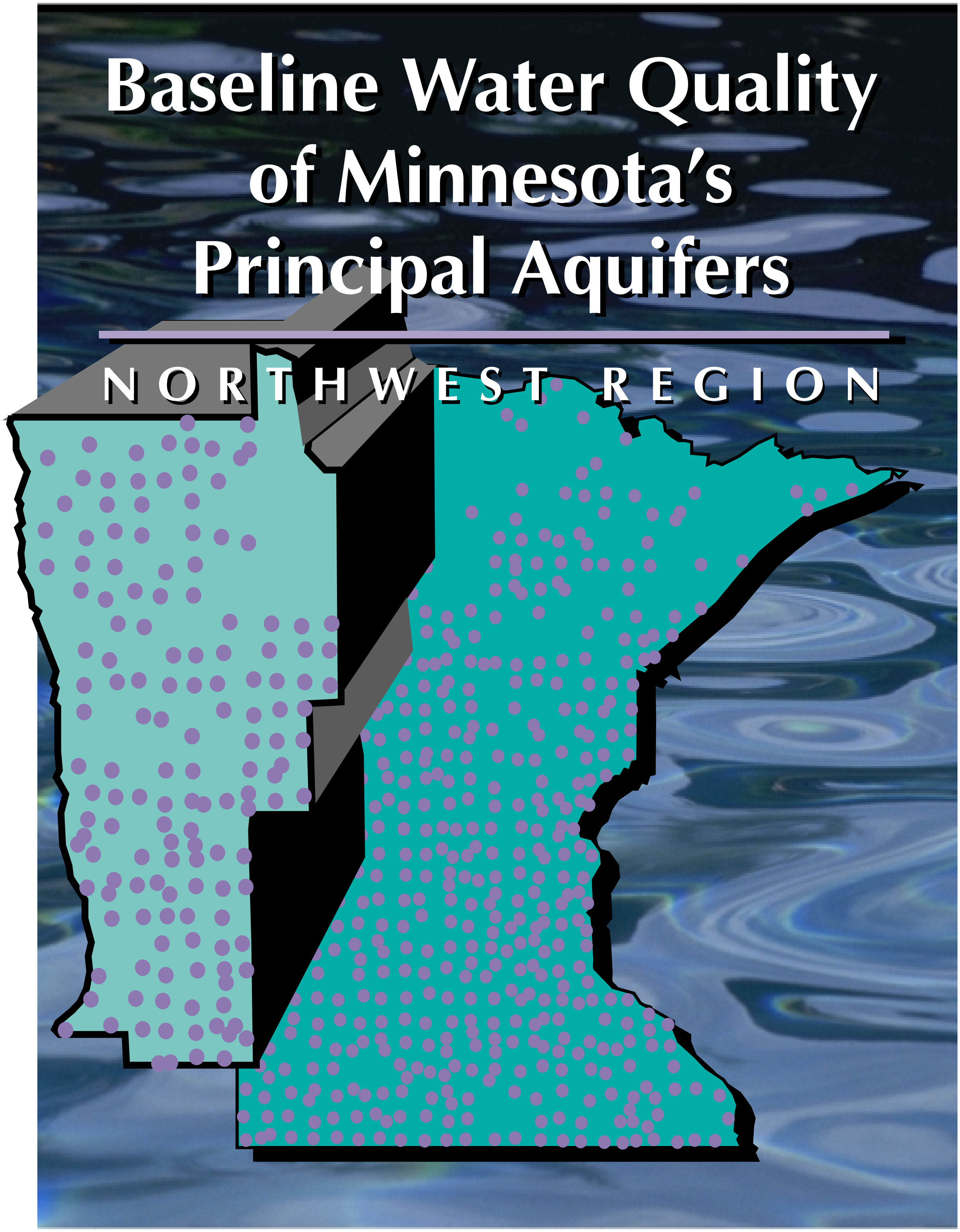
Baseline Water Quality of Minnesota's Principal Aquifers

NORTHWEST REGION



Minnesota Pollution Control Agency

Baseline Water Quality of Minnesota's Principal Aquifers - Region 3, Northwest Minnesota

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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 Minnesota Pollution Control Agency (MPCA), Region 3 in Northwest 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.

List of 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

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Executive Summary

In 1993, 1994, and 1995 the Minnesota Pollution Control Agency's (MPCA) Ground Water Monitoring and Assessment Program (GWMAP) staff sampled 182 primarily domestic wells in MPCA Region 3, which encompasses Northwest 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 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. Wells in Region 3 are completed in either Cretaceous, buried drift, water table, or unconfined drift aquifers. One well from each of these four aquifer types was located within a nine-square mile target area centered on each grid node. Wells were sampled for 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 specific conductance. Statewide, 954 wells were sampled from thirty different aquifer types.

Median concentrations of most chemicals in drift aquifers were slightly greater than concentrations in similar aquifers statewide. Iron and sulfate were much greater. Concentrations of most dissolved chemicals were much greater in the Cretaceous aquifers than in the drift aquifers and compared to Cretaceous aquifers statewide. Concentrations of most dissolved solids were highest in Cretaceous aquifers, intermediate in buried drift aquifers, and lowest in surficial aquifers. Boron in Cretaceous aquifers and arsenic in buried drift aquifers are the primary chemicals of concern in ground water. Aquifers in Region 3 appear to be well protected from human influence, although this may be partly due to agricultural practices in the region.

Research needs for Region 3 include:

1. identifying and mapping important surficial aquifers;
2. obtaining a better understanding of the relationship between surface water and ground water in the stagnation moraine areas;
3. evaluating the distribution of arsenic in buried drift aquifers; and
4. determining the extent of Cretaceous aquifers.

Monitoring needs for Region 3 include:

1. collecting an additional 20 samples from the Cretaceous aquifers and analyzing the data to establish background concentrations;
2. establish ambient monitoring networks in surficial aquifers which are used for municipal supply; and
3. establishment of sampling, data management, and data analysis protocol.

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 3. Region 3 is located in northwestern Minnesota and includes the counties of Becker, Beltrami, Clay, Clearwater, Douglas, Grant, Kittson, Lake of the Woods, Marshall, Mahnomen, Norman, Otter Tail, Pennington, Pope, Red Lake, Roseau, Stevens, Traverse, Wilkin (Figure B.1). The regional office is located in Detroit Lakes.

The following information needs for Region 3 were identified in Myers et al., 1992:

- baseline water quality and trends in major aquifers;
- contamination assessment in outwash plains; and
- impacts from aquaculture, feedlots, logging, mining, old dumps, and lawn and garden fertilizers.

Assistance needs were identified in the following areas:

- data interpretation; and
- expansion of the existing state network.

The baseline study conducted by GWMAP may be used to fulfill the informational needs of baseline water quality assessment and, to a limited extent, the contamination assessment in outwash plains. The baseline study can assist with data interpretation through analysis of data for the region, and by describing analysis methods useful in local interpretation. At this time, there is no intent to reestablish a statewide monitoring network. If such a network was established, it would primarily serve as a trend monitoring network. Sampling would therefore be conducted on a smaller number of wells and with much greater frequency than conducted for the baseline study.

The purpose of this report is to provide baseline water quality information for Region 3. Comparisons are made between water quality in the principal aquifers of Region 3 to that in the remainder of the state. Significant differences in ground water quality between Region 3 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. (1992) 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, specific conductance, 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 Figure B.2 for the Cretaceous aquifer; in Figure B.3 for the surficial aquifers; and in Figure B.4 for the buried drift aquifers. Sampling is summarized by aquifer in Table A.1 and for all data in Table A.2. Detailed aquifer descriptions are provided in Section 3.5.

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 chemical and each aquifer;
- conducting hypothesis tests between aquifers and different well diameter classes;
- conducting factor analysis related to the distribution of chemicals in the principal aquifers; 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 types; 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.6 for the four aquifer types sampled in Region 3. All concentrations are in ug/L (ppb) except for Eh (mV), temperature (^{o}C), pH (negative log of the hydrogen ion concentration), and specific conductance (umhos/cm).

Examples of how to use information from Tables A.3 through A.6 in site applications are provided in MPCA, 1998a. To use these data in site applications, the coefficients presented in Tables A.7 and A.8 will be needed. The sample size for Cretaceous aquifers was insufficient to calculate these coefficients. **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 between two or more months. Concentrations of sampled chemicals and chemical parameters were compared between different aquifers.

Concentrations of many chemicals differed between different aquifers. Median chemical concentrations were compared between the aquifers and the results are summarized in Table A.9. 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, pH, temperature, and specific conductance).

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. Temperature, specific conductance, pH, and concentrations of bicarbonate (alkalinity), antimony, arsenic, boron, bromide, chloride, fluoride, lithium, molybdenum, phosphorus, potassium, silver, sodium, strontium, sulfate, sulfur, total dissolved solids, and total suspended solids in the Cretaceous aquifer were generally higher than concentrations in the Quaternary aquifers. Eh and concentrations of barium, iron, manganese, and silicate were lower in the Cretaceous aquifer. These distribution patterns are similar to results found statewide. Ground water in the Cretaceous aquifer represents water which is highly mineralized and reflects impacts of parent materials. Water quality of Cretaceous aquifers is poor, with boron, sodium, sulfate, and total dissolved solids being the greatest concerns.
2. Water quality of the buried Quaternary (drift) aquifers was generally intermediate between water quality of Cretaceous aquifers and of the surficial drift aquifers. Exceptions were silicate and arsenic, which were highest in the buried drift aquifers. These most likely represent impacts of parent material, since these aquifers are buried, well protected, and have long residence times.

3. Water quality of the surficial drift aquifers was good. Concentrations of bicarbonate, calcium, and total dissolved solids were higher than in similar aquifers statewide.

3.3. Health and Risk

Drinking water criteria for individual chemicals are summarized in Table A.10. 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.11 and A.12, 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)**. Boron is the chemical of greatest concern in ground water of Region 3. The HRL for boron was exceeded in all five Cretaceous samples and in 12 samples from the buried drift. The Maximum Contaminant Level (MCL) of 50 ug/L for arsenic was exceeded in six samples from the buried drift aquifers. The MCL is not a strictly health-based value, but the MCL for arsenic is often applied in risk analyses. The HRL was exceeded for selenium, nitrate, barium, and manganese in two, one, one, and one well, respectively. The HBV for molybdenum was exceeded in one well.

The number and percent of samples exceeding non-health-based ground water drinking criteria are summarized in Tables A.13 and A.14, 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 3, 103, 1, and 18 wells for the Cretaceous, buried drift, buried unconfined drift, and water table drift aquifers, respectively. Criteria for sulfate were exceeded in 14 wells, ten of which were from buried drift aquifers. The SMCL for sodium was exceeded in five wells, all in the Cretaceous or buried drift aquifers. The SMCL for aluminum was exceeded in six wells, five of which were in buried drift aquifers. Drinking criteria for chloride and fluoride was exceeded in three and one well, respectively.

Some chemicals have the same toxic endpoint. For example, Table A.10 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

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

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. Discussion of Individual Chemicals

Concentrations of boron, nitrate, volatile organic compounds (VOCs) and arsenic are discussed in this section. These chemicals either represent a potential health concern (arsenic and boron) or are important anthropogenic chemicals of concern (nitrate and VOCs).

3.4.1. Nitrate

Throughout much of Minnesota, nitrate is an important chemical of concern. This is particularly true for some of the more intensive agricultural areas of the state. In Region 3, however, nitrate does not appear to represent a concern in ground water, as illustrated in figure B.5. The HRL of 10000 ug/L for nitrate was exceeded just once (10400 ug/L), and nitrate was detected in only 17 of the 182 wells sampled. Estimated mean concentrations were 200 ug/L or less. Nitrate concentrations did not differ between surficial and buried drift aquifers, despite surficial aquifers typically being considered hydrologically sensitive.

Nitrate was not correlated with any other sampled parameter. The low concentrations of nitrate are related to the presence of reducing conditions within aquifers of Region 3, since agricultural inputs should be high. Measured Eh values, particularly for the water table aquifers, are less than values from similar aquifers statewide. Nitrate will undergo dentrification under reducing conditions. Reasons for the reducing conditions may be related to characteristics of the unsaturated zone, particularly concentrations of organic matter and clay in soil. Another possible cause of low nitrate concentrations may be that many of the surficial aquifers occur within beach ridge deposits, which are not intensively farmed. However, this would not explain the presence of reducing conditions in ground water. Additional information, particularly for the unsaturated zone, is needed to determine the cause of reducing conditions within surficial aquifers.

3.4.2. Volatile Organic Compounds

VOC results are summarized in Table A.15. There were only nine wells in which a VOC was detected (Figure B.6). This represents 4.9 percent of the sampled wells, which is below the overall statewide rate of 11 percent. Only one well had more than one VOC detected. Statewide, 2.6 percent of sampled wells had more than one VOC detected. Five of the detected VOCs were chloroform, a trihalomethane chemical often assumed to result from well disinfection. Chloroform may also be naturally occurring at low levels. Two wells had chlorinated aliphatic chemicals, which are commonly associated with the use of degreasers. Two wells had chemicals commonly associated with fuel oils and gasoline (benzene, toluene, xylene, and ethylbenzene), although some of these chemicals are also naturally occurring at low concentrations.

Five of the detections occurred in buried drift aquifers, three in surficial drift aquifers, and one in Cretaceous bedrock. There was no clear pattern to the distribution of VOCs, except that most of the detections were outside the Lake Agassiz basin. There were no strong correlations between the occurrence of VOCs and other sampled chemicals.

VOCs do not represent a health concern in Region 3. The occurrence of gasoline-related chemicals and chlorinated solvents was particularly low.

3.4.3. Arsenic

The Maximum Contaminant Level (MCL) of 50 ug/L was exceeded in six wells from buried drift aquifers. The MCL is not strictly health-based, but considers factors such as treatability. A strictly health-based value for arsenic is likely to be less than 10 ug/L, perhaps as low as 2 or 3 ug/L. A drinking criteria of 3.0 ug/L was exceeded in 52 percent of the sampled wells. A concentration of 10 ug/L was exceeded in 32 percent of the sampled wells. Higher concentrations of arsenic occur in all aquifers, but the rate of exceedance is highest in the buried drift aquifers. Median concentrations of arsenic in the Cretaceous, buried drift, and surficial drift aquifers were 3.2, 5.5, and 2.1 ug/L, respectively. These are very high concentrations and represent a potential health concern in Region 3.

The distribution of arsenic, illustrated in Figure B.7, is difficult to understand. The Minnesota Arsenic Research Study (MARS) being conducted by the Minnesota Department of Health (MDH) is focused on the southeastern and southern portions of Region 3, where there are several exceedances of the current drinking standard. The behavior of arsenic in the environment is complicated, since arsenic has properties of both metals and nonmetals. In addition, concentrations of arsenic in ground water vary widely with the solubility-controlling mineral. For example, iron oxides will have low solubility and will keep arsenic concentrations below 1 ug/L, other oxides have a higher solubility in which arsenic concentrations can be greater than 50 ug/L, and sulfides can be even more soluble, with equilibrium concentrations of about 200 ug/L (MPCA, 1998a). Arsenic can also be mobile in soil, and there are several potential anthropogenic sources of arsenic, including sludges, atmospheric deposition, industrial uses, and pesticides.

Arsenic concentrations are generally much greater in shale than in other sedimentary rocks. Concentrations in igneous rocks are intermediate between shale and other sedimentary rocks. Since shale also contains higher concentrations of many other trace elements, a shale source for the arsenic should be indicated by correlations with other trace elements. Correlation analysis of arsenic with other sampled chemicals is illustrated in Table A.16 for all data and for samples in which arsenic concentrations were less than 1 ug/L or greater than 25 ug/L. The correlations are not particularly strong, which is typical of a data set derived from a wide variety of geologic and hydrologic settings. Nevertheless, some patterns are evident. An important observation from Table A.16 are the large number of positive correlations between arsenic and other trace metals for arsenic concentrations exceeding 25 ug/L. These correlations were not evident for the remainder of the data.

Soule (personal communication) observed higher concentrations of arsenic in stagnation moraines. These are hydrologically active areas, being both the focal point for recharge to the regional system and containing a large number of aquifers. Despite this, individual aquifers within stagnation moraines are not as easily defined as outwash or alluvial aquifers. There is a considerable mixing of geologic materials in stagnation moraines. This differs from the relatively uniform deposits found in alluvial and outwash aquifers. Consequently, the chemistry of aquifers in stagnation moraines is impacted by a wide variety of geologic materials. The distribution of arsenic in ground water is too complicated to understand with the available information. There were no spatial or temporal patterns to the data. There was no effect of well depth or static water elevation. There was no effect of oxidation-reduction potential, although it should be noted that oxidation-reduction potential values less than about 0 mV probably do not represent actual values in the aquifer because of instrument drift.

Arsenic represents a potential health concern in Region 3. Unfortunately, there is insufficient information to understand the distribution of arsenic. Drilling depth and location are therefore not effective management tools for arsenic. The primary management tools are reverse osmosis, which is expensive, oxidation methods, which can also be expensive, and filtration, which is less costly but also less effective than the other two methods.

3.4.4. Boron

Until the drinking criteria for arsenic is lowered, boron will be the primary chemical of concern in ground water of Region 3. Concentrations were much greater in Cretaceous aquifers (median = 1192 ug/L), which follows the statewide pattern of high concentrations in Cretaceous aquifers. In surficial drift aquifers, concentrations were less than 35 ug/L and there were no exceedances of the HRL. The median concentration in buried drift aquifers was 139 ug/L, but the HRL of 600 ug/L was exceeded in 12 wells (10 percent of sampled wells).

Unlike arsenic, the distribution of boron is more easily understood. Correlation analysis was performed for boron and other chemicals. Correlation analysis quantifies the fraction of variability in the concentration of one chemical accounted for by variability in another chemical. The correlation coefficient, R^2, represents this fraction. For example, if R^2 for boron and iron concentrations was 0.50, then 50 percent of the variability in boron concentrations can be accounted for by variation in iron concentrations. Boron was most strongly correlated with bromide (R^2 = 0.452), chloride (R^2 = 0.499), fluoride (R^2 = 0.754), lithium (R^2 = 0.638), potassium (R^2 = 0.647), sodium (R^2 = 0.841), and sulfate (R^2

= 0.540), all of which are at high concentration in seawater. This explains the high boron concentrations in Cretaceous aquifers, since these aquifers consist of material deposited in ancient seas.

The distribution of boron concentrations in the buried drift aquifers of Region 3 is shown in Figure B.8. Boron concentrations in all five Cretaceous wells exceeded the drinking criteria of 600 ug/L. The distribution of boron in Quaternary wells closely follows the distribution of Cretaceous bedrock (see Myers et al., 1992). Boron is a relatively mobile chemical in ground water. Since most of the Lake Agassiz basin is an area of regional ground water discharge, upward flow of boron-rich ground water from Cretaceous deposits into buried drift deposits is likely. Within buried drift aquifers of the Lake Agassiz basin, boron concentrations increase with increasing depth because these aquifers are closer to Cretaceous bedrock. Drilling shallower wells within the Lake Agassiz basin is a method for keeping boron concentrations within acceptable limits. However, there are many places within the lake basin where it is difficult to find aquifers within 120 feet of the land surface.

3.5. Aquifers

The hydrology and geology of Region 3 is described in numerous reports, although there is no specific report which encompasses the entire area. The Hydrologic Investigations Reports for the Bois de Sioux (Maclay et al., 1968), Pomme de Terre (Cotter and Bidwell, 1966), Chippewa (Cotter et al., 1968), Buffalo (Maclay et al., 1969), Otter Tail (Winter et al., 1969), Wild Rice (Winter et al., 1970), Red Lake (Bidwell et al., 1970), Roseau (Winter et al., 1967), Two Rivers (Maclay et al., 1967), and Middle River (Maclay et al., 1965) watersheds provide information about climate, the water budget, surface water, and ground water. Annual precipitation in Region 3 ranges from about 21 inches in the west to about 24.5 inches in the east. Annual runoff to surface rivers varies from near zero in the southwest to about 5 inches in the east. Annual recharge to surficial aquifers may be greater than these amounts and will vary widely with annual precipitation and local geology. The major rivers in the region are gaining streams in that they have a baseflow component (ground water discharges to them). Regional atlases are being completed for the southern Red River Valley and eastern Otter Tail County.

The hydrogeology of Region 3 is dominated by the type of glacial event which last occurred in a particular area. Stagnation areas exist along an arc extending from the northeastern to the southeastern part of Region 3 and passing through central Otter Tail and Becker counties. These stagnation areas are very active hydrologically, serving as recharge points for regional ground water systems and providing important sources of water for municipal and irrigation use. The geology of these areas is very complex and water quality varies considerably between aquifers as a result of this complexity. Areas of ground moraine are present throughout the remainder of Region 3 outside of the Lake Agassiz basin. These areas are much less active hydrologically, but because they are in close proximity to the stagnation moraines and hence, recharge areas, there are generally ample supplies of high-quality water. The Lake Agassiz basin includes beach ridges and the lake plain. The beach ridges are old shorelines of Lake Agassiz. They consist of coarse-textured deposits, primarily sand. Vertically, there may be several ancient beaches, but these aquifers are not well connected. Instead, water enters the uppermost beach deposit and quickly moves horizontally to the base of the ridges, where numerous wetlands and springs exist. This contrasts with aquifers found under the lake plain. These aquifers are covered with thick lake deposits, often in excess of 50 feet, and they are recharged in the stagnation areas to the east. Ground water primarily flows upward through the lake sediments, resulting in very long travel times which increase closer to the land surface. For example, along an east to west transect in Norman County, ground water ages were less than 2000 years under the beach ridges but increased rapidly to several thousand years old. Ground water ages in an approximate nest of wells completed at depths of 65, 120, and 180 feet were 25000, 18000, and 11000 years, respectively, reflecting the upward nature of flow. In areas of the lake plain where Cretaceous deposits underlie buried drift aquifers, water quality of the deeper aquifers is highly impacted by Cretaceous aquifers which discharge upward into the drift deposits. An idealized hydrologic cross-section is illustrated in Figure B.9.

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. Recharge to regional aquifers occurs almost exclusively within stagnation moraines and may be as much as 10 inches, but is more typically about 5 inches. Local ground water systems develop in beach ridge areas. Recharge in these aquifers is generally in excess of six inches, but the aquifers rapidly discharge a short distance down-gradient. Ground-water flow in shallow systems is controlled by local factors such as topography. Flow within the deeper system follows surface water drainage and aquifers are often found in buried river valleys. Aquifers within the stagnation moraines are well connected hydrologically, but these aquifers are discontinuous to the west. This is particularly true within the lake plain, where the aquifers have been dissected by more recent glacial advances.

Ground water quality information was collected as part of the DNR regional hydrologic assessments in the southern portion of Region 3. This information is not yet available, however. Sporadic water quality information has been collected in other areas of Region 3, but this has been done in an attempt to find good sources of water. Consequently, this data is not representative of the regional water quality.

3.5.1. Surficial Drift Aquifers

Surficial drift aquifers include two CWI designations. These are the QWTA and QBUA aquifers. Differences in classification of these two aquifers is based on presence of 10 or more feet of confining material. Water quality of the QBUA aquifers is similar to water quality for the water table aquifers and much different than water quality of buried, confined aquifers. The only chemicals which differed between the QBUA and QWTA aquifers were barium, iron, total organic carbon, and total suspended solids, which were higher in the QWTA aquifers, and Eh, which was higher in the QBUA aquifer.

Surficial drift aquifers occur in stagnation moraines, beach deposits, alluvial deposits, and outwash deposits. The hydrology and water quality of these aquifers differ. Beach deposits include shoreline (beach ridge) deposits and lake sands deposited in near shore environments. The shoreline deposits vary in thickness from a few feet to more than

30 feet. Many beach deposits have been overlain by near-shore or till deposits. Beach ridges provide adequate ground water supply in areas where they are more than 20 feet thick. Water levels in the beach ridge aquifers may vary by several feet within a few months, since these are highly permeable deposits, there is considerable recharge, and because travel paths to discharge points are short.

Outwash deposits primarily occur near stagnation moraines. These are areas of relatively uniform sands greater than 20 feet in thickness. They comprise some of the most important aquifers within Region 3. The Pelican River aquifer is an important outwash aquifer located in western Becker County, in the vicinity of Detroit Lakes.

Alluvial sands comprise another important surficial aquifer group, particularly within the Lake Agassiz basin. These occur along existing drainage channels, such as the Buffalo, South Branch of the Buffalo, Wild Rice, and Red Lake rivers. These aquifers are typically less than 20 feet thick and represent rapid recharge-discharge systems. Some of these aquifers, however, can be considerably thicker and are important sources of water for municipalities and irrigation. The Buffalo aquifer in Clay County and the Wahpeton Buried aquifer in Wilkin County are important surficial aquifers.

Many surficial aquifers can be found in areas of stagnation moraines. These aquifers receive up to six inches of recharge annually and there is extensive surface water (lake) interaction with ground water. Although these aquifers appear to be discontinuous vertically and laterally, the hydrologic systems in these areas are well connected. This is due to the heterogeneous nature of deposits in these areas, which allow for rapid vertical transport of water through preferential pathways. These aquifers are important locally and they are also the primary points of recharge for regional aquifer systems.

The data for this study was not divided among these four types of deposits. Water quality cannot be compared between them. Trojan (unpublished) observed that dissolved solid concentrations were lowest in beach ridge deposits and highest in alluvial deposits located in the lake plain.

Surficial drift aquifers do not appear to be highly impacted by human activity. Concentrations of chloride and nitrate are low, and VOC detections are infrequent. There are three reasons for this. First, although much of the region is intensively farmed, small grains are an important crop, resulting in lower nitrogen inputs. Second, some of the more sensitive hydrologic areas, such as the beach ridges, are not intensively farmed. Third, lake clays and glacial tills appear to be more protective of ground water than in other areas of the state.

Drinking water criteria were exceeded in at least one well for sulfate, iron, aluminum, chloride, selenium, barium, and nitrate. These chemicals are discussed below.

Sulfate

The drinking criteria of 500000 ug/L for sulfate was exceeded once each in the water table (QWTA) and buried unconfined (QBUA) aquifers. Median concentrations in these two aquifers were 8760 and 16980 ug/L, respectively. These are well below the drinking criteria but slightly greater than statewide median concentrations for similar aquifers. There were nine samples with sulfate in excess of 100000 ug/L. Sulfate was most strongly correlated with calcium (R^2 = 0.537), chloride (R^2 =0.504), magnesium (R^2 = 0.477), potassium (R^2 = 0.439), and total dissolved solids (R^2 = 0.642). There is a strong spatial pattern to the distribution of sulfate, with all samples that had a concentration greater than 50000 ug/L being south of the Norman county line, and all samples that had a concentration greater than 100000 ug/L being in the lake plain. These results suggest strong interaction between underlying Cretaceous and buried Quaternary deposits. Although drift aquifers may be recharged directly by percolation through the unsaturated zone, water quality is largely influenced by the deeper regional system which is discharging upward into these aquifers. Sulfate concentrations are a concern in the southwest corner of Region 3.

Iron

The Secondary Maximum Contaminant Level (SMCL) for iron (300 ug/L) was exceeded in 45 wells, 18 in buried unconfined aquifers (QBUA) and 27 in QWTA aquifers. Median concentrations in QWTA and QBUA aquifers were 2533 and 1193 ug/L, respectively. These are well above the statewide medians of 367 and 300 ug/L, respectively, for these two aquifer types. There is no spatial pattern to the distribution of iron. Iron was well correlated with total suspended solids (R^2 = 0.930), phosphorus (R^2 =

0.620), total organic carbon (R^2 = 0.515), nitrate (R^2 = -0.558), Eh (R^2 = -0.585), dissolved oxygen (R^2 = -0.427), and manganese (R^2 = 0.402). The results are typical of iron behavior in the environment, with increasing concentrations in more reducing environments and strong associations between iron and suspended material in ground water. In Region 3, however, parent materials appear to have considerably more iron than in other areas of the state. The source of the iron is not Cretaceous bedrock, since iron concentrations in Cretaceous aquifers were less than half the concentrations in drift aquifers. Although filtration may remove a large amount of the iron in ground water, it will not reduce concentrations below the SMCL.

Selenium

The HRL for selenium (30 ug/L) was exceeded in two samples. Median concentrations in QBUA and QWTA aquifers were 3.0 and 2.4 ug/L, respectively. Selenium is relatively mobile in soil and high soil concentrations are common in arid and semiarid climates. Selenium, however, was not correlated with any measured chemical nor was there any spatial pattern to the distribution. Selenium does not appear to represent a health concern in ground water, since there were no other samples with concentrations exceeding 10 ug/L.

Aluminum

The MCL of 50 ug/L for aluminum was exceeded in one well. Median concentrations of aluminum were very low (< 1 ug/L). The strongest correlation of aluminum was with lead (R^2 = 0.386). Only two additional samples had concentrations exceeding 10 ug/L. Aluminum does not represent a drinking water concern in Region 3.

Nitrate

The HRL of 10000 ug/L for nitrate was exceeded in one well (10400 ug/L). Twelve samples had nitrate concentrations in excess of 1000 ug/L, which is considered to be a concentration indicative of human impacts. Most of these detections were in areas of stagnation moraines and outwash deposits. The strongest correlations of nitrate were with dissolved oxygen (R^2 = 0.572), Eh (R^2 = 0.429), iron (R^2 = -0.558), and total suspended solids (R^2 = -0.507). Median Eh values and concentrations of dissolved oxygen, iron, and manganese in samples with detectable nitrate were 238 mV, 2390 ug/L, 39 ug/L, and 52 ug/L, respectively, compared to values of 179 mV, < 300 ug/L, 2254 ug/L, and 202 ug/L in samples with no detectable nitrate. The negative correlation with suspended sediment reflects the association of iron with suspended sediments, leading to reducing conditions in ground water. The results indicate that surficial aquifers in which nitrate will be stable are susceptible to nitrate contamination, but that most surficial aquifers in Region 3 have relatively reducing environments in which nitrate will undergo denitrification. Additional information on geochemistry of surficial aquifers would be useful in mapping sensitive surficial aquifers in Region 3.

Barium

The HRL of 2000 ug/L for barium was exceeded once in surficial aquifers (2392 ug/L). Median concentrations in QBUA and QWTA aquifers were 88 and 133 ug/L, respectively. These are slightly higher than median concentrations in similar aquifers statewide. The highest concentrations of barium were located in areas of stagnation moraines. Barium was most strongly correlated with iron (R^2 = 0.453) and total suspended solids (R^2 = 0.494). The concentration of suspended solids in the one well exceeding the HRL was 954000 ug/L. Barium does not represent a drinking water concern in Region 3.

Chloride

The SMCL of 250000 for chloride was exceeded in one well (354530 ug/L). Except for one well, all wells with chloride concentrations greater than 10000 ug/L were located in the southern half of Region 3. Chloride was correlated with dissolved oxygen (R^2 = 0.469), magnesium (R^2 = 0.436), potassium (R^2 = 0.546), sulfate (R^2 = 0.578), and total dissolved solids (R^2 = 0.503). The median concentrations of 2660 and 3940 ug/L in QBUA and QWTA aquifers indicate chloride is not a drinking water concern in Region 3.

3.5.2. Buried Drift Aquifers

Well-sorted sand and gravel were deposited in bedrock valleys, alluvial channels, and as outwash plains by advancing and retreating glaciers. These deposits were subsequently covered by lacustrine deposits in the lake plain or by till east of the lake plain. The confined buried 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. Buried sand and gravel aquifers occur throughout Region 3 and constitute the most important source of drinking water in the region. These aquifers are well protected from contamination resulting from human activity at the land surface. When these aquifers overlie Cretaceous bedrock, there is interaction between the buried drift aquifers and the Cretaceous aquifers, primarily as a result of ground water flowing upward from the Cretaceous aquifers into the buried drift deposits.

Like the surficial drift aquifers, water quality of the buried drift aquifers is variable. In addition to the effects of Cretaceous bedrock, residence times in ground water affect water quality. Buried aquifers are part of a regional ground water system which predominantly flows east to west, discharging to the Red River of the North. Portions of the region drain to the Rainy River, while the eastern edge of the region drains to the Mississippi River. Regional systems are recharged in areas of stagnation moraines. Trojan (unpublished) estimated recharge rates of 3 to 6 inches to the surficial aquifers and 1 to 2 inches to the upper portion of the buried system in the stagnation areas. Trojan (unpublished), using computer-simulated modeling, estimated vertical travel times of less than 100 years within the upper 75 feet of the system, less than 1000 years to the deeper portions of the regional system (> 200 feet depth), but then much slower travel times horizontally within the buried system. Water quality varies in response to these increasing residence times.

Water quality criteria were exceeded for sulfate, sodium, iron, boron, aluminum, arsenic, chloride, and manganese. These are discussed separately below.

Manganese

The drinking criteria of 1000 ug/L for manganese was exceeded in one well (1421 ug/L). The median concentration was 86 ug/L. The highest concentrations tended to be in the southern half of the study area. The strongest correlations were with sulfate (R^2 = 0.585), calcium (R^2 = 0.642), iron (R^2 = 0.418), and silicate (R^2 = 0.407). Manganese does not represent a drinking water concern in buried aquifers of Region 3.

Chloride

The drinking criteria of 250000 ug/L for chloride was exceeded in two wells. The median concentration was 3080 ug/L. Concentrations increased from east to west, with the highest concentrations near the Red River of the North, particularly in the southern half of Region 3. Chloride was correlated with boron (R^2 = 0.708), bromide (R^2 = 0.422), fluoride (R^2 = 0.648), lithium (R^2 = 0.511), potassium (R^2 = 0.447), and sodium (R^2 = 0.748), all reflective of interaction with Cretaceous ground water. In areas where buried drift aquifers are underlain by Cretaceous bedrock, chloride concentrations will be elevated and may be a drinking water concern.

Iron

Iron exceeded its SMCL of 300 ug/L in 87 percent (105 wells) of the samples from buried drift aquifers. The median concentration was 1339 ug/L, which is close to the statewide rate of 1179 ug/L. Iron concentrations were correlated with alkalinity (R^2 = 0.519), calcium (R^2 = 0.555), magnesium (R^2 = 0.544), pH (R^2 = -0.588), and silicate (R^2 = 0.420). The highest iron concentrations are in the southern half of the study area, while the lowest concentrations are in the northwest portion of Region 3. Iron, which stains plumbing fixtures, is a concern in Region 3.

Arsenic

Arsenic was discussed extensively in Section 3.4.3. Most of that discussion applies to the buried drift aquifers. The median concentration of 5.5 ug/L is much higher than the statewide rate of 2.6 ug/L for the buried drift aquifers. The current drinking standard of 50 ug/L was exceeded in six wells, but concentrations of 3, 10, and 25 ug/L were exceeded in 52, 32, and 18 percent of the 121 sampled wells. Despite extensive analysis of the data, few conclusions can be made about the distribution of arsenic in ground water. Arsenic concentrations increase somewhat with depth and more reducing conditions, but these relationships were not strong. The highest concentrations of arsenic occur in areas of stagnation moraines. When the samples with the highest concentrations of arsenic are separated from the remainder of the data, several correlations exist with other trace elements, suggesting a shale or possibly igneous rock source for the arsenic. The shale does not appear to be Cretaceous, however, since arsenic concentrations were relatively low in Cretaceous aquifers. A health-based drinking criteria for arsenic is likely to be somewhere between 2 and 10 ug/L. Consequently, arsenic probably represents the most important chemical of concern in buried aquifers of Region 3.

Aluminum

The MCL of 50 ug/L for aluminum was exceeded in five wells. The median concentration was very low at 0.80 ug/L. Aluminum was correlated only with phosphorus (R^2 = 0.420). All wells with high concentrations of aluminum also had high concentrations of total suspended solids, suggesting that aluminum is associated with suspended material and can thus be filtered.

Boron

Boron was discussed extensively in Section 3.4.4. The HRL of 600 ug/L was exceeded in 12 wells. The strongest correlations were with barium, chloride, fluoride, lithium, potassium, sodium, strontium, and sulfate. These are chemicals which have high concentrations in Cretaceous aquifers. Boron concentrations are greatest in the western portion of Region 3, where Cretaceous bedrock exists. Since boron concentrations were very high in Cretaceous aquifers, the high boron concentrations in buried drift aquifers are the result of interaction with Cretaceous aquifers.

Sodium

The SMCL of 250000 ug/L for sodium was exceeded in three wells. The distribution of sodium nearly parallels that of boron and chloride. Correlations were observed with chloride ($R^2 = 0.708$), boron ($R^2 = 0.926$), fluoride ($R^2 = 0.714$), lithium ($R^2 = 0.600$), potassium ($R^2 = 0.422$), and sulfate ($R^2 = 0.442$). As with chloride and boron, concentrations of sodium will be a potential concern in areas where buried drift aquifers are underlain by Cretaceous bedrock.

Sulfate

The MCL of 500000 ug/L for sulfate was exceeded in 10 wells, with the highest concentration being 1343370 ug/L. Several wells in the southwestern part of the study area had concentrations in excess of 500000 ug/L. Sulfate was correlated with sodium ($R^2 = 0.442$), boron ($R^2 = 0.926$), calcium ($R^2 = 0.444$), lithium ($R^2 = 0.722$), potassium $R^2 = 0.755$), and strontium ($R^2 = 0.739$). Sulfate follows distribution patterns similar to sodium, boron, and chloride, with high concentrations in areas where buried drift aquifers are underlain by Cretaceous bedrock.

3.5.3. Cretaceous aquifers

Cretaceous sediments overlie Precambrian rocks in approximately ten percent of Region 3. Cretaceous deposits occur primarily along the Red River of the North, but scattered areas of Cretaceous bedrock have been found along existing river channels in the

Agassiz lake plain. Cretaceous deposits are generally more than 150 feet below the land surface, often much deeper.

Cretaceous deposits consist of interbedded shale, siltstone, and sandstone. Aquifers most often occur at the base of the Cretaceous deposits in sandstone. These water-bearing units are usually not laterally continuous and are confined by overlying till. Regionally, ground water flows laterally through the Cretaceous deposits and discharges upward into the overlying buried drift aquifer system. Buried bedrock valleys filled with drift are also important discharge points for Cretaceous aquifers. Cretaceous aquifers are assumed to be recharged much farther west in North and South Dakota (Woodward and Anderson, 1986).

Water quality of Cretaceous aquifers in Region 3 differs from Cretaceous aquifers statewide. Water quality in Cretaceous aquifers of Region 3 has a much stronger signature of seawater, reflective of the deposition environment. Sodium, potassium, and chloride account for more than fifty percent of the major cations and anions, and concentrations of boron, fluoride, bromide, and lithium are much greater than in Cretaceous aquifers statewide. Ground water is strongly reducing, with a median Eh of 90 mV.

Water quality of Cretaceous aquifers is poor. In addition to high concentrations of dissolved solids, concentrations of boron, sodium, and sulfate are at levels of potential concern. In addition to these chemicals, drinking water criteria were exceeded for fluoride, molybdenum, and iron. These chemicals are discussed separately below.

Boron

Boron was discussed extensively in Section 3.4.4. The median concentration of 1192 is very high and the HRL of 600 ug/L was exceeded in all five Cretaceous wells. Boron was strongly correlated with bromide (R^2 = 1.000), chloride (R^2 = 0.900), sodium (R^2 = 1.000), and sulfate (R^2 = 0.900). Boron represents a chemical of concern in Cretaceous aquifers and strongly influences water quality of overlying drift aquifers.

Sulfate

The MCL of 500000 ug/L for sulfate was exceeded in two wells. The median concentration was 185070 ug/L. The lowest concentration was 174930 ug/L. Sulfate was correlated with alkalinity, sodium, boron, and bromide (R^2 = 1.000). Sulfate imparts a bad taste to water and has laxative effects. Sulfate concentrations are a drinking water concern in Cretaceous aquifers.

Sodium

The SMCL of 250000 ug/L for sodium was exceeded in two samples. The median concentration was 230648 ug/L, with the lowest concentration being 116105 ug/L. Sodium was correlated with boron and bromide (R^2 = 1.000), and with chloride and sulfate (R^2 = 0.900). Sodium may increase the risk of hypertension and represents a drinking water concern in Region 3.

Molybdenum

The HBV of 30 ug/L for molybdenum was exceeded in one well. The median concentration was below the detection limit of 4.2 ug/L. Molybdenum was correlated with arsenic and total organic carbon (R^2 = 0.894). These relationships provide little insight into the distribution of molybdenum, but the chemical does represent a drinking water concern in Region 3.

Fluoride

The MCL of 4000 ug/L for fluoride was exceeded in one well. The median concentration of 1940 ug/L is much greater than the statewide rate of 430 ug/L. Fluoride may lead to mottling of teeth and represents a drinking water concern in Cretaceous ground water.

Iron

The SMCL of 300 ug/L for iron was exceeded in three wells. The median concentration was 582 ug/L. Iron concentrations appear to be strongly related to oxidation-reduction conditions within an aquifer. Correlation coefficients were -0.900 with Eh and 0.900 with manganese. Other correlations were observed with cobalt, barium, magnesium, and calcium (R^2 = 0.900). Iron stains plumbing fixtures and is a ground water quality concern in Region 3.

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 three aquifers sampled in MPCA Region 3 in northwestern Minnesota. Sample size was sufficient for the buried and surficial drift aquifers so that these values may serve as background concentrations for the aquifers in Region 3.
2. There were differences in concentrations of many chemicals between different aquifers. The Cretaceous aquifer had high concentrations of bicarbonate (alkalinity), antimony, boron, bromide, chloride, fluoride, lithium, potassium, sodium, strontium, sulfate, and total dissolved solids compared to other aquifers. Surficial drift aquifers had low concentrations of many chemicals, with the exception of iron and manganese. The buried drift aquifer had very high concentrations of arsenic and higher concentrations of molybdenum compared to other aquifers. Concentrations of most other chemicals were intermediate between the Cretaceous and surficial drift aquifers.
3. Health-based drinking standards (HRL or HBV) were exceeded for the following compounds:

- manganese - one exceedance in a buried drift aquifer;
- nitrate - one exceedance in a surficial drift aquifer;
- selenium - two exceedances in surficial drift aquifers;
- arsenic - six exceedances in buried drift aquifers;
- barium - one exceedance in a surficial drift aquifer;
- boron - 17 exceedances, five in Cretaceous aquifers and 12 in buried drift aquifers; and
- molybdenum - one exceedance in a Cretaceous aquifer.

4. Non-health based standards (MCL or SMCL) were exceeded for the following compounds:
   - iron - 127 exceedances, scattered among all aquifers, although the greatest rate of exceedance was for buried drift aquifers;
   - aluminum - five exceedances in buried drift aquifers;
   - chloride - two exceedances in buried drift aquifers;
   - fluoride - one exceedance in a Cretaceous aquifer;
   - sodium - five exceedances in Cretaceous or buried drift aquifers; and
   - sulfate - 14 exceedances, mostly in Cretaceous and buried drift aquifers.
5. Median concentrations of many chemicals in Cretaceous aquifers were greater than in similar aquifers statewide. Concentrations of most chemicals were slightly higher in surficial and buried drift aquifers of Region 3 compared to similar aquifers statewide. Iron and sulfate concentrations were much greater in Region 3.
6. Volatile organic compounds were detected in 9 wells or 4.9 percent of the samples. Only one well with a detectable VOC had more than one VOC detected. Chloroform was the most frequently detected VOC. No drinking water criteria for VOCs were exceeded.

4.2. Research Recommendations

The drift aquifers of Region 3 have been studied with increasing frequency in the past ten years. Ground water supplies are limited in this part of the state and there is concern over preserving the quality of water in aquifers such as the Wahpeton Buried Valley aquifer, the Buffalo aquifer, and the Pelican Sand Plain aquifer. Also, high concentrations of arsenic in parts of Region 3 are being investigated through the Minnesota Department of Health's Minnesota Arsenic Research Study. Data from over 2000 sites has been compiled or sampled as part of this project. Nevertheless, aquifers in this part of Minnesota appear to be well protected due to the types of agriculture being practiced, lack of farming in some sensitive hydrologic settings such as the beach ridges, and more highly reducing conditions within ground water compared to similar aquifers statewide. Reasons for the reducing conditions are unclear, since surficial aquifers receive considerable recharge in spring.

There are few research needs related to water quality. Research recommendations for Region 3 include:

1. continuing to identify and map surficial aquifers in Region 3;
2. obtaining a better understanding of the relationship between surface water and ground water in the stagnation moraine areas for the purpose of providing better estimates of recharge rates and predicting land use impacts on ground water quality;
3. determining the cause of high arsenic concentrations in buried drift aquifers for the purpose of providing information useful for well installation, rather than relying on expensive water treatment systems; and
4. determining the extent of Cretaceous aquifers in Region 3, since they have poor water quality and significantly impact the quality of water in overlying buried drift aquifers.

4.3. Monitoring Needs

Although research needs for Region 3 are limited, there are some important monitoring needs. This is because water supply in this part of the state is limited and aquifers which become impacted may present serious water supply issues locally. 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 3 are discussed below.

1. Baseline data : the baseline data for the drift aquifers is sufficient to be considered representative of background. These data can simply be updated over time. The data base for Cretaceous aquifers should be expanded by approximately 20 wells and the data analyzed to establish baseline conditions. Information in this report provides an initial estimate of background water quality in Cretaceous aquifers, but the values may change as additional data is incorporated.
2. Ambient monitoring : ambient monitoring is needed in aquifers potentially impacted by humans. These are aquifers, such as the Buffalo Aquifer and Pelican Sand Plain Aquifer, which provide water for municipalities. Intensive agriculture, including increased irrigation, coupled with increasing population, may eventually impact these important aquifers.
3. Sampling, data management, and data analysis protocol should be established and documented. Protocols developed by other agencies or ground water groups can be identified.

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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 Cretaceous aquifer (KRET).
4. Descriptive statistics for the Quaternary buried artesian aquifer (QBAA).
5. Descriptive statistics for the Quaternary buried unconfined aquifer (QBUA).
6. Descriptive statistics for Quaternary water table aquifers (QWTA).
7. Coefficients for log-censored data from analysis of descriptive statistics, for each aquifer and chemical. See MPCA, 1998a, for application of these coefficients.
8. Coefficients for normal and log-normal data from analysis of descriptive statistics, for each aquifer and chemical. See MPCA, 1998a, for application of these coefficients.
9. 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. Different letters within a row indicate different median concentrations between aquifers.
10. Summary of water quality criteria, basis of criteria, and endpoints, by chemical parameter.
11. Number of samples exceeding health-based water quality criteria, by aquifer.
12. Percentage of samples exceeding health-based water quality criteria, by aquifer.
13. Number of samples exceeding non-health-based water quality criteria, by aquifer.
14. Percentage of samples exceeding non-health-based water quality criteria, by aquifer.
15. Summary of VOC detections for Region 3.

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

Aquifer	Number of Samples
Cretaceous aquifer (KRET)	5
Quaternary buried artesian aquifer (QBAA)	121
Quaternary buried unconfined aquifer (QBUA)	27
Quaternary water table aquifer (QWTA)	29

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

Chemical	No. of samples	No. of missing	Maximum reporting limit (ug/L)	No. detections above censoring value	No. censored values
Alkalinity	182	0	nnd[1]	182	0
Aluminum (Al)	182	0	0.060	139	43
Antimony (Sb)	182	0	0.008	107	75
Arsenic (As)	182	0	0.060	167	15
Barium (Ba)	182	0	1.4	181	1
Beryllium (Be)	182	0	0.010	65	117
Bismuth (Bi)	81	101	0.040	1	80
Boron (B)	182	0	13	179	3
Bromide (Br)	182	0	0.20	13	169
Cadmium (Cd)	182	0	0.020	95	87
Calcium (Ca)	182	0	nnd	182	0
Cesium (Cs)	81	101	0.010	2	79
Chloride (Cl)	182	0	200	182	0
Chromium (Cr)	182	0	0.050	155	27
Cobalt (Co)	182	0	0.0020	182	0
Copper (Cu)	182	0	4.6	81	101
Dissolved Oxygen	182	0	300	54	128
Eh	182	0	nnd	182	0
Fluoride (F)[2]	155	27	[2]	155	0
Iron (Fe)	182	0	3.2	181	1
Lead (Pb)	182	0	0.03	150	32
Lithium (Li)	182	0	4.5	166	16
Magnesium (Mg)	182	0	nnd	182	0
Manganese (Mn)	182	0	0.90	179	3
Mercury (Hg)	53	129	0.10	6	47
Molybdenum (Mo)	182	0	4.2	81	101
Nickel (Ni)	182	0	6.0	58	124
Nitrate-N (NO_3-N)	182	0	500	17	165
Orthophosphate	13	169	nnd	13	0
pH	182	0	nnd	182	0
$\text{Phosphorus}_{\text{total}}$	182	0	14.9	181	1
Potassium (K)	182	0	118.5	181	1
Rubidium (Rb)	182	0	555.5	16	166
Selenium (Se)	182	0	0.1	158	24
Silicate (Si)	182	0	nnd	182	0
Silver (Ag)	182	0	0.0090	43	139

Table A.2 continued.

Chemical	No. of samples	No. of missing	Maximum reporting limit (ug/L)	No. detections above censoring value	No. censored values
Sodium (Na)	182	0	nnd	182	0
Specific Conductance	182	0	nnd	182	0
Strontium (Sr)	182	0	0.60	182	0
Sulfate	182	0	300	165	17
Sulfur (S)	182	0	21.8	182	0
Temperature	182	0	nnd	182	0
Thallium (Tl)	182	0	0.0050	37	145
Tin (Sn)	81	101	0.040	40	41
Titanium (Ti)	182	0	0.0035	49	133
Total dissolved solids	182	0	nnd	182	0
Total organic carbon	181	1	500	180	1
Total phosphate	169	13	20	157	13
Total suspended solids	182	0	nnd	182	0
Vanadium (V)	182	0	4.7	109	73
Zinc (Zn)	182	0	2.7	116	66
Zirconium (Zr)	81	101	0.030	41	34
1,1-Dichloroethane	182	-	0.2	-	-
1,1-Dichloroethene	182	-	0.5	-	-
1,1-Dichloropropene	182	-	0.2	-	-
1,1,1-Trichloroethane	182	-	0.2	-	-
1,1,1,2-Tetrachloroethane	182	-	0.2	-	-
1,1,2-Trichloroethane	182	-	0.2	-	-
1,1,2,2-Tetrachloroethane	182	-	0.2	-	-
1,1,2-Trichlorotrifluoroethane	182	-	0.2	-	-
1,2-Dichlorobenzene	182	-	0.2	-	-
1,2-Dichloroethane	182	-	0.2	-	-
1,2-Dichloropropane	182	-	0.2	-	-
1,2,3-Trichlorobenzene	182	-	0.5	-	-
1,2,3-Trichloropropane	182	-	0.5	-	-
1,2,4-Trichlorobenzene	182	-	0.5	-	-
1,2,4-Trimethylbenzene	182	-	0.5	-	-
1,3-Dichlorobenzene	182	-	0.2	-	-
1,3-Dichloropropane	182	-	0.2	-	-
1,3,5-Trimethylbenzene	182	-	0.5	-	-
1,4-Dichlorobenzene	182	-	0.2	-	-
2,2-Dichloropropane	182	-	0.5	-	-
2-Chlorotoluene	182	-	0.5	-	-
4-Chlorotoluene	182	-	0.5	-	-
Acetone	182	-	20	-	-
Allyl chloride	182	-	0.5	-	-
Bromochloromethane	182	-	0.5	-	-
Bromodichloromethane	182	-	0.2	-	-
Benzene	182	-	0.2	-	-
Bromobenzene	182	-	0.2	-	-
Bromoform	182	-	0.5	-	-
Bromomethane	182	-	0.5	-	-

Table A.2 continued.

Chemical	No. of samples	No. of missing	Maximum reporting limit (ug/L)	No. detections above censoring value	No. censored values
cis-1,2-Dichloroethene	182	-	0.2	-	-
cis-1,3-Dichloropropene	182	-	0.2	-	-
Carbon tetrachloride	182	-	0.2	-	-
Chlorodibromomethane	182	-	0.5	-	-
Chlorobenzene	182	-	0.2	-	-
Chloroethane	182	-	0.5	-	-
Chloroform	182	-	0.1	-	-
Chloromethane	182	-	0.5	-	-
1,2-Dibromo-3-chloropropane	182	-	0.5	-	-
Dibromomethane	182	-	0.5	-	-
Dichlorodifluoromethane	182	-	0.5	-	-
Dichlorofluoromethane	182	-	0.5	-	-
1,2-Dibromoethane	182	-	0.5	-	-
Ethylbenzene	182	-	0.2	-	-
Ethyl ether	182	-	2	-	-
Hexachlorobutadiene	182	-	0.5	-	-
Isopropylbenzene	182	-	0.5	-	-
Methylene chloride	182	-	0.5	-	-
Methyl ethyl ketone	182	-	10	-	-
Methyl isobutyl ketone	182	-	5	-	-
Methyl tertiary butyl ether	182	-	2	-	-
n-Butylbenzene	182	-	0.5	-	-
Naphthalene	182	-	0.5	-	-
n-Propylbenzene	182	-	0.5	-	-
o-Xylene	182	-	0.2	-	-
p&m-Xylene	182	-	0.2	-	-
p-Isopropyltoluene	182	-	0.5	-	-
sec-Butylbenzene	182	-	0.5	-	-
Styrene	182	-	0.5	-	-
tert-Butylbenzene	182	-	0.5	-	-
trans-1,2-Dichloroethene	182	-	0.1	-	-
trans-1,3-Dichloropropene	182	-	0.2	-	-
Trichloroethene	182	-	0.1	-	-
Trichlorofluoromethane	182	-	0.5	-	-
Tetrachloroethene	182	-	0.2	-	-
Tetrahydrofuran	182	-	10	-	-
Toluene	182	-	0.2	-	-
Vinyl chloride	182	-	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 Cretaceous aquifer (KRET).

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	90 or 95th percentile	Min	Max	State Median
						ug/L		ug/L	ug/L	ug/L
Alkalinity	5	0	ins[1]	ins	ins	353000	ins	323000	534000	356000
Aluminum	5	0	ins	ins	ins	3.0	ins	0.12	30	1.5
Antimony	5	0	ins	ins	ins	0.025	ins	0.020	0.040	0.025
Arsenic	5	0	ins	ins	ins	3.2	ins	1.6	21	1.3
Barium	5	0	ins	ins	ins	14	ins	2.5	24	20
Beryllium	5	2	ins	ins	ins	0.020	ins	< 0.010	0.060	< 0.010
Boron	5	0	ins	ins	ins	1192	ins	947	3104	410
Bromide	5	1	ins	ins	ins	0.30	ins	< 0.20	2.0	< 0.20
Cadmium	5	2	ins	ins	ins	0.22	ins	< 0.020	0.46	0.050
Calcium	5	0	ins	ins	ins	51523	ins	12750	85287	132699
Chloride	5	0	ins	ins	ins	85880	ins	25040	447280	5840
Chromium	5	0	ins	ins	ins	3.0	ins	0.50	5.8	0.14
Cobalt	5	0	ins	ins	ins	0.15	ins	0.11	0.40	0.60
Copper	5	3	ins	ins	ins	< 5.5	ins	< 5.5	49	13
Dissolved oxygen	5	5	ins	ins	ins	< 300	ins	< 300	< 300	< 300
Eh	5	0	ins	ins	ins	90	ins	-22	197	144
Fluoride	4	0	ins	ins	ins	1940	ins	690	7500	430
Iron	5	0	ins	ins	ins	582	ins	65	5946	1514
Lead	5	0	ins	ins	ins	0.27	ins	0.11	5.0	0.45
Lithium	5	0	ins	ins	ins	137	ins	12	161	35
Magnesium	5	0	ins	ins	ins	19772	ins	4713	38648	51635
Manganese	5	0	ins	ins	ins	35	ins	12	74	112
Mercury	2	2	ins	ins	ins	< 0.10	ins	< 0.10	< 0.10	< 0.10
Molybdenum	5	3	ins	ins	ins	< 4.2	ins	< 4.2	32.9	< 4.2
Nickel	5	5	ins	ins	ins	< 6.0	ins	< 6.0	< 6.0	< 6.0
Nitrate-N	5	4	ins	ins	ins	< 500	ins	< 500	2400	< 500
pH	5	0	ins	ins	ins	7.70	ins	7.48	8.80	7.0
Phosphorus	5	0	ins	ins	ins	150	ins	43	439	140
Potassium	5	0	ins	ins	ins	12787	ins	5961	14702	5474
Rubidium	5	5	ins	ins	ins	< 555.2	ins	< 555.2	< 555.2	< 555.2
Selenium	5	0	ins	ins	ins	6.9	ins	3.3	8.4	1.5
Silicate	5	0	ins	ins	ins	5617	ins	3407	14220	10955
Silver	5	1	ins	ins	ins	0.050	ins	< 0.0090	0.13	< 0.0090
Sodium	5	0	ins	ins	ins	230648	ins	116105	743427	76187
Specific Conductance	5	0	ins	ins	ins	1256	ins	1004	3370	1436
Strontium	5	0	ins	ins	ins	439	ins	316	1263	754
Sulfate	5	0	ins	ins	ins	185070	ins	174930	735390	420390
Sulfur	5	0	ins	ins	ins	68323	ins	60749	228086	162675
Temperature	5	0	ins	ins	ins	9.00	ins	8.70	10.5	10.0
Thallium	5	3	ins	ins	ins	< 0.0050	ins	< 0.0050	0.062	< 0.0050
Titanium	5	5	ins	ins	ins	< 0.0035	ins	< 0.0035	< 0.0035	< 0.0035
Total dissolved solids	5	0	ins	ins	ins	790000	ins	716000	2412000	1110000

Table A.3 continued.

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	90 or 95th percentile	Min	Max	State Median
Total organic carbon	5	0	ins	ins	ins	2600	ins	2000	6100	2800
Total phosphate-P	5	0	ins	ins	ins	60	ins	10	190	50
Total suspended solids	5	0	ins	ins	ins	4000	ins	2000	52000	8000
Vanadium	5	4	ins	ins	ins	< 4.7	ins	< 4.7	7.1	7.2
Zinc	5	1	ins	ins	ins	18	ins	< 2.7	124	26

Table A.4 : Descriptive statistics for the Quaternary buried artesian aquifer (QBAA).

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	90 or 95th percentile	Min	Max	State Median
				ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
Alkalinity	121	0	normal	343025	355585	344000	461800	148000	502000	328000
Aluminum	121	34	log-censored	0.57	45	0.75	47	< 0.060	611	0.88
Antimony	121	65	log-censored	0.0089	0.075	< 0.0080	0.050	< 0.0080	0.18	0.011
Arsenic	121	12	log-censored	3.7	139	5.5	51	< 0.060	91	2.6
Barium	121	1	log-censored	83	815	88	471	1.3	1391	61
Beryllium	121	76	log-censored	0.0076	0.042	< 0.010	0.039	< 0.010	0.040	< 0.010
Bismuth	61	60	ins	-	-	< 0.040	< 0.040	< 0.040	0.50	
Boron	121	1	log-censored	138	1428	139	1019	< 13	1485	98
Bromide	121	113	log-censored	0.0082	0.60	< 0.20	0.36	< 0.20	2.5	< 0.20
Cadmium	121	68	log-censored	0.015	1.6	< 0.020	1.2	< 0.020	2.4	< 0.020
Calcium	121	0	log-normal	91159	116252	78618	217996	1263	476013	79537
Cesium	61	59	ins	-	-	< 0.010	< 0.010	< 0.010	0.020	
Chloride	121	0	log-normal	4774	9669	3080	58036	290	860510	2320
Chromium	121	17	log-censored	0.44	3.7	0.49	2.5	< 0.050	3.4	0.49
Cobalt	121	0	log-normal	0.34	0.47	0.41	1.6	0.12	5.1	0.46
Copper	121	67	log-censored	4.7	46	< 5.5	31	< 5.5	110	< 5.5
Dissolved oxygen	121	88	log-censored	130	3706	< 300	2490	< 300	7220	< 300
Eh	121	0	log-normal	99	124	147	260	10	287	158
Fluoride	102	0	none	-	-	440	1046	210	2620	380
Iron	121	0	log-normal	1563	2188	1339	6108	5.7	11311	1179
Lead	121	26	log-censored	0.13	2.5	0.14	1.4	0.020	13	0.18
Lithium	121	8	log-censored	23	209	24	161	< 4.5	447	14
Magnesium	121	0	log-normal	35343	47446	33023	85735	424	206048	30515
Manganese	121	2	log-censored	85	878	86	501	0.80	1421	131
Mercury	38	32	log-censored	0.072	0.20	< 0.10	0.18	< 0.10	0.20	< 0.10
Molybdenum	121	56	log-censored	4.6	16	4.7	14	< 4.2	16	< 4.2
Nickel	121	81	log-censored	5.2	18	< 6.0	14	< 6.0	40	< 6.0
Nitrate-N	121	114	log-censored	38	1443	< 500	500	< 500	3200	< 500
Ortho-phosphate-P	12	0	log-normal	80	127	75	410	30	410	
pH	121	0	normal	7.30	7.36	7.30	7.79	6.60	8.00	7.3
Phosphorus	121	1	log-censored	116	635	123	493	15	828	102
Potassium	121	1	log-censored	3812	12189	3735	10906	118	16418	3068
Rubidium	121	109	log-censored	224	845	< 555.2	674	< 555.2	1346	< 555.2

Table A.4 continued.

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	90 or 95th percentile	Min	Max	State Median
Selenium	121	22	log-censored	2.0	41	1.8	11	0.90	21	2.4
Silicate	121	0	log-normal	13941	14461	12752	14645	5612	16506	11914
Silver	121	103	log-censored	0.0028	0.0052	< 0.0090	0.040	< 0.0090	0.090	< 0.0090
Sodium	121	0	log-normal	37334	66573	24325	194139	1683	687461	18812
Specific Conductance	121	0	log-normal	905	1087	635	1786	228	2820	619
Strontium	121	0	none	-	-	348	1594	0.50	3255	304
Sulfate	121	17	log-censored	20827	2575824	29940	702252	270	1890240	7300
Sulfur	121	0	log-normal	8258	12377	10079	225175	125	607335	8110
Temperature	121	0	log-normal	8.47	8.75	8.30	10.2	6.70	13.0	8.9
Thallium	121	99	log-censored	0.0016	0.050	< 0.0050	0.028	< 0.0050	0.15	< 0.0050
Tin	61	33	log-censored	0.0037	0.85	< 0.040	0.53	< 0.040	1.5	0.060
Titanium	121	85	log-censored	0.0020	0.014	< 0.0035	0.0091	< 0.0035	0.046	< 0.0035
Total dissolved solids	121	0	log-normal	633140	716968	484000	1945600	244000	3144000	430000
Total organic carbon	120	1	log-censored	2876	8222	2900	7280	400	17500	2600
Total phosphate-P	109	7	log-censored	75	534	80	420	< 20	580	60
Total suspended solids	121	0	log-normal	3787	5872	6000	20000	1000	516000	5000
Vanadium	121	46	log-censored	6.0	20	5.9	16	< 4.7	30	<4.7
Zinc	121	60	log-censored	10	185	10	115	< 2.7	453	13
Zirconium	61	26	log-censored	0.039	1.0	0.040	0.45	< 0.030	3.6	< 0.030

Table A.5 : Descriptive statistics for the Quaternary buried unconfined aquifer (QBUA).

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	90 or 95th percentile	Min	Max	State Median
				ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
Alkalinity	27	0	normal	332181	343198	298000	445000	192000	473000	281000
Aluminum	27	3	log-censored	0.85	27	0.91	23	< 0.060	27	0.91
Antimony	27	10	log-censored	0.018	5.0	0.020	0.088	< 0.0080	0.093	0.016
Arsenic	27	0	log-normal	2.2	4.2	2.5	37	< 0.060	40	1.9
Barium	27	0	log-normal	81	117	83	407	13	495	71
Beryllium	27	22	log-censored	0.0094	2.4	< 0.010	0.020	< 0.010	0.020	< 0.010
Bismuth	9	9	ins	-	-	< 0.040	-	< 0.040	< 0.040	< 0.040
Boron	27	2	log-censored	36	47	27	525	< 13	528	23
Bromide	27	26	ins	-	-	<0.20	0.16	< 0.20	0.20	< 0.20
Cadmium	27	17	log-censored	0.013	47	<0.020	0.88	0.020	1.4	< 0.020
Calcium	27	0	none	-	-	81307	188518	25427	196599	78821
Cesium	9	9	ins	-	-	< 0.010	ins	< 0.010	< 0.010	< 0.010
Chloride	27	0	log-normal	3143	5518	2660	48366	280	48870	3625
Chromium	27	4	log-censored	0.42	12	0.64	2.3	< 0.050	2.6	0.69
Cobalt	27	0	normal	0.54	0.61	0.50	1.1	0.14	1.2	0.46
Copper	27	15	log-censored	4.5	18	< 5.5	57	< 5.5	65	< 5.5
Dissolved oxygen	27	16	log-censored	636	654	< 300	8440	< 300	10740	< 300

Table A.5 continued.

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	90 or 95th percentile	Min	Max	State Median
Eh	27	0	normal	166	176	222	366	71	371	220

Fluoride	24	0	log-normal	335		350	840	200	960	305
Iron	27	1	log-censored	510	551	1193	4943	< 3.2	5698	367
Lead	27	4	log-censored	0.16	55	0.14	6.6	< 0.030	7.6	0.19
Lithium	27	4	log-censored	12	20	11	95	< 4.5	105	7.1
Magnesium	27	0	log-normal	31996	37986	28256	73674	9964	75489	26539
Manganese	27	1	log-censored	122	130	172	518	< 0.90	621	152
Mercury	8	8	ins	-	-	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Molybdenum	27	20	log-censored	1.9	12	< 4.2	16	< 4.2	19	< 4.2
Nickel	27	21	log-censored	5.6	8.0	< 6.0	13	< 6.0	14	< 6.0
Nitrate-N	27	22	log-censored	46	140	< 500	3760	< 500	5400	< 500
Ortho-phosphate-P	1	0	ins	-	-	60	ins	60	60	10
pH	27	0	log-normal	7.18	7.58	7.20	7.78	6.90	7.96	7.2
Phosphorus	27	0	log-normal	56	82	50	442	15	508	57
Potassium	27	0	none	-	-	2557	7313	589	7779	1796
Rubidium	27	26	ins	-	-	< 555.2	681	< 555.2	765	< 555.2
Selenium	27	2	log-censored	2.8	11	3.0	38	< 1.0	54	3.2
Silicate	27	0	normal	11891	12235	11312	14637	7245	14896	10867
Silver	27	19	log-censored	0.0060	9.0	< 0.0090	0.040	< 0.0090	0.040	< 0.0090
Sodium	27	0	none	-	-	4017	167933	1438	206307	5906
Specific Conductance	27	0	none	-	-	502	1.5	252	1710	533
Strontium	27	0	none	-	-	113	1004	39	1026	112
Sulfate	27	0	log-normal	20431	43231	16980	196522	270	709770	5280
Sulfur	27	0	log-normal	7682	15195	5376	589566	320	218984	5406
Temperature	27	0	normal	8.54	8.67	8.40	10.3	7.10	10.3	8.8
Thallium	27	18	log-censored	0.0021	31	< 0.0050	0.096	< 0.0050	0.15	< 0.0050
Tin	9	4	log-censored	0.0046	27	< 0.030	0.46	< 0.030	0.46	0.060
Titanium	27	23	log-censored	0.0029	2.3	< 0.0035	0.0064	< 0.0035	0.0068	< 0.0035
Total dissolved solids	27	0	none	-	-	384000	1368800	248000	1512000	350000
Total organic carbon	27	0	log-normal	2224	3000	2100	11340	600	13100	1900
Total phosphate-P	26	0	none	-	-	40	372	10	470	40
Total suspended solids	27	0	none	-	-	6000	16400	1000	18000	2000
Vanadium	27	12	log-censored	5.5	8.7	5.4	16	< 4.7	16	< 4.7
Zinc	27	3	log-censored	13	34	14	266	< 2.7	342	12
Zirconium	9	4	log-censored	0.021	20	0.030	0.31	< 0.030	0.31	

Table A.6 : Descriptive statistics for the Quaternary water table aquifer (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	29	0	normal	302207	334601	303000	479000	125000	486000	237500
Aluminum	29	6	log-censored	0.52	21	0.76	45	< 0.060	82	1.2
Antimony	29	0	none	0.015	-0.15	0.020	0.26	0.0070	0.41	0.017
Arsenic	29	3	log-censored	1.4	34	1.8	17	< 0.060	22	1.3
Barium	29	0	log-normal	139	195	133	1386	21	2392	85

Table A.6 continued.

Chemical	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95th percentile	Min	Max	State Median
Beryllium	29	17	log-censored	0.0076	0.040	< 0.010	0.035	< 0.010	0.040	< 0.010
Bismuth	11	11	ins	-	-	< 0.040	< 0.040	< 0.040	< 0.040	< 0.40
Boron	29	0	log-normal	35	4.5	33	217	15	240	24
Bromide	29	29	ins	-	-	< 0.20	< 0.20	< 0.20	< 0.20	< 0.20
Cadmium	29	0	none	-	-	0.020	0.24	0.020	0.29	< 0.020
Calcium	29	0	none	-	-	83448	165113	25585	181342	74237

Cesium	11	11	ins	-	-	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Chloride	29	0	log-normal	5359	11015	3940	295310	410	354530	5810
Chromium	29	6	log-censored	0.46	4.5	0.45	3.2	< 0.050	3.5	0.55
Cobalt	29	0	log-normal	0.50	0.61	0.50	1.5	0.15	1.7	0.48
Copper	29	16	log-censored	4.5	31	< 5.5	33	< 5.5	51	6.3
Dissolved oxygen	29	19	log-censored	153	22061	< 300	12490	< 300	13400	< 500
Eh	29	0	normal	163	185	144	260	24	261	187
Fluoride	25	0	none	-	-	330	894	220	1020	300
Iron	29	0	normal	2619	3391	2533	7577	39	7788	811
Lead	29	2	log-censored	0.10	1.6	0.13	3.5	< 0.030	6.0	0.18
Lithium	29	4	log-censored	9.0	46	8.9	58	< 4.5	72	5.7
Magnesium	29	0	log-normal	31463	36224	30196	64789	18322	68079	22224
Manganese	29	0	normal	195	239	181	439	3.3	447	176
Mercury	5	5	ins	-	-	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Molybdenum	29	22	log-censored	2.7	9.3	< 4.2	8.7	< 4.2	10	< 4.2
Nickel	29	17	log-censored	5.5	21	< 6.0	20	< 6.0	26	< 6.0
Nitrate-N	29	25	log-censored	203	12591	< 500	9600	< 500	10400	< 500
pH	29	0	normal	7.22	7.30	7.30	7.60	6.76	7.70	7.2
Phosphorus	29	0	log-normal	70	94	68	303	15	310	56
Potassium	29	0	log-normal	2729	3318	2555	8153	1088	8894	1766
Rubidium	29	26	log-censored	388	694	< 555.2	671	< 555.2	702	< 555
Selenium	29	0	log-normal	2.5	13	2.4	9.2	0.90	9.3	2.1
Silicate	29	0	normal	11853	12725	11927	15723	6077	16850	10819
Silver	29	16	log-censored	0.0079	0.067	< 0.0090	0.050	< 0.0090	0.050	< 0.0090
Sodium	29	0	none	-	-	5836	144740	1759	190579	4986
Specific Conductance	29	0	log-normal	0.57	0.68	541	1485	272	1550	465
Strontium	29	0	log-normal	149	184	156	582	69	747	105
Sulfate	29	0	log-normal	7273	16757	8760	282375	270	359820	4250
Sulfur	29	0	log-normal	3369	6780	3371	104237	189	139710	4603
Temperature	29	0	normal	8.77	9.07	8.80	10.1	7.00	10.1	8.8
Thallium	29	25	log-censored	0.0021	0.022	< 0.0050	0.019	< 0.0050	0.028	< 0.0050
Tin	11	4	log-censored	0.043	0.14	0.050	0.15	< 0.030	0.15	0.059
Titanium	29	20	log-censored	0.0025	0.0093	< 0.0035	0.0087	< 0.0035	0.0088	< 0.0035
Total dissolved solids	29	0	none	-	-	390000	1111000	228000	1206000	340000
Total organic carbon	29	0	log-normal	31431	3962	3100	9600	1100	10700	2400
Total phosphate-P	29	5	log-censored	50	442	50	600	< 20	990	40
Total suspended solids	29	0	normal	9448	11684	10000	22000	2000	24000	4000
Vanadium	29	11	log-censored	6.2	18	5.7	15	< 4.7	16	5.4
Zinc	29	2	log-censored	18	230	17	158	< 2.7	176	12
Zirconium	11	4	log-censored			0.13	0.59	< 0.030	0.59	0.30

Table A.7: 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	QBAA		QBUA		QWTA	
	a	b	a	b	a	b
Aluminum	-0.560	2.227	-0.165	1.668	-0.659	1.900
Antimony	-4.726	1.090	-4.019	0.817	-4.168	1.158
Arsenic	1.306	1.852	-	-	0.302	1.650
Barium	4.424	1.163	-	-	-	-
Beryllium	-4.879	0.868	-4.666	0.445	-4.881	0.844
Boron	4.926	1.193	3.594	1.202	-	-
Bromide	-4.806	2.156	-	-	-	-
Cadmium	-4.204	2.382	-4.362	1.962	-	-
Chromium	-0.826	1.092	-0.877	1.254	-0.766	1.158
Copper	1.558	1.164	1.495	1.331	1.511	0.983
Dissolved oxygen	4.868	1.709	6.455	1.486	5.031	2.536
Iron	-	-	6.235	1.888	-	-
Lead	-2.044	1.504	-1.862	2.044	-2.293	1.417
Lithium	3.137	1.125	2.454	1.101	2.192	0.838
Manganese	4.437	1.194	4.810	1.053	-	-
Mercury	-2.636	0.515	-	-	-	-
Molybdenum	1.535	0.628	0.642	1.174	1.006	0.626
Nickel	1.646	0.643	1.723	0.453	1.712	0.674
Nitrate-N	3.629	1.860	3.823	2.322	5.315	2.105
Phosphorus	4.752	0.868	-	-	-	-
Potassium	8.246	0.593	-	-	-	-
Rubidium	5.410	0.678	-	-	5.961	0.297
Selenium	0.699	1.054	1.014	1.065	0.929	0.853
Silver	-5.870	1.491	-5.113	1.122	-4.846	1.092
Sulfate	9.944	2.458	-	-	-	-
Thallium	-6.436	1.751	-6.167	1.748	-6.185	1.201
Tin	-3.304	1.604	-3.075	1.682	-3.150	0.603
Titanium	-6.224	0.992	-5.840	0.426	-5.997	0.673
Total Organic carbon	7.964	0.536	-	-	-	-
Total phosphate-P	4.316	1.002	-	-	3.921	1.107
Vanadium	1.785	0.621	1.697	0.593	1.822	0.536
Zinc	2.336	1.472	2.588	1.546	2.916	1.286
Zirconium	-3.243	1.665	-3.879	1.526	-	-

Table A.8: Coefficients for normal and log-normal data from analysis of descriptive statistics, for each aquifer and chemical. See MPCA, 1998a, for application of these coefficients.

Chemical Parameter	QBAA		QBUA		QWTA	
	std. dev.	n	std. dev.	n	std. dev.	n
Alkalinity	69197	121	69591	27	85162	29
Aluminum	-	-	-	-	-	-
Arsenic	-	-	0.7638	27	0.7346	29
Barium	-	-	0.3918	27	0.3881	29
Boron	-	-	-	-	0.2912	29
Calcium	0.2958	121	-	-	-	-
Cesium	-	-	-	-	-	-
Chloride	0.6556	121	-	-	0.8226	29
Chromium	-	-	-	-	-	-
Cobalt	0.26237	121	0.24	27	0.2174	29
Eh	0.2506	121	67	27	58	29
Fluoride	-	-	0.8654	24	-	-
Iron	0.5576	121	-	-	2031	29
Lead	-	-	-	-	-	-
Magnesium	0.2972	121	0.2051	27	0.1608	29
Manganese	-	-	-	-	115	29
Orthophosphate	0.3113	12	-	-	-	-
pH	0.27	121	0.0129	27	0.216	29
Phosphorus	-	-	0.4251	27	0.3465	29
Potassium	-	-	-	-	0.2233	29
Selenium	-	-	-	-	0.3397	29
Silicate	0.08227	121	2169	27	2291	29
Silver	-	-	-	-	-	-
Sodium	0.5832	121	-	-	-	-
Specific Conductance	0.2004	121	-	-	0.1976	29
Strontium	-	-	-	-	0.2402	29
Sulfate	-	-	0.7927	27	0.9531	29
Sulfur	0.9762	121	0.7207	27	0.7985	29
Temperature	0.04258	121	0.77	27	0.812	29
Total dissolved solids	0.2245	121	-	-	-	-
Total organic carbon	-	-	0.3176	27	0.2685	29
Total Phosphate	-	-	-	-	-	-
Total suspended solids	0.4003	121	-	-	5877	29
Zinc	-	-	-	-	-	-

Table A.9 : 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. Different letters within a row indicate different median concentrations between aquifers. For example, median concentrations of a chemical followed by an "a" differ from a chemical followed by a "b".

Chemical	p-value	KRET	QBAA	QBUA	QWTA
		ug/L	ug/L	ug/L	ug/L
Alkalinity	0.002	353000 a	344000 b	298000 c	303000 c
Aluminum	0.205	3.0	0.8	0.91	0.8
Antimony	0.003	0.025 a	< 0.0080 b	0.020 b	0.020 b
Arsenic	0.05	3.2 a	5.5 a	2.5 ab	1.8 b
Barium	0.001	14 c	88 b	83 b	133 a
Beryllium	0.093	0.02	< 0.010	< 0.010	< 0.010
Bismuth	0.849	-	< 0.040	< 0.040	< 0.040
Boron	< 0.001	1192 a	139 b	27 c	33 c
Bromide	< 0.001	0.3 a	< 0.20 b	<0.20 b	< 0.20 b
Cadmium	0.446	0.22	< 0.020	<0.020	0.020
Calcium	0.097	51523	78618	81307	83448
Cesium	0.717	-	< 0.010	< 0.010	< 0.010
Chloride	0.006	85880 a	3080 b	2660 b	3940 b
Chromium	0.077	3.0	0.49	0.64	0.45
Cobalt	0.007	0.15 b	0.41 a	0.50 a	0.50 a
Copper	0.982	< 5.5	< 5.5	< 5.5	< 5.5
Dissolved oxygen	0.096	< 300	< 300	< 300	< 300
Eh	0.001	90 c	147 b	222 a	144 b
Fluoride	< 0.001	1940a	440 b	350 c	330 c
Iron	0.046	582 c	1339 b	1193 ab	2533 a
Lead	0.281	0.27	0.14	0.14	0.13
Lithium	< 0.001	137 a	24 b	11 c	8.9 c
Magnesium	0.137	19772	33023	28256	30196
Manganese	0.003	35 c	86 b	172 ab	181 a
Mercury	0.456	< 0.10	< 0.10	< 0.10	< 0.10
Molybdenum	0.004	< 4.2 a	4.7 a	< 4.2 b	< 4.2 b
Nickel	0.227	< 6.0	< 6.0	< 6.0	< 6.0
Nitrate-N	0.122	< 500	< 500	< 500	< 500
Orthophosphate	0.687	-	75	60	-
pH	0.001	7.7 a	7.30 b	7.20 b	7.30 b
Phosphorus	0.001	150 a	123 a	50 b	68 b
Potassium	< 0.001	12787 a	3735 b	2557 c	2555 c
Rubidium	0.673	< 555.2	< 555.2	< 555.2	< 555.2
Selenium	0.101	6.9	1.8	3.0	2.4
Silicate	0.018	5617 b	12752 a	11312 a	11927 a
Silver	< 0.001	0.050 a	< 0.0090 b	< 0.0090 b	< 0.0090 b
Sodium	< 0.001	230648 a	24325 b	4017 c	5836 c
Specific Conductance	< 0.001	1256 a	635 b	502 b	541 b
Strontium	< 0.001	439 a	348 b	113 c	156 c
Sulfate	0.008	185070 a	29940 b	16980 bc	8760 c
Sulfur	0.007	68323 a	10079 b	5376 b	3371 b
Temperature	0.01	9 a	8.30 b	8.40 b	8.80 b
Thallium	0.179	< 0.0050	< 0.0050	< 0.0050	< 0.0050
Tin	0.888	-	-	< 0.030	0.050
Titanium	0.217	< 0.0035	< 0.0035	< 0.0035	< 0.0035
Total dissolved solids	< 0.001	790000 a	484000 b	384000 c	390000 c

Table A.9 continued.

Chemical	p-value	KRET	QBAA	QBUA	QWTA
Total organic carbon	0.102	2600	2900	2100	3100
Total phosphate-P	0.019	60 ab	80 a	40 b	50 b
Total suspended solids	0.111	4000	6000	6000	10000
Vanadium	0.317	< 4.7	5.9	5.4	5.7
Zinc	0.223	18	10	14	17
Zirconium	0.453	-	0.040	0.030	0.13

Table A.10 : 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	-	-	-
$\text{Phosphorus}_{\text{total}}$	-	-	-
Potassium (K)	-	-	-
Rubidium (Rb)	-	-	-
Selenium (Se)	30	HRL	-
Silicate (Si)	-	-	-
Silver (Ag)	30	HRL	-
Sodium (Na)	250000	SMCL	-
Specific Conductance	-	-	-
Strontium (Sr)	4000	HRL	bone
Sulfate (SO_4)	500000	MCL	-
Sulfur (S)	-	-	-
Temperature	-	-	-

Table A.10 continued.

Chemical	Criteria (ug/L)	Basis of Criteria	Endpoint

Thallium (Tl)	0.6	HRL	gastrointestinal/liver
Titanium (Ti)	-	-	-
Total dissolved solids	-	-	-
Total organic carbon	-	-	-
Total phosphate	-	-	-
Total suspended solids	-	-	-
Vanadium (V)	50	HRL	-
Zinc (Zn)	2000	HRL	-
1,1,1-trichloroethane	600	HRL	gastrointestinal/liver
1,1-dichloroethane	70	HRL	kid
1,1-dichloroethene	6	HRL	gastrointestinal/liver
1,2-dichloroethane	4	HRL	cancer
1,2-dichloropropane	5	HRL	cancer
acetone	700	HRL	cardiaovascular/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	central/ peripheral 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.11 : Number of samples exceeding health-based water quality criteria, by aquifer.

	No. Exceedances			
Chemical	**KRET**	**QBAA**	**QBUA**	**QWTA**
Arsenic (As)	-	6	-	-
Barium (Ba)	-	-	-	1
Boron (B)	5	12	-	-
Manganese (Mn)	-	1	-	-
Molybdenum (Mo)	1	-	-	-
Nitrate (NO_3)	-	-	-	1
Selenium (Se)	-	-	1	1

Table A.12 : Percentage of samples exceeding health-based water quality criteria, by aquifer.

	% Exceedances			
Chemical	**KRET**	**QBAA**	**QBUA**	**QWTA**
Arsenic (As)	-	2.9	-	-
Barium (Ba)	-	-	-	3.4
Boron (B)	100	9.9	-	-
Manganese (Mn)	-	0.83	-	-
Molybdenum (Mo)	20	-	-	-
Nitrate (NO_3)	-	-	-	3.4
Selenium (Se)	-	-	3.7	3.4

Table A.13 : Number of samples exceeding non-health-based water quality criteria, by aquifer.

	No. Exceedances			
Chemical	**KRET**	**QBAA**	**QBUA**	**QWTA**
Aluminum (Al)	-	5	-	1
Chloride (Cl)	-	2	-	1
Fluoride (F)	1	-	-	-
Iron (Fe)	3	105	18	1
Sodium (Na)	2	3	-	-
Sulfate (SO_4)	2	10	1	1

Table A.14 : Percentage of samples exceeding non-health-based water quality criteria, by aquifer.

Chemical	% Exceedances			
	KRET	QBAA	QBUA	QWTA
Aluminum (Al)	-	4.1	-	3.4
Chloride (Cl)	-	1.7	-	3.4
Fluoride (F)	20	-	-	-
Iron (Fe)	60	87	67	3.4
Sodium (Na)	40	2.5	-	-
Sulfate (SO_4)	40	9.1	3.7	3.4

Table A.15 : Summary of VOC detections for Region 3.

Unique No.	CHEMICAL	Concentration	Chemical class
1	toluene	0.3	BTEX
2	1,1-dichloroethane	peak present	Halogenated aliphatic
3	chloroform	0.6	Trihalomethane
4	chloroform	0.4	Trihalomethane
5	benzene	peak present	BTEX
5	xylene	2	BTEX
5	ethylbenzene	0.2	BTEX
5	toluene	0.4	BTEX
5	1,3,5-trimethylbenzene	1.1	BTEX
5	1,2,4-trimethylbenzene	1.6	BTEX
5	naphthalene	0.8	PAH
6	1,2-dichloropropane	0.3	Halogenated aliphatic
7	chloroform	0.9	Trihalomethane
8	chloroform	0.3	Trihalomethane
9	chloroform	0.1	Trihalomethane

Table A.16 : Correlation coefficients of arsenic and some sampled chemicals. Data are for the buried drift aquifer only.

Chemical	All data	As > 25 ug/L	As < 1 ug/L
Aluminum	0.075	0.567	-0.037
Antimony	0.250	0.239	-0.380
Beryllium	-0.118	-0.008	-0.530
Calcium	0.500	0.278	-0.017
Chromium	-0.131	0.379	-0.131
Cobalt	0.432	0.350	-0.213
Copper	0.289	0.318	-0.150
Fluoride	-0.180	-0.159	-0.390
Iron	0.346	0.036	-0.015
Lead	-0.041	0.339	-0.046
Magnesium	0.401	0.242	-0.207
Mercury	0.106	-0.168	0.468
Molybdenum	0.524	0.231	-0.079
Nickel	-0.370	0.411	-0.359
pH	-0.371	-0.572	-0.207
Phosphorus	0.009	0.010	-0.388
Potassium	0.440	0.256	-0.160
Silicate	0.309	0.084	-0.111
Strontium	0.437	0.277	-0.332
Sulfate	0.415	0.234	-0.134
Tin	-0.078	0.994	-0.403
Titanium	0.155	0.570	-0.480
Total dissolved solids	0.370	0.270	-0.255
Total organic carbon	-0.090	-0.015	-0.440
Vanadium	0.330	0.406	-0.407
Zinc	0.360	0.271	-0.065

Appendix B - Figures

Figure B.1 : Location of Region 3

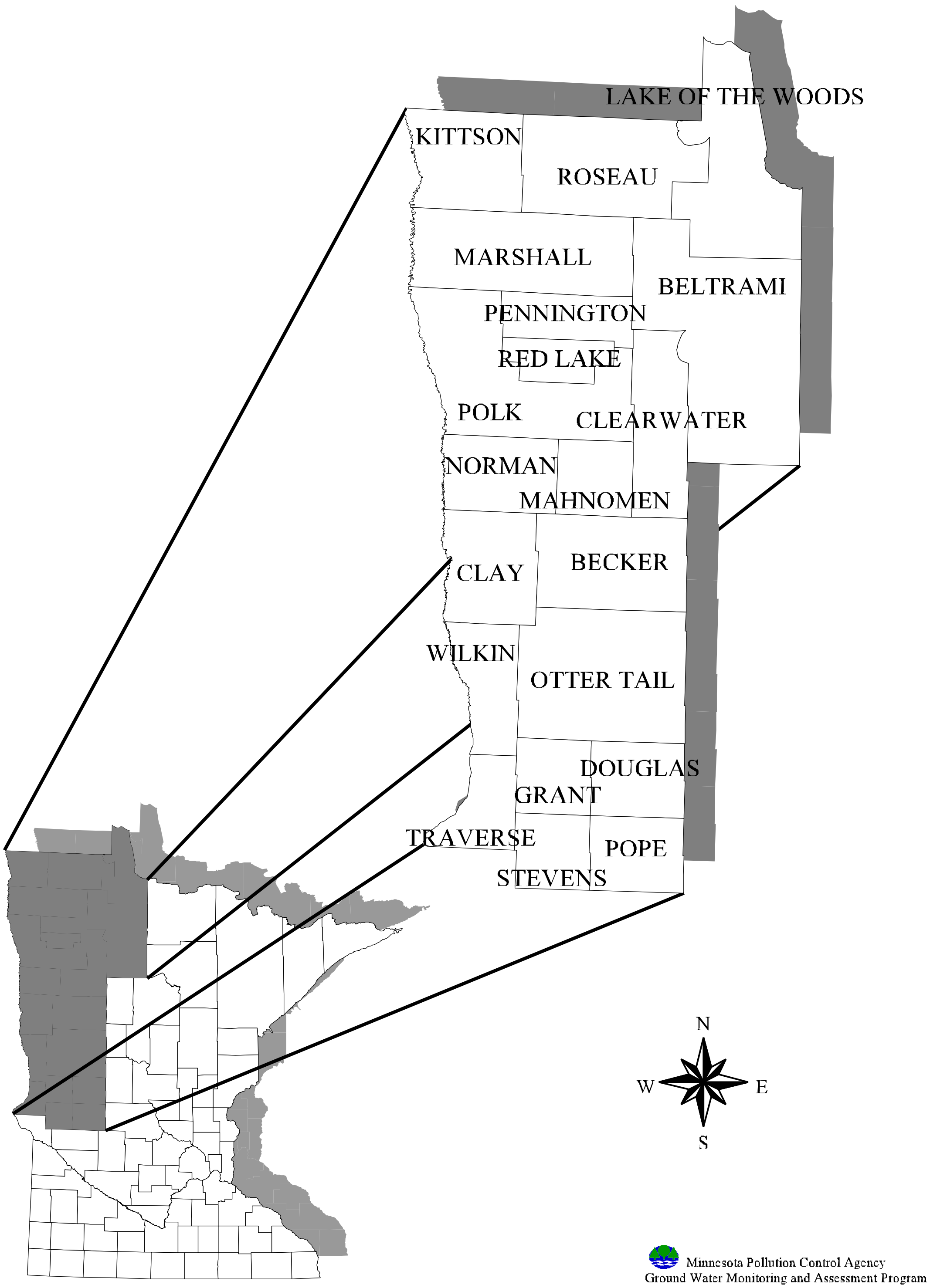


Figure B.2 : Location of wells sampled from Cretaceous (KRET) aquifer.

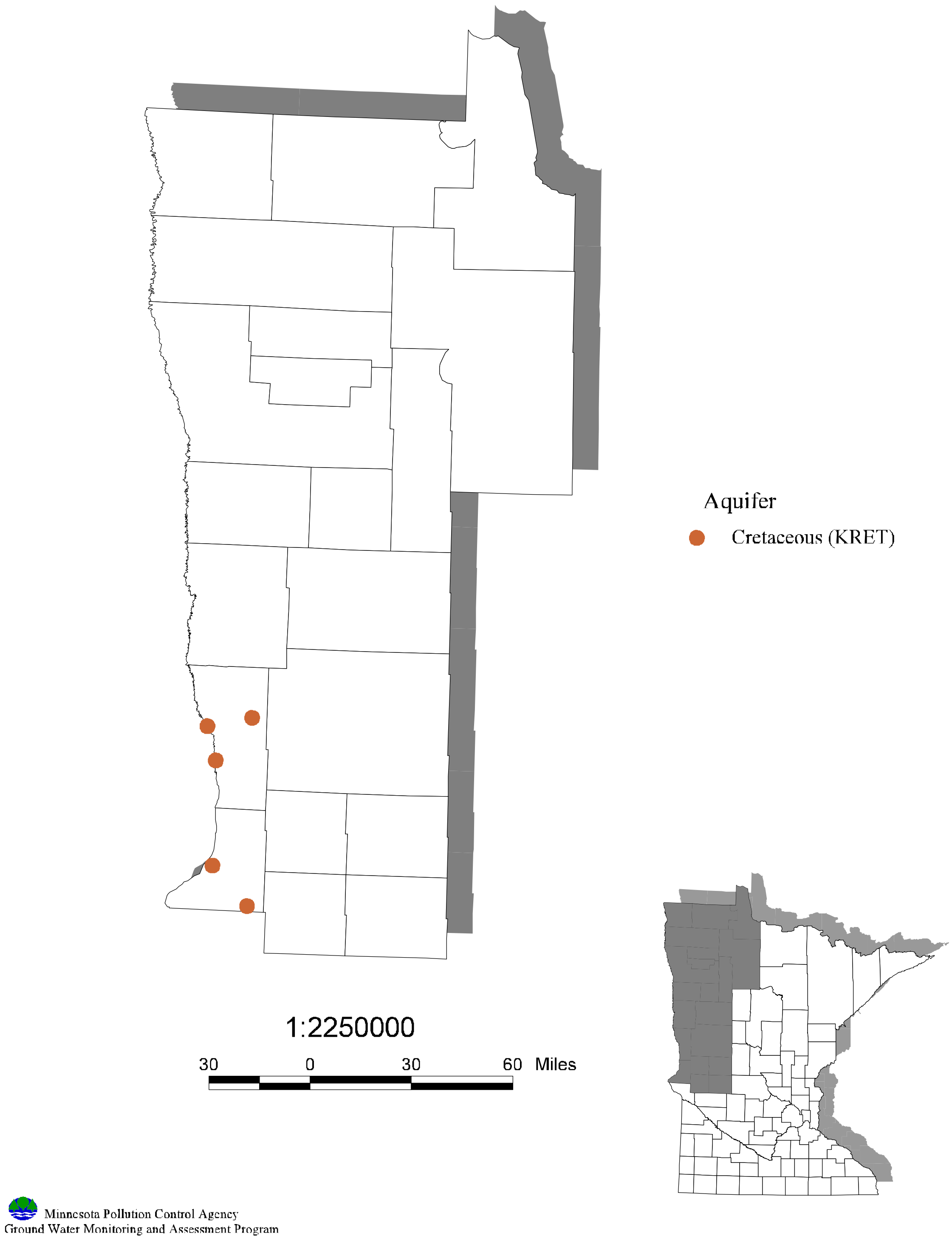


Figure B.3 : Location of wells sampled from surficial Quaternary (QBUA, QWTA) aquifers.

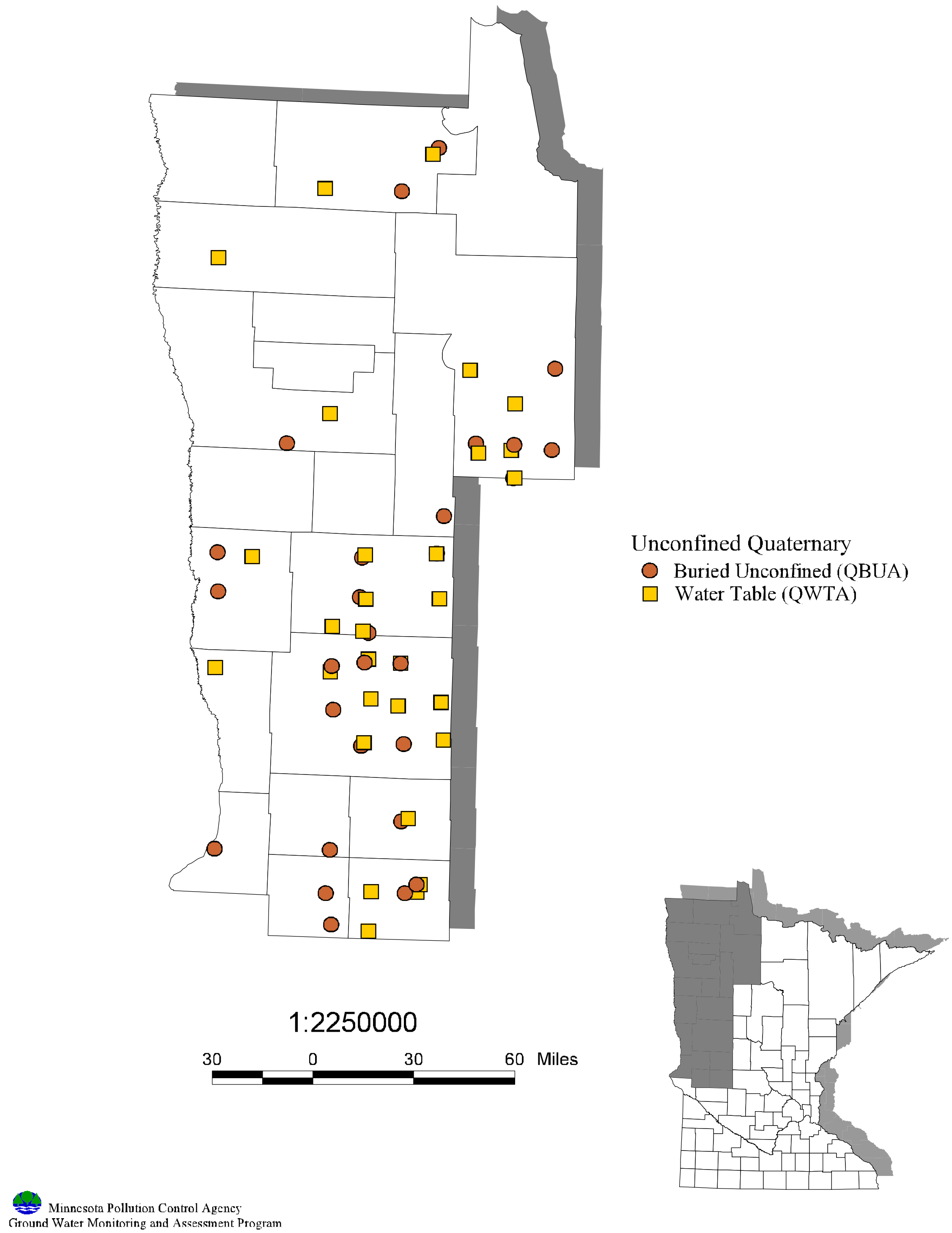


Figure B.4 : Location of wells sampled from Quaternary, buried (QBAA) aquifers.

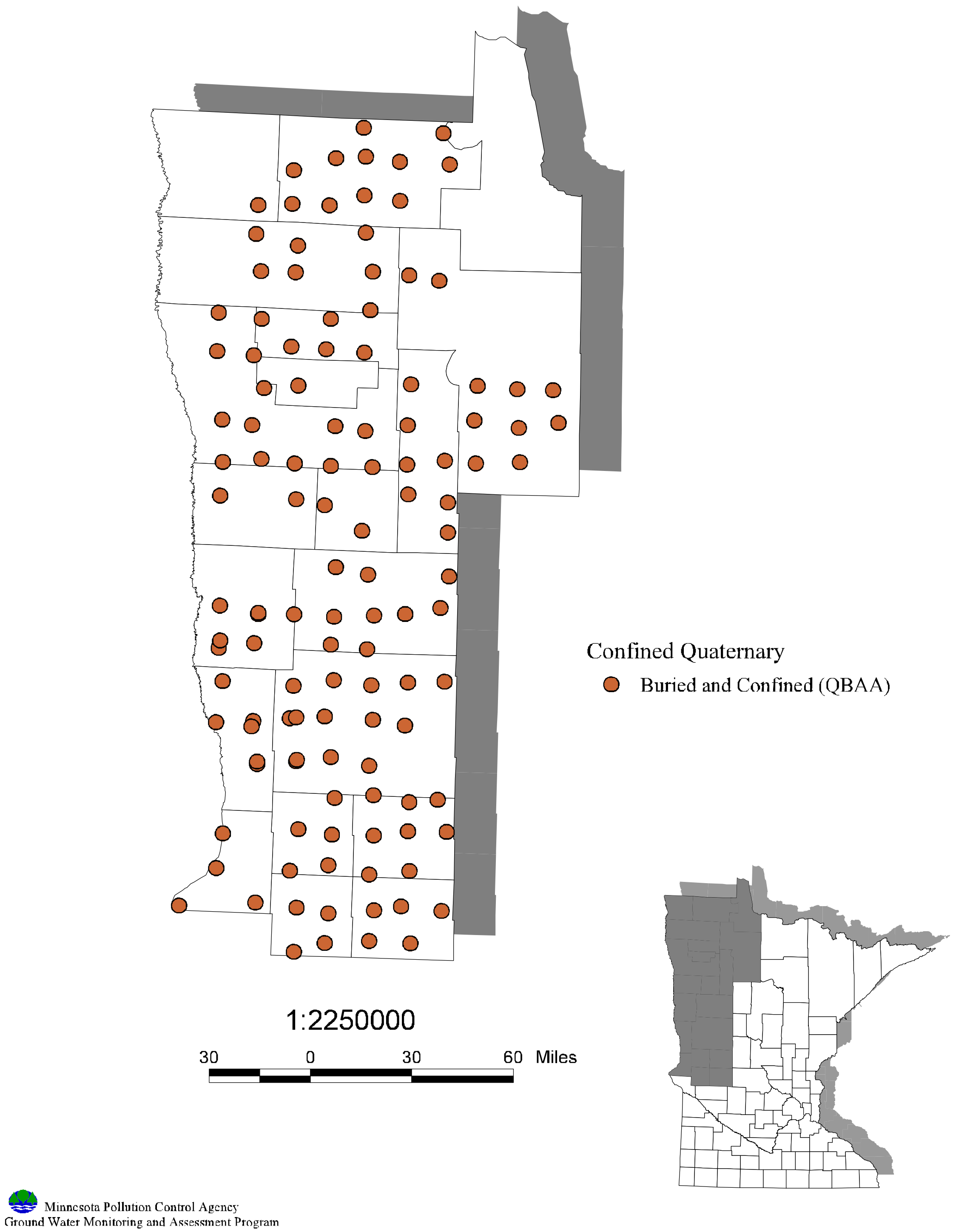
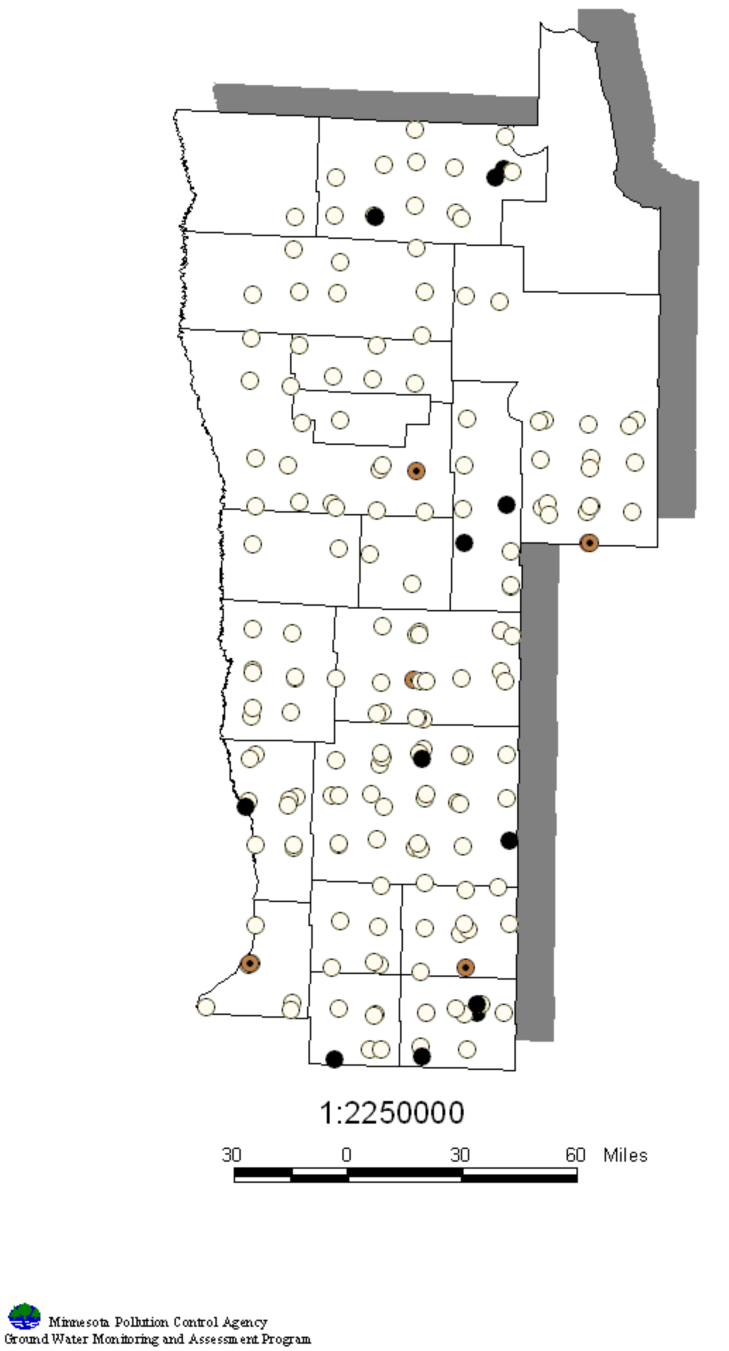


Figure B.5 : Distribution of nitrate in Region 3.



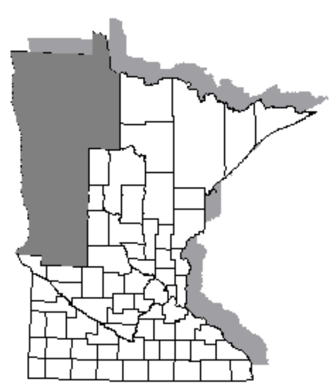


Figure B.6 : Distribution of Volatile Organic Compounds in Region 3.

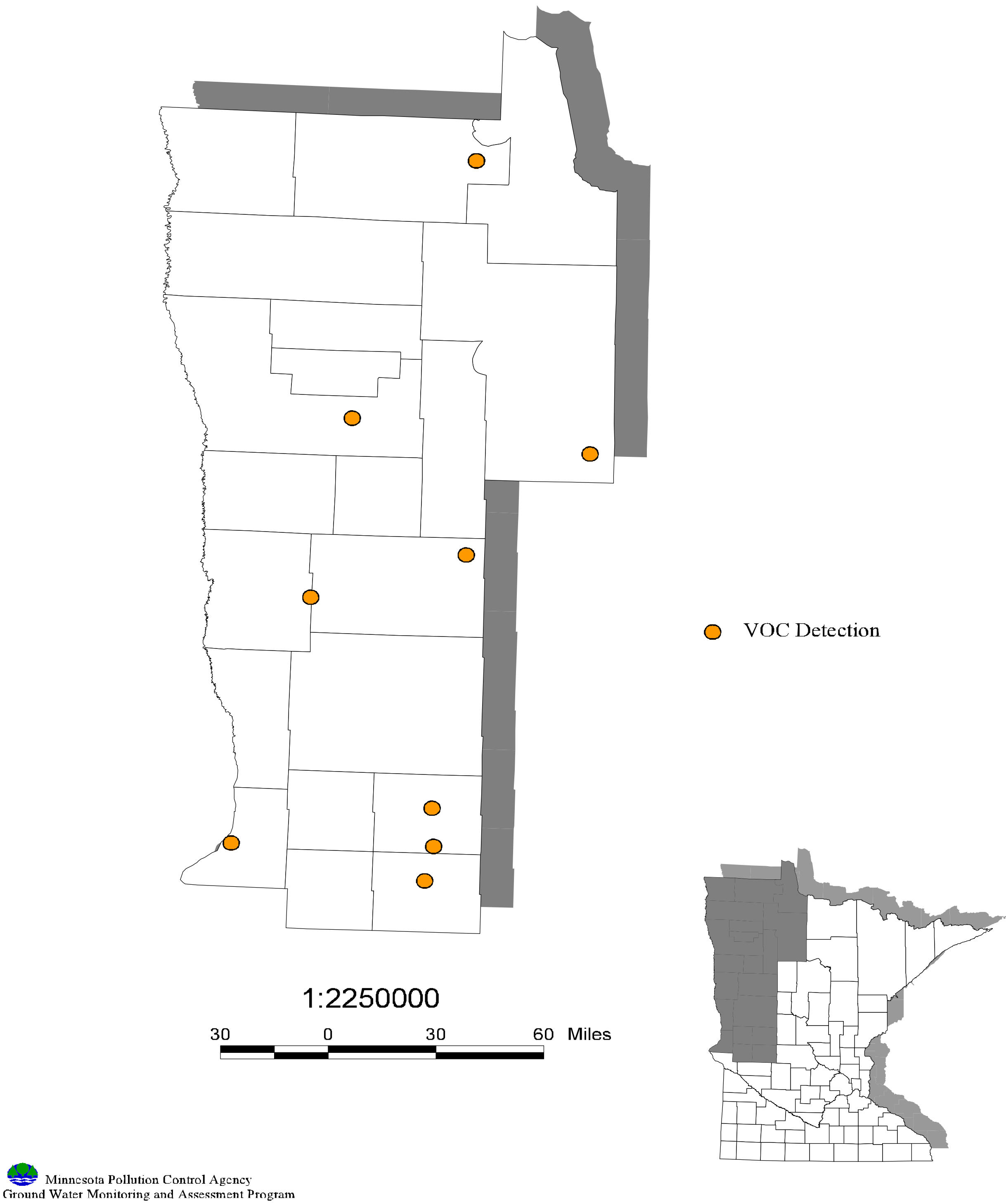


Figure B.7 : Distribution of arsenic in Region 3.

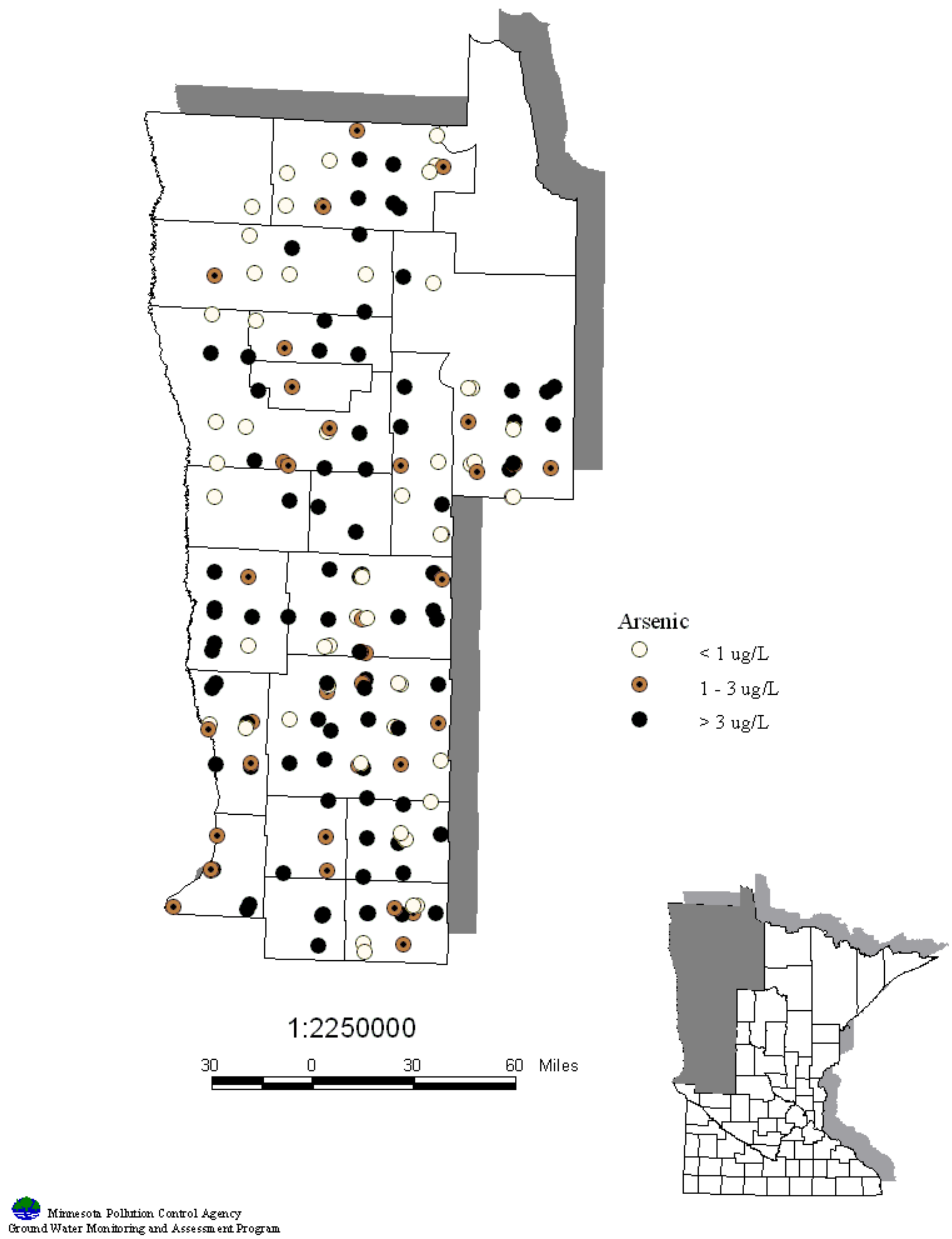


Figure B.8 : Distribution of boron in Region 3. The thick black line represents the easternmost extent of Cretaceous deposits (modified from Meyers et al., 1992).

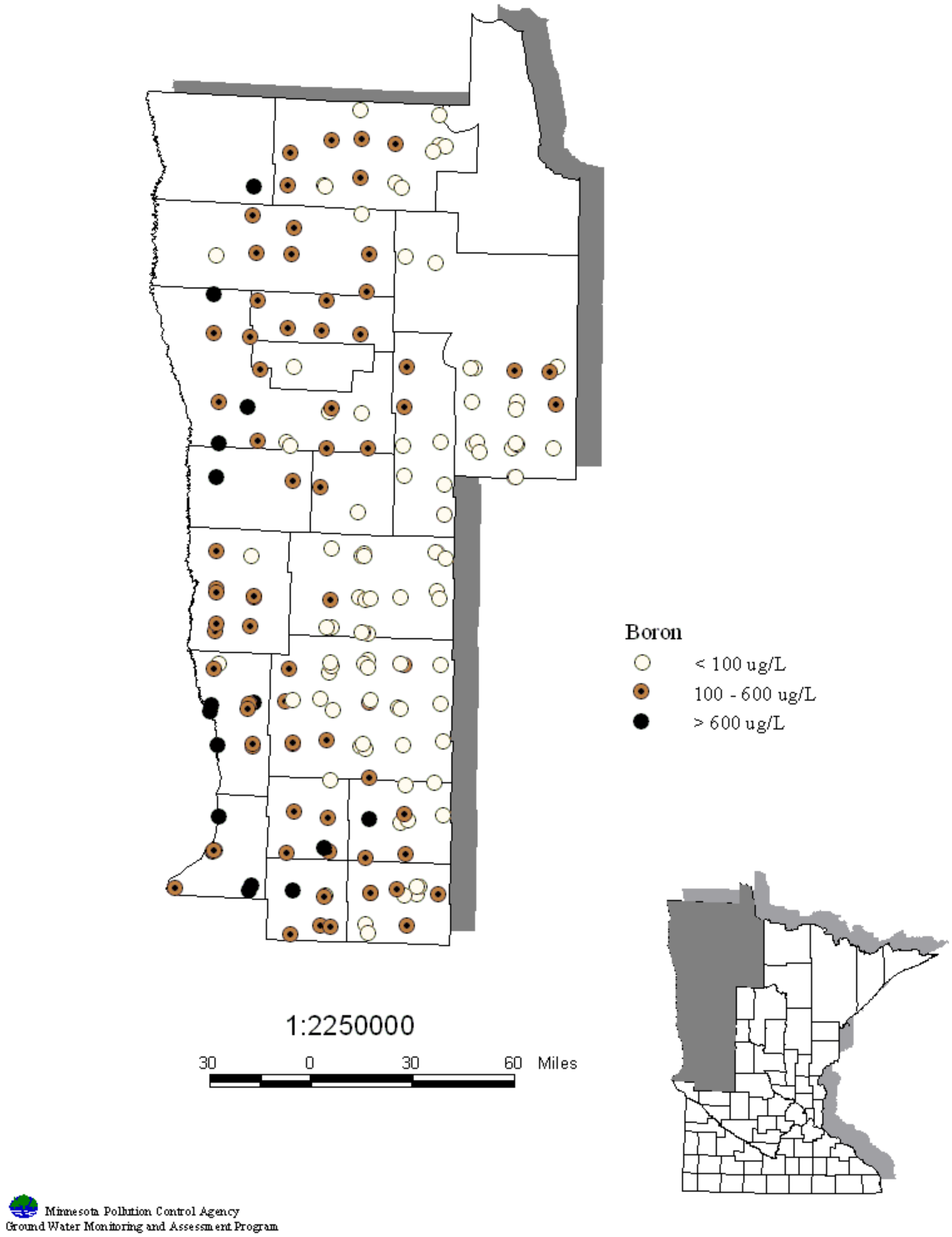


Figure B.9 : Idealized east to west hydrologic cross-section for Region 3.