Baseline Water Quality of Minnesota's Principal Aquifers

SOUTHWEST REGION

Minnesota Pollution Control Agency

Baseline Water Quality of Minnesota's Principal Aquifers - Region 4, Southwest 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 4 in southwest Minnesota. Information in this report, when used in conjunction with *Baseline Water Quality of Minnesota's Principal Aquifers* (MPCA, 1998a), can be used by water resource managers to identify baseline or background water quality conditions in areas or aquifers of concern, prioritize ground water problems, and assist in site decision-making, provided the limitations and assumptions outlined in the document are understood. Although data have been carefully analyzed, compiled, and reviewed independently, mistakes are inevitable with a data set this large. If mistakes are found in this report, please forward them to GWMAP staff. Errata sheets will be prepared as needed.

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

ABBREVIATIONS

CWI - County Well Index

GWMAP - Ground Water Monitoring and Assessment Program

HBV - Health Based Value

HI - Hazard Index

HRL - Health Risk Limit

MCL - Maximum Contaminant Level

MPCA - Minnesota Pollution Control Agency

QA/QC - Quality Assurance/Quality Control

RLs - Reporting Limits

SMCL - Secondary Maximum Contaminant Level

USGS - United States Geological Survey

UTM - Universal Trans Mercator

VOC - Volatile Organic Compound

EXECUTIVE SUMMARY

In 1993 and 1994, the Minnesota Pollution Control Agency's (MPCA) Ground Water Monitoring and Assessment Program (GWMAP) sampled 132 primarily domestic wells in MPCA Region 4, which encompasses southwestern Minnesota. This sampling effort was part of the statewide baseline assessment (baseline study). The objectives of this 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. One well was sampled from each aquifer located within a nine-square mile target area centered on each grid node. Sampling parameters included major cations and anions, 34 trace inorganics, total organic carbon, volatile organic compounds (VOCs), and field measurement of dissolved oxygen, oxidation-reduction potential, temperature, pH, alkalinity, and electrical conductivity. Statewide, 954 wells were sampled from thirty different aquifers.

Ground water quality in southwest Minnesota is controlled by several factors. Water quality in surficial aquifers which receive direct recharge from precipitation is controlled by oxidation-reduction conditions within the aquifers. Concentrations of most chemicals are greater in surficial aquifers of Region 4 than similar aquifers statewide. Nitrate is the primary chemical of concern in these aquifers, which include water-table aquifers and some Precambrian bedrock aquifers (e.g., Sioux Quartzite). If there is a source of nitrogen to ground water (such as agriculture), poor well construction (particularly large diameter wells), fractured bedrock near the land surface, ground water recharge, and screening wells closer to the top of an aquifer are factors which increase the likelihood of having high nitrate concentrations. Water quality of deeper, buried aquifers is controlled by parent material. Concentrations of most chemicals in the buried drift aquifers were much greater than in similar aquifers statewide. Chemicals of potential concern in deeper aquifers include boron, manganese, molybdenum, sulfate, and iron. Concentrations of these chemicals were greatest along the Coteau des Prairie, even though this is not the oldest ground water in the region. Concentrations of most chemicals in Cretaceous aquifers were slightly greater than similar aquifers statewide. Like the buried drift aquifers, concentrations of boron, manganese, molybdenum, sulfate, and iron were greatest along the Coteau des Prairie. Nitrates occasionally exceeded drinking criteria in wells from deep, confined aquifers, but these occurrences appear to be the result of poor well construction.

The primary research needs for Region 4 include:

- developing a conceptual model of regional flow;
- identifying primary recharge and discharge areas and quantities;
- correlating water quality with chemistry of parent material, particularly for boron; and
- defining the geochemical sensitivity of surficial aquifers to nitrate contamination.

Monitoring needs for Region 4 include:

- establishing a centralized data base to expand and update baseline water quality information;
- determining trends in nitrate concentrations of surficial aquifers;
- determining the effectiveness of Best Management Practices on water quality of surficial aquifers; and
- establishing rigorous and uniform field 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 4. Region 4 is located in southwestern Minnesota and includes the counties of Big Stone, Chippewa, Cottonwood, Jackson, Kandiyohi, Lac Qui Parle, Lincoln, Lyon, McLeod, Meeker, Murray, Nobles, Pipestone, Redwood, Renville, Rock, Swift, and Yellow Medicine (Figure B.1). The regional office is located in Marshall.

The following information needs for Region 4 were identified in Myers et. al., 1991:

- long-term water quality monitoring;
- water quality assessments;
- baseline regional water quality;
- impacts from agricultural chemical use, industrial discharges, irrigation, and household hazardous wastes; and
- intensive monitoring in areas that lack alternative water supplies.

Assistance needs were identified in the following areas:

- data collection and interpretation; and
- coordination of existing programs.

The baseline study conducted by GWMAP is ideally suited to fulfilling the informational need of establishing baseline regional water quality data. Information from the baseline study can be used to identify types of long-term monitoring that would be most useful in Region 4. Through analysis of the baseline data, GWMAP provides assistance in the area of data interpretation.

The purpose of this report is to provide baseline water quality information for Region 4. Comparisons are made between water quality in the principal aquifers of Region 4 to that in the remainder of the state. Significant differences in ground water quality between Region 4 and the statewide data were determined, factors contributing to these differences were identified, and potential health implications were investigated. **NOTE: Water quality is a relative term which may have multiple meanings. In this report, water quality typically refers to water chemistry. Specific instances occur where water quality relates to potential effects on humans consuming ground water or general quality of water. The reader should be aware of these different applications of water quality.**

1. BASELINE DESIGN AND IMPLEMENTATION

Design and implementation of the baseline study are described in Myers et. al., (1991) and MPCA (1994, 1995, and 1998a). A systematic grid design was implemented, with sampling nodes spaced at eleven mile intervals. All major aquifers with a suitable domestic well located within a nine square mile area centered on each grid node were sampled. The County Well Index (CWI)(Wahl and Tipping, 1991) was used to provide information on wells within the sampling area. CWI aquifer codes are summarized in Table A.1. Wells were purged until stabilization criteria were met. Sampling parameters included field parameters (dissolved oxygen, oxidation-reduction potential, pH, temperature, electrical conductivity, and alkalinity) major cations and anions, VOCs, total organic carbon, and 34 trace inorganic chemicals. Tritium and pesticides were sampled in select wells. Samples were not filtered. Rigorous analysis of the data was conducted. Sampling and analysis methods are described in MPCA 1996 and 1998b, respectively. Sample locations, by aquifer, are illustrated in Figures B.2 and B.3 for drift and bedrock aquifers, respectively. Sampling is summarized by aquifer in Table A.1 and for all data in Table A.2.

2. ANALYSIS METHODS

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

- establishing descriptive statistics (mean, median, minimum, etc.) for each parameter and each aquifer;
- 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 aquifers; 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.11 for the nine aquifers sampled in Region 4. All concentrations are in ug/L (ppb) except for Eh and redox potential (mV), temperature (^{o}C), pH (negative log of the hydrogen ion concentration), and specific conductivity (umhos/cm). Sample sizes for the Precambrian crystalline (PCCR) and Precambrian undifferentiated (PCUU) aquifers were small and no further discussion of these aquifers is presented. The four samples for the Sioux Quartzite aquifer (PMSX) and four samples for the Quaternary undifferentiated aquifer (QUUU) represent all the samples collected statewide for these aquifers. QUUU wells were separated from other Quaternary groups because analysis of data from these wells indicate water quality in them is significantly different from that in other Quaternary wells (MPCA, 1998a).

Examples of how to use information from Tables A.3 through A.11 in site applications are provided in MPCA, 1998a. To use these data in site applications, the coefficients presented in Tables A.12 and A.13 will be needed. **Mean and median concentrations are considered to represent background concentrations with which site or other local water quality information can be compared.** Upper 95th percent confidence limits and 95th percentiles represent extremes in the distribution for a chemical. The distribution of a chemical indicates whether concentrations need to be log-transformed and whether concentrations below the detection limit will be encountered during subsequent sampling.

3.2. Group Tests

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

Aquifers

Chemical concentrations were compared between the Cretaceous (KRET), Sioux Quartzite (PMSX), buried confined drift (QBAA), buried unconfined drift (QBUA), surficial drift (QWTA), and undifferentiated drift (QUUU) aquifers. Results are summarized in Table A.14. To interpret results in this table, read across a row for each chemical. Median concentrations are given in ug/L (except for Eh, redox, pH, temperature, and specific conductivity). If there are letters after the concentrations, then there were statistically significant differences (at the 0.05 level) in concentrations between aquifers for that parameter. Aquifers with different letters had statistically different concentrations, with increasing concentrations for a given parameter indicated by an increasing letter progression (a, b, c, ...). A simple example is for sulfate. The median sulfate concentration for water table aquifers (QWTA, 96171 ug/L) has a letter “a” following it, while the median concentration for Cretaceous aquifers (KRET, 684153 ug/L) has a “b” after it. These two aquifers had different sulfate concentrations. All other aquifers had concentrations intermediate between the QWTA and KRET aquifers, as indicated by the letters “ab” after the concentration.

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

1. Concentrations of boron, iron, phosphorous, potassium, sodium, strontium, sulfate, total sulfur, total dissolved solids, and nickel were greater in Cretaceous (KRET) aquifers compared to most other aquifers. Eh and concentrations of antimony, barium, nitrate, and selenium were lower. The results reflect the importance of parent material and dissolution time on water quality in the KRET aquifer.
2. Concentrations of antimony, nickel, nitrate, titanium, and Eh were greater in the Sioux Quartzite aquifer (PMSX) compared to most other aquifers. Concentrations of iron, selenium, strontium, and zinc were lower. The primary control on water quality for this aquifer appears to be interaction with

recharge water percolating through the unsaturated zone, as reflected by the high Eh and high concentrations of antimony, nitrate, and nickel. Recharge water is typically well oxygenated, contains lower concentrations of dissolved solids than ground water, and has chemistry reflective of impacts from the soil zone.

3. Concentrations of boron, iron, phosphorus, selenium, sodium, and zinc were greater in the buried drift aquifers (QBAA and QBUA) compared to most other aquifers. Concentrations of nickel, nitrate, and Eh were lower. Concentrations of most chemicals were intermediate. The results reflect the wide range of aquifer conditions encountered in the buried drift aquifers. All other factors being equal, nitrate will be a concern in shallow, oxygenated aquifers and boron, manganese, iron, and sulfate will be a concern in deep, anoxic buried aquifers.
4. Concentrations of barium and selenium were greater in the water table aquifers (QWTA) compared to most other aquifers. Concentrations of boron, potassium, sodium, strontium, sulfate, total dissolved solids, and zinc were lower. These results reflect waters which are relatively young, but it is surprising that concentrations of nitrate, dissolved oxygen, chloride, and Eh were not greater in these aquifers. The reason is probably that most wells are completed in the lower portions of these aquifers, where there is less interaction with processes occurring at the land surface. Water quality of these aquifers will vary dramatically with depth (see point 5 below).
5. Eh and concentrations of antimony, chloride, cobalt, nickel, nitrate, potassium, sulfur, titanium, and zinc were greater in the undifferentiated surficial aquifers (QUUU) compared to other aquifers. Concentrations of barium, boron, and phosphorus were lower. These wells, more than any other, reflect interaction with processes occurring at the land surface. Antimony, chloride, nickel, nitrate, Eh, and possibly potassium all reflect direct inputs from the unsaturated zone. These wells are often large diameter wells which are poorly constructed.

Well Diameter

Concentrations were compared between wells having different well diameters. Results are presented in Table A.15. There are many chemicals for which concentrations differed between well diameter classes, but most of the differences are attributable to different controlling factors in large- and small-diameter wells. Wells with diameters of 24 inches or greater were all used for domestic supply and are dug wells. These wells are prone to leakage along casing joints. These wells receive direct recharge from the unsaturated zone. Consequently, they have high redox potentials (see Section 3.5.3.). Concentrations of nitrate, dissolved oxygen, nickel, selenium, chloride, and antimony are high in these wells. These are all either mobile chemicals or indicators of oxygenated water. Nitrate was the only chemical which represents a health concern in these wells, and median concentrations were at or above the drinking water criteria for nitrate in 24, 30, and 36 inch diameter wells.

The primary control on water quality in small diameter wells (less than 12 inches) is parent material and residence time. Wells from these size classes had greater concentrations of iron, boron, sodium, sulfate, and total dissolved solids compared to wells from other size classes. These are all chemicals which will increase with residence time and reflect the geologic material comprising the aquifer.

Two wells were from the 12 to 16 inch diameter class. Both of these wells are municipal wells and they had chemical signatures different from both the smaller and larger diameter classes. Eh was lowest in these wells. They had very high iron and manganese concentrations and detectable concentrations of nitrate and dissolved oxygen. These results indicate wells which are not in chemical equilibrium, since nitrate and dissolved oxygen would not be expected in wells with high iron and manganese concentrations and low Eh values. Since these are municipal wells, they pump water over a large vertical portion of the aquifer and thus pull in oxidized, nitrate- and oxygen-rich waters from the top of the aquifer as well as reduced, iron- and manganese-rich water from the lower portion of the aquifer. These wells are good candidates for chemical analysis during the period in which they are pumped, since water quality may change with duration of pumping.

3.3. Health and Risk

Drinking water criteria for individual chemicals are summarized in Table A.16. 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.17 and A.18, respectively. **In anticipation of a change in the HRL for**

manganese from 100 ug/L to a value of 1000 ug/L or greater, the drinking criteria for manganese used in this report is modified from the HRL (MDH, 1997). Sample size was not sufficient for the Precambrian (PCCR, PCUU, and PMSX) and undifferentiated drift (QBUU and QUUU) to provide meaningful results. The primary chemical of concern is boron, which exceeded the HRL (600 ug/L) in 42, 31, 11, and eight percent of the wells sampled in the Cretaceous (KRET), buried confined drift (QBAA), buried unconfined drift (QBUA), and surficial drift (QWTA) aquifers, respectively. Nitrate exceeded the HRL (10000 ug/L) in 16, 6, 33, and 25 percent of wells sampled in these four aquifers, respectively. Manganese exceeded 1000 ug/L in 11, 12, 0, and eight percent of wells sampled in these four aquifers, respectively. Other exceedances included vanadium and zinc, each once in KRET aquifers, and antimony once in a QBAA aquifer.

The number and percent of samples exceeding non-health-based ground water drinking criteria are summarized in Tables A.19 and A.20, respectively. Non-health-based drinking water criteria include chemicals with a Maximum Contaminant Level (MCL) or Secondary Maximum Contaminant Level (SMCL). Iron exceeded the SMCL in 74, 100, 67, and 67 percent of the sampled wells in the KRET, QBAA, QBUA, and QWTA aquifers. Other exceedances included sodium in the KRET (four wells) and QBAA (five wells) aquifers, sulfate in the KRET (13 wells), PCUU (one well), PMSX (two wells), QBAA (28 wells), QBUA (two wells), QBUU (one wells), QUUU (two wells), and QWTA (one well) aquifers, and aluminum in the KRET (three wells) and QBAA (three wells) aquifers.

Some chemicals have the same toxic endpoint. For example, Table A.16 indicates that barium and nitrate both affect the cardiovascular/blood system. A useful calculation is to estimate the probability that chemicals with the same endpoint will exceed drinking water criteria. To make this calculation, a hazard index (HI) is used to add the contribution of each chemical with similar endpoints:

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

where C represents the concentration (ug/L) of a chemical. If the HI exceeds 1.0 in an individual well, further investigation is recommended to evaluate the potential factors controlling chemical concentrations and the validity of the exposure assumptions. These calculations were not made for this report, primarily because there are a limited number of samples for all aquifers except the buried drift. The calculations would therefore be potentially misleading. These calculations were made for statewide data and are reported in MPCA, 1998a.

3.4. Aquifers

The hydrology and geology of Region 4 is described in numerous reports. The Hydrologic Investigations Reports for the Rock River (Anderson et. al., 1976a), Des Moines River (Anderson et. al., 1976b), Cottonwood River (Broussard et. al., 1973), Yellow Medicine River (Novitzki et. al., 1969), and Redwood River (Van Voast et. al., 1970) watersheds provide information about climate, the water budget, surface water, and ground water. Precipitation across the region varies from about 26 inches in the east to 22 inches in the west. Annual runoff to surface rivers (ground water recharge) varies from more than four inches in the east to less than two inches in the west. Annual recharge to surficial aquifers is likely to be greater than these amounts, but will vary widely with annual precipitation. Most of the major rivers in the region are gaining streams in that they have a baseflow component (ground water discharges to them).

The geology and ground water hydrology of an area as vast as that covered by Region 4 is complex. The entire region is underlain by rocks of Precambrian age. These rocks form a nearly impermeable boundary to ground water flow, with only a small number of wells intercepting fractures within these rocks. Cretaceous bedrock covers approximately eighty percent of the region, being absent where Precambrian bedrock is near the land surface. Cambrian bedrock occurs in the extreme eastern portion of the region. A discussion of effects of individual deposits on water quality is beyond the scope of this paper. However, when specific water quality issues are considered, characteristics of the bedrock are important. For example, Setterholm (personal communication) suggests that the Pierre Shale, although limited in extent in southwest Minnesota, may be an important component of drift and impact water quality in this area of the state.

Quaternary deposits cover almost the entire area and range in thickness from a few feet to several hundred feet. Most of the Quaternary material consists of fine-textured till (unsorted, unstratified sediment that has been transported or deposited by a glacier). Scattered buried sand and gravel outwash deposits occur within the till and serve as the primary source of ground water in the region. Modern streams and rivers follow former glacial melt channels. Consequently, outwash deposits, which make up the sand and gravel aquifers, are typically found adjacent to modern streams and rivers.

Today, ground water originates as precipitation which percolates through the soil and vadose zone and into the saturated zone (ground water). Little information exists to identify where regional ground water originates. Potential important recharge points include topographic highs (such as along the Bemis Moraine), surficial sand and gravel deposits, and along the interface between Precambrian bedrock and overlying deposits. Regional ground water flow is also poorly understood. Numerous hydrogeologic cross-sections in the United States Geological Survey (USGS) Hydrologic Investigations

Reports indicate predominantly downward flow through the Quaternary deposits and into Cretaceous bedrock. However, ground water discharge may occur along the Precambrian bedrock surface and in areas of ground water discharge, such as along streams and rivers.

Although there is a large amount of water quality information in the literature, there has been no systematic attempt to identify water quality relationships between the various geologic units. Water quality varies widely throughout the region. Information regarding the locations of various geologic deposits, including chemical analysis for a wide range of parameters, were reported by Patterson (1995) and Patterson et. al., (1995). However, a conceptual flow model for the regional flow system, identification of primary recharge and discharge points and quantities, estimation of travel times, and correlations between chemistry of tills and water chemistry must be completed to determine which geologic and hydrologic controls are most important for ground water quality.

Buried and surficial drift aquifers comprise the most important source of ground water in Southwest Minnesota. Locally, Cretaceous aquifers are important sources of drinking water. Less important are Precambrian aquifers, including the Sioux Quartzite and crystalline aquifers. Consequently, four aquifer groups are discussed - the buried drift, the surficial drift, the Cretaceous, and the Precambrian.

3.4.1. Buried Drift Aquifers

Most wells in Southwest Minnesota are completed in Quaternary sand and gravel (drift) deposits (Bradt, 1997). Quaternary sediments (drift) represent several glacial advances and retreats which occurred over the last two million years. During each retreat, water from the melting ice left behind sand and gravel deposits (outwash) which tend to form long, narrow channels oriented parallel or perpendicular to northwest-southeast trending end moraines. Subsequent glacial events buried these deposits beneath confining materials such as till and lacustrine sediments. Water within these deposits is therefore considered to be buried and may be under confined conditions. Two aquifers make up the buried drift aquifer group. These are buried, confined drift aquifers (QBAA) and buried unconfined drift aquifers (QBUA). A third aquifer group, the buried undifferentiated aquifers (QBUU) are not considered in this analysis because there were only three samples collected from them.

Buried sand and gravel deposits act as independent aquifers. However, taken as a whole, these buried aquifers form a regional hydrologic system in which water moves vertically and horizontally in response to differences in hydraulic potential (Anderson et. al., 1976a). Movement of water within the deeper portions of this system is slow because of the low permeability of most of the glacial deposits. Most ground water greater than 100 feet below the land surface is relatively old. Bradt (1997) estimated ground water ages, based on carbon-14 dating, of 5,000, 10,000, 17,000, and 24,000 years before present in wells 215, 193, 390, and 320 feet deep. These dates do not precisely fit the model of increasing age with depth.

Ground water flow in Southwest Minnesota is complex for several reasons:

- Precambrian bedrock aquifers (PMSX) crop out in some areas and may act as points of focused recharge;
- Cretaceous bedrock underlies much of the area and can affect water quality in areas where Cretaceous and drift aquifers interact;
- a surface water divide runs approximately northwest to southeast through the region, with water to the northeast discharging to the Minnesota River and water to the southwest discharging to the Missouri River;
- although downward flow appears to occur through much of the region, upward flow may occur locally near surface water discharge points (predominantly rivers) or where there are large changes in surface or bedrock topography;
- there are many buried bedrock valleys which are not yet mapped and have significant effects on local hydrology; and
- surficial aquifers occur locally, but their relationship with the deeper drift aquifer system is unknown.

Extensive hydrologic information, including climatic data and both surface and ground water data, can be found in the USGS watershed reports from the area (Anderson et. al., 1976a; Broussard et. al., 1973; and Novitzki et. al., 1969; Van Voast et. al., 1970).

Data from various reports are summarized in Table A.21. Data from the GWMAP baseline study is included. Median concentrations are provided. **Caution should be exercised when reviewing data from the literature. Mean concentrations and standard deviations are often represented in these reports, but these reflect simple arithmetic values. In this context, they have no meaning because the data are generally not normally distributed and non-detections are either eliminated or assigned arbitrary values during the analysis. A general rule of thumb is if the mean and median are relatively close and there were no values below the reporting limit (RL), then the mean and standard deviations are reasonable values. If the mean and median are far apart or there were values below the RL, the mean concentration and standard deviation are misleading. Mean concentrations reported in this paper were determined with rigorous statistical methods and are considered to be accurate.**

The data presented in Table A.21 indicates reasonable correlation between the different studies. The USGS watershed reports tend to focus on shallow ground water systems more than either the Regional Assessment or the GWMAP baseline study. This accounts for the lower values for total dissolved solids, calcium, magnesium, sulfate, and the higher values for nitrate, chloride, and possibly boron. Two important conclusions can be drawn from Table A.21. First, there are sufficient data to assess regional water quality conditions. Second, rigorous analysis of the GWMAP data can be performed and applied to Southwest Minnesota since the baseline data appear to be within ranges defined from previous studies. This is important because GWMAP sampling and analysis techniques are well documented in MPCA, 1996 and 1998b. The data can therefore undergo a much more intensive analysis than would be possible for the other data sources.

Concentrations of most chemical parameters are greater in buried drift aquifers of southwest Minnesota than in similar aquifers statewide (see Tables A.7 and A.8). The greatest differences were for, in decreasing order, sulfate, boron, lithium, sodium, strontium, total dissolved solids, and manganese. Concentrations of calcium, magnesium, iron, potassium, arsenic, antimony, zinc, selenium, chloride, cobalt, total organic carbon, nitrate, copper, cadmium, molybdenum, and vanadium were also greater in the buried, confined aquifers of Southwest Minnesota compared to the remainder of the state. Eh and concentrations of orthophosphate were somewhat lower compared to the statewide values. Ground water ages reported by Bradt (1997) were in the range of 5,000 to 25,000 years before present, which are close to the values of 5,000 to 23,000 years before present reported from similar aquifers in the southern Red River Valley of Minnesota (Trojan, 1998). Despite this, the water chemistry in these regions of the state differs, with much greater concentrations of most chemical parameters in Southwest Minnesota. These data suggest different geochemical controls on water quality in Southwest Minnesota, probably associated with parent material and climate (recharge).

From a human health perspective, boron represents the largest concern in buried, confined drift aquifers. The median concentration of 342 ug/L is more than half of the drinking water criteria (HRL = 600 ug/L). Thirty-one percent of sampled wells exceeded the drinking criteria. Other chemicals which may represent health concerns include manganese, nitrate, and molybdenum. The median manganese concentration of 280 ug/L is 28 percent of the criteria used in this report (1000 ug/L). Twelve percent of sampled wells exceeded 1000 ug/L. Six percent of sampled wells exceeded the HRL for nitrate (10000 ug/L), but the median concentration for nitrate was less than 500 ug/L. Incidence of high nitrate concentration are apparently localized. There were no exceedances of the drinking criteria for molybdenum (30 ug/L), but the median concentration of 5.3 ug/L is greater than 28 percent of the HRL. Sulfate, which does not have a health-based criteria [Maximum Contaminant Level (MCL) = 500000] but does impart a bad taste and odor to water and has laxative effects, is also a concern for domestic supply. The median concentration of 362760 ug/L is about 72 percent of the MCL. The MCL was exceeded in 28 percent of sampled wells. Iron also does not have a health-based criteria [Secondary Maximum Contaminant Level (SMCL) = 300 ug/L], but can stain plumbing fixtures and is important in its effect on the distribution of many other chemicals. The SMCL was exceeded in all samples from the buried drift. The median concentration of 2018 ug/L is about seven times greater than the SMCL. An additional concern is hardness, primarily caused by calcium and magnesium. The median hardness of 607000 ug/L as $CaCO_3$ is considered to be very hard and will cause scaling of pipes unless softened.

Boron, iron, manganese, molybdenum, nitrate, and sulfate were retained as chemicals of concern for further analysis. Correlation coefficients between these chemicals of concern and several water quality parameters are summarized in Table A.22. The water quality parameters can roughly be divided into major cations and anions (calcium, magnesium, barium, strontium, chloride, sodium, and alkalinity), oxidation-reduction parameters (Eh and dissolved oxygen), location data [Universal Trans Mercator (UTM) coordinates], well information (well depth and diameter), total dissolved solids, and tritium. A correlation coefficient describes the percentage of variability in a chemical concentration which can be accounted for by the independent variable. For example, the correlation coefficient between boron and barium was -0.684. Because the sign is negative, boron concentrations decrease with increasing barium concentrations. About sixty-eight percent of the variability in boron concentrations can be explained by concentrations of barium.

All correlations in Table A.22 were significant at a level of 0.05 (five percent), except where indicated. Generally, correlation coefficients between -0.500 and 0.500 are not considered to be very strong, even if they are statistically significant. Most of the correlations fell within this range of values. Some conclusions derived from Table A.22 are summarized below.

1. Calcium and sulfate showed a very strong relationship. This suggests that gypsum ($CaSO_4$) is an important source of sulfate in ground water. Gypsum was identified in core samples from till (Patterson, personal communication). The relationship between calcium and sulfate is strong enough to allow prediction of sulfate concentration based on calcium concentration and is given by:

   Sulfate (in ug/L) = 2.85 * calcium (in ug/L).

   The molar ratio for this relationship is 1.2, which is close to the ratio of 1.0 that would result if gypsum accounted for all sulfate and calcium. The primary control on sulfate and calcium concentrations is therefore parent material (i.e., gypsum) and not ground water residence time.

Sulfate in equilibrium with gypsum would have a concentration in excess of 1000000 ug/L, more than twice the MCL of 500000 ug/L. There are no effective controls for sulfate in most aquifers in Southwest Minnesota and ground water is undersaturated with respect to sulfate. Increased residence time will lead to increases in concentration of sulfate. Lower sulfate waters would therefore be expected in younger ground water or in areas where gypsum is not controlling sulfate concentrations. Barium, which substitutes for calcium in many minerals, may locally provide an effective solubility control, but concentrations of barium are generally too low for this reaction to be important.

2. Nitrate was poorly correlated with most parameters, but was positively correlated with chloride. This may be due to agricultural inputs from animal manure application in agricultural fields. The best indicators for nitrate were redox parameters, well diameter, and geographic location, although geographic location is also related to redox parameters. Nitrate increases to the west, to the south, in oxygenated ground water, and in larger diameter wells. The occurrence of nitrate in ground water therefore appears to be more closely related to its stability in ground water than to inputs of nitrogen.
3. Boron was most strongly correlated with sodium and potassium, although a strong negative correlation was observed with barium. Boron is present in the minerals kernite ($Na_2B_4O_7 \cdot 4H_2O$), tourmaline [$(Na,Ca)(Li,Mg,Al)(Al,Mn,Fe)]_6(BO_3)$, and sodium tetraborate. These minerals may account for the strong correlation between sodium and boron concentrations. The correlation with potassium suggests Cretaceous deposits may have an influence on boron concentrations in the buried drift aquifers, although till may have significant quantities of Cretaceous material as a result of glacial weathering. Figure B.4 illustrates the distribution of boron in Region 4. Although elevated boron concentrations were found throughout much of southwest Minnesota, the greatest concentrations were found along an approximate northwest-southeast trend centered through the region. This coincides with units mapped as Hummocky Highlands and the Coteau Slope (Patterson, 1995). However, there is also a bedrock high approximately centered on the western edge of this region. Consequently, it is unclear if the drift deposits are the source of boron, particularly if there is considerable Cretaceous material within the drift deposits, or if ground water is moving along the bedrock interface and then discharging upward through Cretaceous deposits into the drift. Additional chemical information for the till and Cretaceous deposits would provide useful information into the mechanisms leading to elevated boron concentrations.
4. Manganese concentrations were most strongly correlated with calcium. The lack of correlation with redox parameters was surprising, since manganese is typically found at low concentrations in oxidized ground water and increases in concentration as ground water becomes more reducing. Concentrations of manganese in glacial deposits of Southwest Minnesota were typically less than

1000 mg/kg (Patterson, 1995), but some samples were as great as 2500 to 3500 mg/kg. Calcium concentrations in these samples appeared to correlate well with manganese. If carbonates are the source of manganese, concentrations of manganese should be about 1000 ug/L (MPCA, 1998a). The concentrations of manganese in parent material suggests that manganese concentrations, which are on average well below 1000 ug/L, are being controlled by some other process such as adsorption or co-precipitation with iron, aluminum, and organic matter. Residence time appears to be a secondary factor, since the correlations with major cations, anions, and total dissolved solids were weak.

5. Molybdenum showed poor correlations with most parameters. The strongest correlations for molybdenum are not included in Table A.22. They include copper, titanium, and vanadium. These are metals with which molybdenum is likely to form metal ores. Consequently, the distribution of molybdenum in ground water is controlled by parent material. Molybdenum dissolution from these parent materials is very slow, as indicated by the poor correlation with major cations and anions. Patterson (1995) showed that concentrations in source tills were less than 8 mg/kg, although concentrations were highly variable. There was no apparent distribution pattern for molybdenum in ground water, except that low concentrations were observed in the eastern portion of the region where Cambrian sandstone deposits occur. Molybdenum alone does not appear to represent a health concern since there were no exceedances of the HBV (30 ug/L), but concentrations in buried drift aquifers of southwest Minnesota are elevated. Consequently, molybdenum may contribute significantly to overall risk if other chemicals with the same toxic endpoint occur at elevated concentrations (e.g., cadmium, tin, and some organic chemicals).

6. Iron exceeded the SMCL of 300 ug/L in all samples. However, it is unclear what species of iron were present in ground water since samples were not filtered. Iron is important in redox reactions in ground water and high concentrations of reduced iron (+2) results in staining of plumbing fixtures. It is therefore important to identify the form of iron present. Although iron was correlated with Eh (a measure of oxidation-reduction potential), the strongest correlation was with total suspended solids. This correlation was strong enough to allow prediction of the concentration of iron based on total suspended solid concentrations:

   Iron (in ug/L) = 0.30 * total suspended solids (ug/L).

Surprisingly, this relationship held across the entire range of iron concentrations, meaning that thirty percent of iron is associated with suspended material in ground water samples taken from the buried drift aquifers. Like many constituents, concentrations of iron were greatest along the Hummocky

Highlands and Coteau Slope (Patterson, 1995). Since this is suspected to be an area where the regional ground water system is being recharged and ground water should be relatively young, the primary controls on iron concentration are parent material and redox conditions.

Figure B.5 illustrates dissolved oxygen and Eh within the buried drift aquifers of Region 4. The Hummocky Highland and Coteau Slope areas show the greatest concentrations of oxygen and the highest Eh values, supporting these areas as sources of recharge for the regional ground water system. However, these areas consistently show the greatest concentrations for most chemicals of concern. Because concentrations of most chemicals are greatest in aquifers which reflect the youngest water in the buried drift system, ground water quality in the buried drift aquifers of Region 4 appear to primarily be controlled by the chemistry of parent material. It is unclear if the vadose zone materials, saturated tills, or Cretaceous deposits are the source of these chemicals of concern. The lack of a depth relationship for most parameters, weak correlations involving the major cations and anions, and lack of a regional flow model hamper an understanding of the processes which most likely lead to poor water quality. Increasing residence times certainly lead to an increase in concentrations of most chemicals, but the overall effect of residence time appears to be less important than parent material. Redox reactions appear to have limited impact on the distribution of most chemicals of concern, with the exception of nitrate.

3.4.2. Surficial Drift Aquifers

Well-sorted surficial outwash, crevasse fillings, and terrace gravel were deposited during the last glacial advance and retreat of the Des Moines lobe. The outwash was deposited in a network of long and narrow melt-water channels that commonly are followed by present stream courses. These major outwash deposits constitute the surficial aquifers in much of Southwest Minnesota. These aquifers generally contain sufficient saturated material to yield large quantities of water, but yield varies laterally and decreases toward the edge of the aquifers. They are unconfined and hydraulically connected to streams (Adolphson, 1983). They are limited in extent and are vulnerable to contamination from human activity at the land surface (Bradt, 1997). Extensive hydrologic information, including climatic data and both surface and ground water data, can be found in the USGS watershed reports from the area (Anderson et. al., 1976; Broussard et. al., 1973; and Novitzki et. al., 1969; Van Voast et. al., 1970).

Two aquifers comprise the surficial drift group. These are water-table wells (QWTA) and undifferentiated wells (QUUU). Most of the QUUU wells are large diameter (greater than 16 inches). The following discussion focuses on the QWTA wells.

Water quality information for surficial drift aquifers in southwest Minnesota, including GWMAP data and data from two other studies, is illustrated in Table A.23. These aquifers generally are oxygenated, contain detectable nitrate, have relatively high oxidation-reduction potentials, and have relatively low concentrations of iron, manganese, and total dissolved solids compared to buried drift aquifers. However, the water quality of surficial drift aquifers in Region 4 differs significantly compared to similar aquifers in other areas of the state. In particular, concentrations of sulfate, lithium, antimony, strontium, boron, and chloride are elevated in Southwest Minnesota. In addition, concentrations of sodium, copper, vanadium, potassium, total dissolved solids, magnesium, bicarbonate, calcium, fluoride, nitrate, and dissolved oxygen are also greater in Southwest Minnesota compared to the rest of the state, while only aluminum, chromium, and possibly manganese are lower in concentration.

Water quality information from surficial aquifers in this region of Minnesota is generally lacking. The report by Adolphson (1983) provides information on the distribution and potential yield of several of these aquifers, but chemical interpretations are limited. These aquifers are an important source of ground water, particularly with the expansion of rural water systems. However, they are extremely vulnerable to contamination by nitrate because of potential high nitrogen inputs and the oxidizing conditions within the aquifers. They may also be sensitive to elevated concentrations of other water quality parameters if they are pumped heavily, thus inducing inflow of water from buried drift aquifers.

The water quality summary for water-table aquifers (Table A.11) indicates median concentrations of iron (811 ug/L) which exceed the SMCL (300 ug/L). The mean vanadium concentration of 9.5 ug/L is about 20 percent of the HRL (50 ug/L), although there were no exceedances of the drinking criteria. The HRL for nitrate was exceeded in three of the eleven wells sampled, while the HRL for boron was exceeded in one well. A concentration of 1000 ug/L for manganese was exceeded in one well. The MCL of 500000 ug/L for sulfate was exceeded in one well. In general, water quality within the surficial aquifers was good despite the elevated concentrations of many constituents compared to the remainder of the state. However, these results may be somewhat misleading since rural water systems and other municipal supplies were not sampled. This may account for the greater nitrate concentration in the study by Adolphson compared to the GWMAP data.

Assuming nitrate, iron, sulfate, manganese, vanadium, and boron are chemicals of concern, correlations for these chemicals are illustrated in Table A.24. There were fewer significant correlations than for the buried drift aquifers. Water table aquifers are more responsive than buried drift aquifers to processes occurring in the vadose zone. Redox processes are a more important control on water quality in surficial aquifers than either parent material or residence time. The following conclusions were developed for the water-table aquifers.

1. Boron correlations were greatest with calcium, strontium, sodium (all positive), and barium (negative). Boron concentrations in general were relatively low, except for the single exceedance of

the HRL. This well had very high concentrations of total dissolved solids, manganese, calcium, and sodium. It is possible the well is either misclassified or is located in glacial deposits rich in boron-bearing minerals, as suggested by the elevated concentrations of sodium and calcium. Assuming this well is an anomaly, boron does not appear to represent a health concern in water table aquifers.

2. Iron showed poor correlations with most parameters. The most significant correlation was with Eh and this relationship was negative. A negative correlation was also observed with well diameter. Iron concentrations increased to the east and north, perhaps reflecting increased residence times and subsequently, greater dissolution of parent materials. The relationship with suspended solids was strong and was described by:

   Iron (in ug/L) = 0.21 * total suspended solids (in ug/L).

   The relationship was not as strong as for the buried drift aquifers, but this may be due to the much smaller sample size. Although iron concentrations exceed the SMCL in most wells, they are lower than observed for the buried drift aquifers. The low iron concentrations in general appear to reflect aquifers which are highly oxidized.

3. Manganese concentrations showed no highly significant correlations with the parameters listed in Table A.24. The greatest correlation was with nitrate (-0.80). This is an important result. Manganese and nitrate form a redox boundary, with more oxidizing conditions being reflected by the presence of nitrate. Once nitrate disappears, manganese concentrations begin to increase as manganese controls the redox of the system. However, the manganese redox window is small. The highly significant correlation between nitrate and manganese suggests that surficial aquifers in Southwest Minnesota have redox conditions which are variable and potentially affect the stability of nitrate. Since nitrate is by far the most important chemical of concern in the surficial aquifers, it is important to know if conditions within the aquifer will lead to denitrification and therefore a reduction in nitrate concentrations. Manganese, which is easily estimated in the field with sampling kits, is a potentially valuable indicator of these conditions.

4. Nitrate was most highly correlated with Eh, again reflecting the dominant role oxidation-reduction reactions have on the stability of nitrate in ground water. Nitrate was also highly correlated with well diameter, increasing in concentration as well diameter increases. Chlorides were also positively correlated with nitrate, probably reflecting agricultural inputs from land application of animal waste. The correlations with geographic location, which show nitrate increasing in concentration to the south and to the west, are probably related more to increasing nitrate stability in ground water than to

increasing inputs of nitrogen associated with agriculture. On the contrary, nitrate inputs from agriculture may decrease to the south and west due to increased production of small grains, more dryland farming, and more land being preserved through the Conservation Reserve Program (CRP).

5. Sulfate was most strongly correlated with calcium. This was the same pattern observed for the buried drift aquifers, although the median sulfate concentrations were lower than for the buried aquifers. Sulfate concentrations could be predicted from calcium concentrations:

   Sulfate (in ug/L) = 1.82 * calcium (in ug/L).

   Again, the molar ratio of 0.76 is close to the theoretical value of 1.0, but the ratio is lower than that calculated for the buried drift aquifers. Surficial drift aquifers statewide had a median sulfate concentration of about 13000 ug/L, well below the median value of about 100000 ug/L in surficial drift aquifers of Southwest Minnesota. Gypsum appears to be controlling the concentration of sulfate in surficial drift aquifers of Southwest Minnesota.

6. Vanadium showed a number of weak correlations, but it was strongly correlated with Eh. Vanadium behaves as an anion and will therefore be mobile within the unsaturated zone. The correlations with well depth, calcium, strontium (all positive), and barium (negative) suggest that percolating recharge water is the primary source of vanadium to ground water. Like molybdenum in buried drift aquifers, vanadium by itself does not appear to represent a health concern. However, vanadium will contribute significantly to overall risk in wells where chemicals with the same toxic endpoint occur.

3.4.3. Cretaceous aquifers

Cretaceous sediments overlie Precambrian rocks in approximately 80 percent of Region 4. Cretaceous deposits are generally absent in areas where Precambrian bedrock outcrops or is near the land surface. These areas occur in the west-central portion of the region and frequently along the Minnesota River. The distribution and thickness of Cretaceous deposits are described in Setterholm, 1990. Cretaceous deposits may exceed 500 feet in thickness, but are more typically less than 300 feet thick.

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 to the major rivers in the area. Buried bedrock valleys filled with drift are also important discharge points for Cretaceous aquifers. Some water may recharge Cretaceous aquifers vertically through the drift along the Coteau des Prairie, although the primary recharge locations for Cretaceous aquifers appear to be in South Dakota (Woodward and Anderson, 1986).

Water quality information for Cretaceous aquifers in Southwest Minnesota are summarized in Table A.25. The data from Woodward and Anderson (1986) consider Cretaceous deposits which lie outside of Region 4. This may account for some of the differences between the data presented in that report and the data from the other studies, which were all completed within Region 4. The data within Region 4 are generally in good agreement, although the chemical parameter list is limited.

Water quality of Cretaceous aquifers in Region 4 is similar to Cretaceous aquifers statewide. There are elevated concentrations of vanadium, copper, manganese, strontium, chloride, calcium, sulfate, magnesium, lead, and aluminum, and lower concentrations of phosphate, antimony, and chromium compared to statewide concentrations, but the differences are not as great as they were for the drift aquifers.

Water quality of Cretaceous aquifers is, on average, poor. There are a number of concerns related both to potential health effects of drinking Cretaceous water and to other effects of using this water. Health criteria were exceeded for boron (eight wells), nitrate (three wells), vanadium (one well), zinc (one well) and manganese (two wells using a criteria of 1000 ug/L). Other criteria were exceeded for aluminum (three wells), iron (14 wells), and sulfate (13 wells). The median concentrations of boron, iron, manganese, molybdenum, strontium, and sulfate were 85, 517, 20, 21, 34, and 128 percent of the drinking water criteria, respectively. In addition to concerns associated with the concentration of these chemicals, there are a number of perplexing results for the Cretaceous aquifers. The median concentration of dissolved oxygen was 1550 ug/L, the median Eh was 144 mV, and nitrate was above its HRL of 10000 ug/L in three wells. These results conflict with the assumption that Cretaceous ground water is very old and therefore probably highly reducing. Boron, nitrate, vanadium, zinc, manganese, aluminum, iron, sulfate, molybdenum, and strontium are discussed below. Correlation coefficients are illustrated in Table A.26.

1. Boron concentrations are within the same range as those for the buried drift system, except along an approximate northwest-southeast line which coincides with the slope of the Coteau des Prairie. Concentrations within this area consistently exceed the HRL of 600 ug/L and frequently exceed concentrations of 2000 ug/L. Since ground water should be moving to the east, this suggests presence of a boron-rich parent material. This line coincides with a region of elevated boron concentrations in the buried drift aquifers, with concentrations in the drift being in the range of 1200 to 1500 ug/L. Correlations involving boron were generally weak (Table A.26). The strongest correlation was with sodium. Boron concentrations increased as sodium concentrations increased.

Boron concentrations also decreased as Eh increased. These results give a complicated picture of boron distribution. Parent material is the primary control on boron concentrations, but residence time and groundwater mixing may also be important factors. Boron is not redox-sensitive, so the increasing concentrations in reducing ground water reflect increased dissolution in older waters.

2. Manganese concentrations were most strongly correlated with other trace minerals, such as nickel, cobalt, molybdenum, and vanadium. Manganese also increased with depth and concentrations of calcium and magnesium. If dissolution and ion exchange were the primary factors affecting distribution of manganese, concentrations would be expected to be positively correlated with sodium, potassium, and chloride. These relationships were not observed. Parent material appears to be the primary factor controlling the distribution of manganese.
3. Aluminum and zinc were not strongly correlated with any parameter. There were four wells with aluminum concentrations greater than 15 ug/L, but the remaining samples had concentrations less than 5 ug/L. Zinc concentrations were below 300 ug/L except for one well which exceeded the HRL (2000 ug/L). There were no apparent patterns to the distribution of aluminum and zinc. Both aluminum and zinc do not appear to represent drinking water concerns.
4. Iron concentrations were not well correlated with many parameters. The strongest correlations were with total suspended solids, manganese, and nitrate. The relationships involving iron were similar to statewide results. Iron increases in concentration as ground water becomes more reducing and iron is strongly associated with suspended material in ground water.
5. The HBV of 30 ug/L for molybdenum and the HRL of 4000 ug/L for strontium were not exceeded in any well, but the median concentrations of 6.2 and 1370 ug/L are about 21 and 34 percent of the drinking standards, respectively. The distribution and relationships involving these two parameters were very similar and also paralleled the results for the buried drift aquifers. Their distribution appears to be related to parent material, since concentrations are greatest along the Coteau des Prairie. As with the drift aquifers, molybdenum and strontium alone do not appear to represent a health concern.
6. The distribution of vanadium shows very strong geographic patterns. These patterns were not evident from the correlation tests, but they are apparent from distribution maps. Concentrations within the Hummocky Hills area (Patterson, 1995) are consistently in excess of 20 ug/L and often exceed 30 ug/L. This is close to the HRL of 50 ug/L. Concentrations decreased along the slope of the Coteau des Prairie and were below the detection level of 4.6 ug/L within the Marshall Till Plain. This pattern is contrary to the regional pattern of ground water flow in which ground water moves to the east and discharges to the Minnesota River.

7. Sulfate represents a large concern for drinking water in Region 4. In addition to imparting a bad taste to water, it has laxative effects and when strongly reducing conditions are encountered, sulfate can be transformed to hydrogen sulfide and a strong odor will develop. The median concentration of 640020 ug/L exceeds the MCL of 500000 ug/L. The distribution pattern of sulfate is striking, with the greatest concentrations being along the Coteau des Prairie. Concentrations decrease toward the northeast, being lowest within the Marshall Till Plain. Although concentrations of sulfate were strongly correlated with calcium, the strongest correlations were with some of the trace elements, including vanadium and nickel. Residence time is probably an important factor affecting concentrations of sulfate, but parent material may be the primary control on those concentrations. Metal sulfides exposed to relatively oxidizing water may be the primary source of sulfate in Cretaceous ground water, although inputs from overlying drift aquifers (i.e., gypsum) are also important.
8. The occurrence of three exceedances of the HRL for nitrate was surprising, as were the high median concentration of dissolved oxygen and the median Eh value of 144 mV. Close examination of the data revealed that all Cretaceous wells sampled for baseline analysis had nitrate concentrations of 500 ug/L or less, except for these three exceedances. The dissolved oxygen concentration in each well was greater than 1550 ug/L and the Eh of each well was greater than 315 mV. These three wells are not typical Cretaceous wells and all occurred in a small area near the northern half of the border between Redwood and Lyon counties. The most plausible explanation for the high nitrate concentrations is poor well construction. Another potential cause of high nitrate concentrations in this area is bedrock close to the land surface, which results in increased hydraulic connection with the land surface.
9. Concentrations of total suspended solids were highly correlated with many of the chemicals of concern in Cretaceous aquifers. Iron, manganese, molybdenum, and sulfate all increased as total suspended solid concentration increased, while nitrate and chloride concentrations decreased. While these relationships are not easily explained, this is an important result, since filtering of water high in total suspended solids may significantly improve overall water quality.

Water quality of Cretaceous aquifers has long been assumed to be poor. While the results of the baseline analysis support this assumption, there are significant local effects on water quality in Cretaceous aquifers. In particular, wells completed within Cretaceous aquifers along the Coteau des Prairie will have very poor water quality and perhaps may represent a health concern to some individuals. Concentrations of boron, vanadium, and to a lesser extent, molybdenum, strontium, and manganese are very high within this area. In addition, sulfate concentrations will be very high. Filtering of ground water is strongly recommended in this area, although it is unclear how much improvement in water quality will be gained by doing this. Ground water derived from Cretaceous aquifers within the Marshall Till Plain and further east and west of the Coteau des Prairie will have improved water quality, although concentrations of many constituents, including sulfate and iron, will be greater than water from most drift aquifers in the region.

3.4.4. Precambrian Aquifers

Precambrian bedrock underlies the entire region. In most cases, this bedrock represents a no-flow boundary for ground water. Some ground water can be derived locally from fractures, but this water is not used for domestic supply unless no other source of water exists. There are some areas within Region 4, most notably in the west-central portion of the region, where Precambrian bedrock outcrops or is located very close to the land surface. There is insufficient glacial material in these areas to complete wells, and ground water is derived from the Precambrian bedrock.

Seven samples were collected from Precambrian aquifers as part of the baseline study. Four of these were from wells completed within the Sioux Quartzite and the remaining three were from crystalline bedrock. Water quality information for Precambrian aquifers in Southwest Minnesota is presented in Table A.27. The data are highly variable. This is partly due to the small sample size, but may also be related to differences in water quality between the Sioux Quartzite and the other Precambrian aquifers.

Because of the small sample size, detailed analysis of the data would not be useful. Some general conclusions can be drawn.

1. Ground water is relatively oxidized, with dissolved oxygen being present in most samples and Eh values being greater than 250 mV. Iron and manganese concentrations were low in most samples.
2. Aquifers along the eastern portion of the Coteau des Prairie slope contained high concentrations of sodium and sulfate in addition to calcium and bicarbonate, while the two samples collected further west contained predominantly calcium, magnesium, and bicarbonate. These differences were very striking and may suggest differences in the bedrock parent material. The mix of calcium-bicarbonate and sodium-sulfate waters to the east conflict with the traditional model of ground water evolution from a calcium-bicarbonate type to a sodium-chloride-sulfate type.
3. Boron concentrations were very high, exceeding the HRL in three samples. The median concentration was more than half of the HRL. Beryllium and manganese also exceeded the drinking water criteria in two wells each, despite low overall concentrations of these two elements. These reflect local effects of parent material.

4. Exceedances of nitrate occurred in two wells, both of which had high concentrations of dissolved oxygen and Eh values in excess of 300 mV. Both wells were small diameter and the presence of nitrate at high concentration reflects aquifers which are fractured and close to the land surface, although the wells themselves were both more than 140 feet deep.

Precambrian aquifers represent a limited source of water for domestic supply in Southwest Minnesota. Water quality is highly variable and appears to differ on the east and west side of the Coteau des Prairie ridge. Concentrations of some trace elements may be relatively high due to enrichment of these elements in parent rock. Water quality of the Sioux Quartzite appears to be poor, with high concentrations of many chemicals, but only four samples were collected from this aquifer.

3.5. Discussion of Individual Chemicals and Chemical Parameters

The distribution of many chemicals in ground water followed geographic patterns which appear to indicate the importance of parent material and to a lesser extent residence time. Increasing residence time leads to increased dissolution of parent material and higher concentrations of chemicals. These patterns were apparent for boron, iron, manganese, sulfate, molybdenum, strontium, and vanadium. These were the primary chemicals of concern in both the buried drift and Cretaceous aquifers. Since the concentration and distribution of these chemicals is largely controlled by natural factors, little additional information can be added to the above discussions. These chemicals will be of greatest concern in those areas where parent materials are enriched in the chemicals.

Nitrate and VOCs are exceptions to the above conditions. The distribution of nitrate concentrations was primarily controlled by oxidation-reduction conditions within an aquifer. Sources of nitrate are possibly important, but the data seem to suggest that nitrogen is introduced relatively uniformly across Region 4, primarily due to agriculture. The distribution of VOCs has not been discussed to this point. This section focuses on more detailed examination of nitrate and VOCs. Information on oxidation-reduction potential, hardness, and arsenic is included.

3.5.1. Nitrogen

Understanding the distribution of nitrate in ground water requires a fundamental understanding of nitrogen and how it behaves in the environment. Nitrogen is a non-metal which can have many different redox forms. Under natural conditions, the most important forms are reduced forms associated with nitrogen gas or soil organic matter. Humans have dramatically altered the nitrogen cycle through soil cultivation, burning of fossil fuels, fertilization, and waste management. Nitrate is an oxidized form of nitrogen and is by far the most important chemical of concern in ground water impacted by humans, excluding isolated instances of aquifer contamination with synthetic organic chemicals.

Nitrogen may be introduced into ground water in many forms - as ammonia from animal and human waste, through interaction with the atmosphere (deposition of nitrogen with precipitation or gas exchange at the surface of an aquifer), with organic matter, or as nitrate from animal waste or fertilizer. Once in ground water, the form in which nitrogen exists is a function of redox conditions within the aquifer. Reduced forms will be oxidized to nitrate above Eh values of about 200 to 250 mV. Nitrate present at these higher Eh values will be stable. Nitrate is therefore a conservative chemical within oxidized ground water. Once oxygen is depleted, nitrate will be used by microbes. Microbes convert nitrate to nitrogen gas through a process called denitrification. Once nitrate is consumed, manganese and then iron enter into solution.

In Region 4, nitrogen inputs to the water table are significant due to agriculture. Typical concentrations of nitrate in soil leachate from fertilized agricultural fields generally exceed the drinking water standard of 10000 ug/L. Consequently, nitrate represents a potential drinking water concern.

To better understand the distribution of nitrate in ground water of Southwest Minnesota, the data can be divided into those samples where nitrate will be stable and those where nitrate will not be stable (will be denitrified). Neve (1996) used a system of classifying ground water into nitrate-stable and nitrate-unstable waters. The following methods present a modified version of this classification system.

1. Nitrate stable waters are those in which the concentration of dissolved oxygen is greater than 300 ug/L (the precision of the field instrument), Eh values are greater than 250 mV, and total iron concentrations are less than 1000 ug/L.
2. Nitrate unstable waters are those in which the concentration of dissolved oxygen is less than 300 ug/L, Eh values are less than 200 mV, and the concentration of total iron is greater than 1000 ug/L.

Using these two groups of data, minimum, median, maximum, and 25th and 75th quartile nitrate concentrations are illustrated in Table A.28. Data which did not fit either of these classification groups were included as a separate group which cannot be related to nitrate stability. The results are striking, with redox conditions in ground water having a major impact on the distribution of nitrate. In addition to the obvious differences in concentrations between nitrate-stable and nitrate-unstable waters, two other important conclusions can be drawn from this data. First, within nitrate-stable samples, the median concentration of nitrate was 9600 ug/L, while the 25th quartile concentration was 520 ug/L. These results suggest that there are nitrogen inputs across most of Region 4, but not uniformly across the region. If a source of nitrogen existed for all nitrate-stable wells sampled, nitrate should have been found in every well. Since it was not, either nitrate sources were not present for the wells with low concentrations or there was some process of nitrate removal occurring in those wells. Land use was not determined for the sampled wells, so potential nitrogen inputs could not be correlated with nitrate concentrations. Second, nitrate concentrations will be very low in certain geochemical environments, regardless of which aquifer is being sampled. This means that geochemical sensitivity of ground water can be used as an important management tool for nitrates. Simple field assessments can be made to make this determination, including measurement of dissolved oxygen, oxidation-reduction potential, dissolved iron, and dissolved manganese. These are discussed in Sections 3.5.3 and 4.2.

Nitrate in Group 1 (stable nitrate conditions) was correlated with several parameters. These are summarized below in order of strength of correlation. All the correlations listed were significant at a level of 0.05.

- chloride: 0.705;
- manganese: -0.680;
- iron: -0.450;
- boron: -0.432;
- UTM-east: -0.432;
- sulfate: -0.414; and
- well depth: -0.395.

Unfortunately, none of the correlations between nitrate and the above parameters can be used to predict a nitrate concentration in ground water because there was too much variability in the nitrate values.

The relationship with chloride is observed in almost all settings impacted by humans. In Region 4, the relationship is most likely due to inputs of chloride from application of animal waste or fertilizer. The correlations with manganese and iron reflect the redox sensitivity of nitrate. Manganese is the better indicator. The correlations with well depth and UTM-east coordinate are interesting. Nitrate concentrations increase to the west and with decreasing well depth. These results are similar to findings of other studies (MPCA, 1998a; MPCA 1998c). The relationship between nitrate and well depth is related to redox. This relationship is illustrated schematically in Figure B.6. The highest concentrations of dissolved oxygen occur at the top of the aquifer where oxygen-rich recharge water percolates into the aquifer. Oxygen is used by microbes and becomes depleted with depth. Nitrate is then used by microbes until it becomes depleted. After nitrate is depleted, manganese, then iron, then sulfate are used. Although these general processes are well understood, the rate of decline in nitrate concentration with depth is not known.

A clear example of the effect of redox on nitrate distribution is shown in Figure B.7. High nitrate concentrations are common in large diameter wells. Eh exceeded 300 mV and oxygen was present in these large diameter wells. Nitrogen inputs in the areas of these wells are no greater than nitrogen inputs in other locations within Region 4. However, nitrogen introduced to large diameter wells will be stable as nitrate because of the redox status created by these wells. The primary effect of large diameter wells is therefore on the redox status of ground water, not on inputs of nitrogen.

3.5.2. Volatile Organic Compounds

VOC results are summarized in Table A.29. There were 19 wells in which a VOC was detected. This represents 14 percent of the sampled wells, which is slightly greater than the overall statewide rate of 11 percent. There were four wells in which more than one VOC was detected. Sixteen of the 25 total detections were chloroform or other trihalomethane compounds, which have historically been considered to result from well disinfection but may actually be naturally-occurring. Concentrations were near the reporting limits. The remaining compounds, except for 1,2-dichloropropane and acetone, are products typically associated with fuel oils.

There were no important correlations between VOCs and other parameters. Like nitrate, most VOCs are affected by redox conditions in an aquifer, but there was no correlation between the distribution of VOCs and any of the redox parameters (iron, manganese, nitrate, oxygen, sulfate, and Eh). Close examination of the data reveals a tendency for trihalomethanes to be detected in the northwestern portion of the study area, while fuel oil products are more frequently detected in the eastern portion of Region 4. Figure B.8 displays the distribution of trihalomethanes and fuel oil compounds in Region 4. Also displayed are distributions of chloride and dissolved oxygen. The data show that detection of trihalomethanes coincides with higher concentrations of chlorides, which may indicate these compounds are naturally-occurring. Low oxygen concentrations are apparent in areas where fuel oil compounds were detected. Fuel oils are degraded in the presence of oxygen but may persist when oxygen is absent.

Despite the relatively high incidence of VOC detection in southwest Minnesota, no concentration exceeded a drinking criteria. VOCs do not represent a drinking water concern in Region 4, except in isolated cases of contamination.

3.5.3. Oxidation-reduction Potential

When microbes consume organic matter for food, the organic matter is oxidized. If organic matter is being oxidized, another chemical must be reduced. Chemicals available for reduction are oxygen, nitrate, manganese, iron, sulfate, and carbon dioxide. These redox chemicals are in a sense independent of each other, since nitrate will not be utilized until most of the oxygen is used, manganese will not be utilized until most of the nitrate is utilized, and so on. This is important since the boundaries at which these chemicals become important are fairly well defined. The oxidation-reduction (redox) potential provides an indication of which chemical is likely to be involved in these redox reactions. Most chemicals are affected by redox conditions in ground water, either because they directly undergo redox reactions or because they are associated with one of the redox chemicals discussed above. For example, arsenic undergoes redox reactions and is therefore directly related to redox potential. Boron is not redox-sensitive but shows a correlation with redox potential because it is strongly associated with iron and manganese, both of which are redox-sensitive.

Eh is a unit of measurement which defines the redox status of ground water. Understanding redox reactions is very complex, partly because of the number of redox reactions that occur in ground water but also because it is very difficult to accurately measure the redox status of ground water. Figure B.9 schematically portrays redox boundaries and chemicals which will be of concern within each boundary. When looking at this figure, it should be clear why it is so important to attempt to determine the redox status of an aquifer. In particular, the redox status will change not only in an aquifer system but within even a single aquifer.

There has been considerable discussion in this report describing the importance and role of redox conditions on the distribution of chemicals in ground water. The following measurements can be conducted in the field and will provide a quick assessment of the redox status of ground water.

1. Dissolved oxygen (DO) is measured in the field either with a probe or with the Winkler (wet chemistry) method. The Winkler method is more accurate but can be difficult to use in some field situations. Accuracy of the DO measurement is 100 ug/L for the Winkler method and 300 ug/L for a probe. If oxygen concentrations are less than 500 ug/L, the sample can be considered anaerobic. The measurement of dissolved oxygen in the field is subject to numerous sources of error, particularly in the sampling equipment, and dissolved oxygen should never be used as the only indicator of ground water redox conditions.
2. Measurement of oxidation-reduction potential (ORP or redox) is accomplished with a redox probe. The measurement must be converted to Eh. This conversion varies with the type of probe and is about 200 mV. A temperature correction is also required and this will be described in the manual for the probe. The redox probe provides a measure of the dominant redox couple operating in a sample. It is therefore only an approximation of the overall redox conditions within the aquifer. The redox probe is subject to drift (reading does not stabilize), particularly in reducing ground water. If possible, the instrument should be allowed to stabilize to within about 10 mV for three successive

readings. The accuracy of the probe varies, but for practical purposes it probably provides an estimate of redox within 25 to 50 mV of the true value in the aquifer.

3. Measurement of dissolved iron and manganese can be conducted directly in the field, usually with color wheels. These instruments measure reduced forms of iron and manganese, which are the desired forms in evaluating redox. These instruments do not measure low level concentrations and the test is primarily to determine if reduced manganese or iron are present. If they are present, nitrate and dissolved oxygen should be very low and Eh will be less than 100 mV.
4. Nitrate measurement in the field is measured in a variety of ways. Most will provide measurements down to about 1000 ug/L. Turbid samples should be filtered. The field test is simple but should be duplicated because the method is imprecise.

In strongly reducing environments, carbon dioxide, hydrogen sulfide, and ammonia can also be tested. Carbon dioxide will be absent in strongly reducing environments, while hydrogen sulfide and ammonia may be present in strongly reducing environments. Interpretation of redox conditions should be done carefully, but Figure B.9 will provide a useful starting point in interpretations.

3.5.4. Hardness

The property of hardness has been associated with encrustations left by some types of waters when they are heated. Most of this type of hardness is associated with calcium and magnesium. Hardness is therefore defined in terms of calcium carbonate. Strontium, barium, iron, manganese, and some heavy metals may also contribute to hardness. Hardness is often calculated by the formula:

Hardness (ug/L as calcium carbonate) = (calcium (ug/L) * 2.5) + (magnesium (ug/L) * 4).

Hardness values less than 60000 ug/L are considered to represent soft water, values between 121000 and 180000 represent hard water, and values greater than 180000 represent very hard water. The median hardness concentrations in the Cretaceous, Sioux Quartzite, buried drift, and surficial drift aquifers were 784385, 809025, 598296, and 406064 ug/L as calcium carbonate, respectively. All of these aquifers would be classified as having very hard water.

Since hardness, as defined here, is directly related to calcium and magnesium, factors which affect the distribution of these two elements affect the distribution of hardness. Calcium and magnesium were strongly correlated with each other. They were also correlated with many trace metals such as vanadium, strontium, cobalt, copper, manganese, and nickel. These correlations are probably related to dissolution of parent material. The most important correlations were between calcium and either total dissolved solids or sulfate. Total dissolved solids is easy to measure in the field, either directly or indirectly by measuring specific conductivity. The correlation with sulfate is even more important, however. The calcium-sulfate correlation was 0.804, compared to a calcium-bicarbonate correlation coefficient of 0.153. This means that sulfates (e.g., gypsum) are an important source of calcium in ground water. Most of the hardness in ground water of Region 4 is therefore attributable to sulfates.

The World Health Organization recommends an upper limit for hardness of 500000 ug/L as calcium carbonate. Many researchers feel the upper limit should be 100000 ug/L. Softening is required to reduce hardness levels in most ground water from Region 4.

3.5.5. Arsenic

Arsenic has not been discussed in this report. Concentrations of arsenic were well below the MCL of 50 ug/L. However, a strictly health-based drinking standard is likely to be set at 10 ug/L or less within the next three to five years. This would dramatically alter the results for arsenic.

Median concentrations of arsenic in the Cretaceous (KRET), Sioux Quartzite (PMSX), buried confined drift (QBAA), buried unconfined drift (QBUA), and surficial drift aquifers (QWTA) were 1.7, 3.2, 4.3, 4.7, and 1.6 ug/L, respectively. Concentrations at the 95th percentile were 5.5, 37 and 18 ug/L in the KRET, QBAA, and QWTA aquifers, respectively. There were no exceedances of the MCL, but 32 samples of the 132 collected in Region 4 exceeded 10 ug/L.

Arsenic concentrations were most highly correlated with redox parameters. Negative correlations were observed with Eh and nitrate and positive correlations were observed with iron, molybdenum, total suspended solids and potassium. However, none of the correlations was particularly strong.

Arsenic concentrations appeared to follow the same general geographic distribution as most other trace inorganics. Concentrations were greatest along the Coteau des Prairie, and it was only in this area where concentrations exceeded 10 ug/L. However, the distribution of arsenic in the remainder of Region 4 appeared random. Wells prone to having high arsenic concentrations will be those wells, completed in buried confined drift aquifers, in which Eh is between about -50 and -150 mV and there is a source of arsenic in the till.

There were 28 arsenic values greater than 10 ug/L in the buried confined drift aquifers (QBAA). The remaining four values greater than 10 ug/L were in unconfined drift aquifers (QBUA, QBUU, and QWTA). The buried confined drift aquifer by far represents the greatest potential concern for arsenic in drinking water.

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. Applications for the research and monitoring recommendations are included in the respective sections.

4.1. Summary

1. Median, minimum, maximum, mean, 95th confidence limit, and 90th or 95th percentile concentrations for a wide range of chemical parameters have been calculated for the nine aquifers (Cretaceous, Precambrian crystalline, Precambrian undifferentiated, Sioux Quartzite, buried confined drift, buried unconfined drift, buried undifferentiated drift, water table, and undifferentiated drift) sampled in MPCA Region 4 in southwestern Minnesota. These values may serve as background concentrations for the aquifers in this region, although small sample sizes exist for the three Precambrian aquifers and the two undifferentiated drift aquifers.
2. There were differences in concentrations of many chemicals between different aquifers. Surficial aquifers had greater Eh and concentrations of nitrate, dissolved oxygen, and other chemicals which indicate an effect of recharge on ground water quality. Deep, buried aquifers had greater concentrations of iron, boron, manganese, molybdenum, and other chemicals which indicate an effect of parent material and residence time (i.e., increased dissolution).
3. There were differences in concentrations of many chemicals between different well diameter classes. Well diameter is often a good indicator of well construction, with larger diameter wells (greater than 16 inches) often being poorly constructed. Wells with diameters less than 12 inches had greater concentrations of iron, boron, sulfate, and other chemicals which indicate an effect of parent material and residence time on water quality. Boron represents the greatest health concern in these wells, with median concentrations being more than half of the drinking water standard of 600 ug/L. Iron concentrations were well above the SMCL of 300 ug/L. Wells with diameters greater than 16 inches had greater concentrations of nitrate, dissolved oxygen, nickel, antimony, Eh, and chemicals which indicate an effect of recharge water. Nitrate represents the greatest health concern in these wells, with concentrations being more than half of the drinking water standard of 10000 ug/L. Two municipal wells with diameters between 12 and 16 inches had high concentrations of iron and manganese and low Eh, but also had nitrate and dissolved oxygen present. These conflicting results indicate wells which are not in chemical equilibrium, probably because they pump large volumes of water across much of the vertical portion of the aquifer. This process pulls in oxygen- and nitrate-

rich water from the top of the aquifer and iron- and manganese-rich water from the bottom of the aquifer.

4. Health-based drinking standards (HRL or HBV) were exceeded for the following compounds:
    - boron - 39 exceedances, including 24 in QBAA wells and eight in KRET wells;
    - nitrate - 17 exceedances, including five in QBAA wells and three each in QWTA, KRET, and QBUA wells;
    - manganese - 15 exceedances of 1000 ug/L, including nine in QBAA wells and two each in the KRET and PMSX wells;
    - antimony - one exceedance in a QBAA well;
    - beryllium - one exceedance each in a PCUU and PMSX well;
    - vanadium - one exceedance in a KRET well; and
    - zinc - one exceedance in a KRET well.
5. Non-health based standards (MCL or SMCL) were exceeded for the following compounds:
    - iron - 112 exceedances, including 78 in QBAA wells, 14 in KRET wells, eight in QWTA wells, and six in QBUA wells;
    - sulfate - 50 exceedances, including 28 in QBAA wells, 12 in KRET wells, and two each in PMSX, QBUA, and QUUU wells;
    - sodium - nine exceedances, including five in QBAA wells and four in KRET wells;
    - aluminum - six exceedances, including three each in QBAA and KRET wells;
    - lead - two exceedances of the action level of 15 ug/L, once each in QBAA and QBUA wells; and
    - chloride - one exceedance in a QBAA well.
6. Median concentrations of most chemicals in the buried drift aquifers (QBAA and QBUA aquifers) of Region 4 exceed statewide median concentrations for similar aquifers. Chemicals of concern in the buried drift aquifer system include boron, manganese, molybdenum, sulfate, and iron, all of which have high median concentrations, and nitrate, which exceeds the drinking water criteria in some wells. The primary control on concentrations of boron, manganese, molybdenum, and sulfate appears to be parent material. Concentrations of these chemicals are greatest along the Coteau des Prairie and slope of the Coteau, although this water is not the oldest water in the regional system. Management options are limited for the buried drift system, although more information about the chemistry of different geologic units may help identify aquifers which represent less of a health concern. Most of the chemicals of concern are correlated with total suspended solid concentrations.

Filtration (e.g., carbon, mechanical filters) of water pumped from buried drift aquifers may reduce potential impacts from these chemicals by removing suspended material.

7. Median concentrations of most chemicals in surficial drift aquifers (QWTA aquifers) of Region 4 exceed statewide median concentrations for similar aquifers. Chemicals of concern in the surficial drift aquifer system include manganese, sulfate, nitrate, vanadium, and iron. The primary control on concentrations of nitrate, iron, and manganese are redox status of the aquifer. In well-oxygenated aquifers, nitrate concentrations are high and may exceed drinking water criteria. Manganese and iron increase as ground water becomes more reducing, and they are good indicators of environments where nitrate will be denitrified. Sulfate concentrations are related to presence of gypsum. Vanadium is a mobile chemical and is probably associated with inputs from the vadose zone. There was no apparent geographic pattern to the distribution of the data, but only 12 samples were taken and none of these were from aquifers where municipalities are pumping water for domestic supply. Concentrations of total suspended solids were strongly correlated with these chemicals, except vanadium and nitrate, suggesting that filtration is a management option for waters high in iron and manganese.
8. Median concentrations of most chemicals in the Cretaceous (KRET) aquifer of Region 4 exceed statewide median concentrations for similar aquifers, but the differences between Region 4 and statewide data were not as great as for the drift aquifers. Chemicals of potential concern in the Cretaceous aquifers include boron, manganese, molybdenum, sulfate, iron, vanadium, aluminum, strontium, and nitrate. The primary control on concentrations of boron, manganese, molybdenum, sulfate, and vanadium appears to be parent material. Concentrations of these chemicals are greatest along the Coteau des Prairie and slope of the Coteau. Nitrate was detected in three wells and exceeded the HRL in each of these wells. These wells appeared to have been large diameter wells which may be poorly constructed. Distributions for iron, strontium, and aluminum could not be readily explained, but may be related to residence time. In general, water quality of the Cretaceous aquifers is poor and may represent health risks, particularly in the Coteau des Prairie area.
9. There were only seven samples collected from Precambrian aquifers, including four from the Sioux Quartzite. The data are insufficient to provide sound results, but Precambrian aquifers appear to have a mixture of water quality. They have elevated concentrations of dissolved oxygen and nitrate and appear to interact with recharge water. However, parent material is an important factor affecting concentrations of boron and beryllium. It is very difficult to predict water quality in these aquifers. Because of their fractured nature, they may readily interact with recharge water, which makes them

vulnerable to contamination. They may also be relatively well protected, in which case concentrations of some trace chemicals may be high.

10. Nitrate inputs are likely to be relatively uniform across most of Region 4 due to agriculture, although locally nitrogen inputs may be very high due to feedlots and sugar beet production. When there is a source of nitrogen to ground water, the fate of nitrate will be controlled by redox conditions within an aquifer. Nitrate will be a drinking water concern in the upper portions of aquifers, in aquifers with fractured bedrock near the land surface, and in large diameter wells. Under these conditions, oxygen will be present and nitrate will be stable until oxygen is consumed by microbes.
11. VOCs were detected in 19 wells. Trihalomethane compounds, primarily chloroform, were the most common VOC found and appeared to be associated with areas of elevated chloride concentrations. Fuel oil compounds were detected next most frequently and were found in oxygen-depleted waters in the eastern portion of the region. Despite the occurrence of these VOCs, no drinking water criteria were exceeded. VOCs do not represent a drinking water concern in Region 4 except in isolated instances of contamination.

4.2. Recommendations

Research Needs

1. Surficial aquifers (QWTA) are very sensitive to ground water contamination with nitrate. There is little information to help understand the distribution of geochemical conditions which control the fate of nitrate in surficial aquifers. The following are research needs for surficial aquifers in Region 4.
    - Establish vertical profiles of dissolved oxygen, nitrate, chloride, sulfate, Eh, dissolved iron, dissolved manganese, and dissolved organic carbon for “typical” surficial aquifers.
    - Determine quantities and patterns of recharge to surficial aquifers. Water levels in observation wells can be used to determine quantities of recharge. Continuous water level data (preferably hourly readings using continuous recorders and data loggers) from observation wells will provide information on the pattern of recharge.
    - Determine seasonal patterns to concentrations of nitrate at the top of the aquifers. Quarterly sampling would accomplish this.
    - Utilize hydraulic information collected from the Department of Natural Resources (DNR) studies of surficial aquifers together with the geochemical and recharge information (from the two points above) to establish ground water models designed to predict fate of nitrate in surficial aquifers under different stress conditions. Stress conditions include drought, excessive precipitation and recharge, ground water pumping for irrigation, livestock, or drinking water supply, increased nitrogen inputs from application of animal waste to agricultural fields, and increased nitrogen inputs associated with shifting to continuous corn rotations or bringing Conservation Reserve Program (CRP) land into agricultural production.
2. Locally, boron concentrations may be a health concern. If the drinking standard for arsenic is decreased, it may also become a health concern in some locations. Molybdenum, vanadium, and sulfate are also chemicals which appear to show a wide range in concentration and may reach concentrations of concern. Local “hot spots” need to be identified. The most likely factor controlling the concentrations of these chemicals in hot spots is parent material. Once the hot spots have been identified, geochemical information should be obtained to determine the relationship between water quality and parent material. Carbon-14 dating or computer modeling may be used to determine the effect of residence time (i.e., dissolution of parent materials) by providing estimates of ground water age.
3. A conceptual regional flow model (not a computer model) needs to be established. The following components would be determined:

- primary recharge and discharge areas;
- quantities of recharge in the primary recharge areas;
- local and regional flow systems;
- interaction between buried aquifers and water in surrounding tills;
- flow within the deep system, especially within buried valleys;
- rates of discharge to streams and rivers;
- permeability of geologic materials; and
- travel times.

Monitoring Needs

1. Baseline data: the baseline data for the buried confined drift (QBAA) and Cretaceous aquifers is sufficient to be considered representative of background. These data can simply be updated over time. Data bases for the buried unconfined drift (QBUA), water table aquifers (QWTA), and Sioux Quartzite (PMSX) should be expanded and the data reanalyzed to establish baseline conditions. Information in this report provides an initial estimate of background water quality in these aquifers, but the values may change as additional data is incorporated. The following specific recommendations are made for baseline enhancement.
    - Establish a central database for Region 4. The primary fields in this database are CWI unique number, UTM coordinates, four-letter aquifer code, source of the data, and chemical concentrations. Other information may be added but is difficult to standardize.
    - Expand the database for QBUA, QWTA, and PMSX aquifers by about fifteen wells each. Wells selected for sampling should have well logs and would preferably be grouted and finished below the middle of the aquifer. The wells do not need to be located within GWMAP grid cells. The parameter list includes major cations and anions and the inorganic trace elements identified in this report as being of concern.
    - Analysis of the data should be conducted at approximately five year intervals, provided data have been collected during this period. Analysis methods similar to those employed by GWMAP should be used.
    - Data from other studies can be incorporated into the baseline data base. Field sampling methods must be documented and meet standard QA/QC protocol.
2. Ambient monitoring: ambient monitoring is needed in aquifers impacted by humans. These will be surficial and Sioux Quartzite aquifers. Nitrate is the only chemical of concern associated with human activity. The objective of ambient sampling is to define a baseline condition, conduct a trend

analysis to determine if ground water quality is changing, and to assess the variability in water quality with time and location. The type of ambient monitoring program that could be established could vary widely, but some recommendations are listed below.

- Set up monitoring networks in several different surficial aquifers, preferably four or more.
- Sampling parameters for laboratory analysis should include nitrate, total Kjeldahl nitrogen, ammonia, major cations and anions, dissolved iron, dissolved manganese, and dissolved organic carbon.
- Field analysis should include electrical conductivity, redox potential, dissolved oxygen, temperature, pH, and alkalinity. The field kits discussed in Section 3.5.3. could also be used.
- Networks should include wells completed at the top, middle, and bottom of the aquifer. A minimum of three wells should be completed for each depth in each aquifer. Existing wells may be used if samples meet QA/QC requirements.
- Sampling should be conducted quarterly on approximately March 15, June 1, August 15, and November 1.
- Sampling should be conducted for a minimum of four years.
- Water levels should be measured at the time of sampling. Ideally, water levels would be recorded monthly and perhaps weekly during the period of spring recharge.

3. Sampling, data management, and data analysis protocol should be established and documented. Protocol developed by other agencies or ground water groups can be utilized.

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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 Cretaceous aquifers (KRET).
4. Descriptive statistics for undifferentiated Precambrian formations (PCCR).
5. Descriptive statistics for undifferentiated Precambrian crystalline formations (PCUU).
6. Descriptive statistics for the Sioux Quartzite (PMSX).
7. Descriptive statistics for buried Quaternary artesian aquifers (QBAA).
8. Descriptive statistics for unconfined buried Quaternary aquifers (QBUA).
9. Descriptive statistics for buried undifferentiated Quaternary aquifers (QBUU).
10. Descriptive statistics for unconfined, undifferentiated Quaternary aquifers (QUUU).
11. Descriptive statistics for Quaternary water table aquifers (QWTA).
12. Coefficients for log-censored data from analysis of descriptive statistics, for each aquifer and chemical. See MPCA, 1998a, for application of these coefficients.
13. Coefficients for log-normal data from analysis of descriptive statistics, for each aquifer and chemical. See MPCA, 1998a, for application of these coefficients.
14. Median concentrations, in ug/L, of sampled parameters for each of the major aquifers. Different letters within a row indicate median concentrations which differed at a significance level of 0.05.
15. Median concentrations (ug/L) of sampled parameters for different well diameters.
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21. Comparison of water quality data for buried drift aquifers from different literature sources for Southwest Minnesota.
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25. Comparison of water quality data for Cretaceous aquifers from different literature sources for Southwest Minnesota.
26. Summary of correlation coefficients between chemicals of concern and sampled parameters for Cretaceous aquifers (KRET).
27. Comparison of water quality data for Precambrian aquifers from different literature sources for Southwest Minnesota.
28. Summary statistics for different nitrate stability groups.
29. Summary information for VOCs detected in Region 4. Wells have been assigned arbitrary values to replace CWI unique numbers.

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

Aquifer	Number of Samples
Cretaceous (KRET)	19
Precambrian Crystalline (PCCR)	2
Precambrian Undifferentiated (PCUU)	1
Sioux Quartzite (PMSX)	4
Quaternary buried artesian aquifer (QBAA)	78
Quaternary buried unconfined aquifer (QBUA)	9
Quaternary buried unconfined undifferentiated (QBUU)	3
Quaternary unconfined undifferentiated (QUUU)	4
Quaternary water table aquifer (QWTA)	12

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

Parameter	No. of samples	No. of missing	Maximum reporting limit (ug/L)	No. detections above censoring value	No. censored values
Alkalinity	132	0	nnd[1]	132	0
Aluminum (Al)	132	0	0.060	105	27
Antimony (Sb)	132	0	0.008	100	32
Arsenic (As)	132	0	0.060	124	8
Barium (Ba)	132	0	1.4	132	0
Beryllium (Be)	132	0	0.010	20	112
Boron (B)	132	0	13	131	1
Bromide (Br)	129	3	0.20	4	125
Cadmium (Cd)	132	0	0.020	84	48
Calcium (Ca)	132	0	nnd	132	0
Chromium (Cr)	132	0	0.050	92	40
Chloride (Cl)	132	0	200	131	1
Cobalt (Co)	132	0	0.0020	131	1
Copper (Cu)	132	0	5.5	84	48
Dissolved Oxygen	132	0	nnd	70	62
Eh	132	0	nnd	132	0
Fluoride (F)[2]	86	46	[2]	86	0
Iron (Fe)	132	0	3.2	128	4
Lead (Pb)	132	0	0.03	119	13
Lithium (Li)	132	0	4.5	122	10
Magnesium (Mg)	132	0	nnd	132	0
Manganese (Mn)	132	0	0.90	128	4
Mercury (Hg)	109	23	0.10	10	99
Molybdenum (Mo)	132	0	4.2	74	58
Nickel (Ni)	132	0	6.0	63	69
Nitrate-N (NO_3-N)	132	0	500	39	93
Ortho-phosphate	36	96	5.0	30	6
pH	132	0	nnd	132	0
$Phosphorus_{total}$	132	0	14.9	128	4
Potassium (K)	132	0	118.5	131	1
Redox	132	0	nnd	132	0
Rubidium (Rb)	132	0	555.3	39	93
Selenium (Se)	132	0	1.0	97	35
Silcate (Si)	132	0	nnd	132	0
Silver (Ag)	132	0	0.0090	30	102
Sodium (Na)	132	0	nnd	132	0
Specific Conductivity	132	0	nnd	132	0
Strontium (Sr)	132	0	0.60	132	0
Sulfate-S (SO_4-S)	132	0	100	132	0
Sulfur (S)	132	0	21.8	132	0
Temperature	132	0	nnd	132	0
Thallium (Tl)	132	0	0.0050	60	72
Titanium (Ti)	132	0	0.0035	58	74
Total dissolved solids	132	0	nnd	132	0
Total organic carbon	132	0	500	131	1
Total phosphate	96	36	20	75	21
Total suspended solids	132	0	nnd	132	0
Vanadium (V)	132	0	4.7	82	50
Zinc (Zn)	132	0	2.7	128	4

Table A.2 Continued

Parameter	No. of samples	No. of missing	Maximum reporting limit (ug/L)	No. detections above censoring value	No. censored values
1,1-Dichloroethane	132	-	0.2	-	-
1,1-Dichloroethene	132	-	0.5	-	-
1,1-Dichloropropene	132	-	0.2	-	-
1,1,1-Trichloroethane	132	-	0.2	-	-
1,1,1,2-Tetrachloroethane	132	-	0.2	-	-
1,1,2-Trichloroethane	132	-	0.2	-	-
1,1,2,2-Tetrachloroethane	132	-	0.2	-	-
1,1,2-Trichlorotrifluoroethane	132	-	0.2	-	-
1,2-Dichlorobenzene	132	-	0.2	-	-
1,2-Dichloroethane	132	-	0.2	-	-
1,2-Dichloropropane	132	-	0.2	-	-
1,2,3-Trichlorobenzene	132	-	0.5	-	-
1,2,3-Trichloropropane	132	-	0.5	-	-
1,2,4-Trichlorobenzene	132	-	0.5	-	-
1,2,4-Trimethylbenzene	132	-	0.5	-	-
1,3-Dichlorobenzene	132	-	0.2	-	-
1,3-Dichloropropane	132	-	0.2	-	-
1,3,5-Trimethylbenzene	132	-	0.5	-	-
1,4-Dichlorobenzene	132	-	0.2	-	-
2,2-Dichloropropane	132	-	0.5	-	-
2-Chlorotoluene	132	-	0.5	-	-
4-Chlorotoluene	132	-	0.5	-	-
Acetone	132	-	20	-	-
Allyl chloride	132	-	0.5	-	-
Bromochloromethane	132	-	0.5	-	-
Bromodichloromethane	132	-	0.2	-	-
Benzene	132	-	0.2	-	-
Bromobenzene	132	-	0.2	-	-
Bromoform	132	-	0.5	-	-
Bromomethane	132	-	0.5	-	-
cis-1,2-Dichloroethene	132	-	0.2	-	-
cis-1,3-Dichloropropene	132	-	0.2	-	-
Carbon tetrachloride	132	-	0.2	-	-
Chlorodibromomethane	132	-	0.5	-	-
Chlorobenzene	132	-	0.2	-	-
Chloroethane	132	-	0.5	-	-
Chloroform	132	-	0.1	-	-
Chloromethane	132	-	0.5	-	-
1,2-Dibromo-3-chloropropane	132	-	0.5	-	-
Dibromomethane	132	-	0.5	-	-
Dichlorodifluoromethane	132	-	0.5	-	-
Dichlorofluoromethane	132	-	0.5	-	-
1,2-Dibromoethane	132	-	0.5	-	-
Ethylbenzene	132	-	0.2	-	-
Ethyl ether	132	-	2	-	-
Hexachlorobutadiene	132	-	0.5	-	-
Isopropylbenzene	132	-	0.5	-	-
Methylene chloride	132	-	0.5	-	-
Methyl ethyl ketone	132	-	10	-	-
Methyl isobutyl ketone	132	-	5	-	-
Methyl tertiary butyl ether	132	-	2	-	-
n-Butylbenzene	132	-	0.5	-	-
Naphthalene	132	-	0.5	-	-
n-Propylbenzene	132	-	0.5	-	-
o-Xylene	132	-	0.2	-	-
p&m-Xylene	132	-	0.2	-	-
p-Isopropyltoluene	132	-	0.5	-	-
sec-Butylbenzene	132	-	0.5	-	-

Table A.2 Continued

Parameter	No. of samples	No. of missing	Maximum reporting limit (ug/L)	No. detections above censoring value	No. censored values
Styrene	132	-	0.5	-	-
tert-Butylbenzene	132	-	0.5	-	-
trans-1,2-Dichloroethene	132	-	0.1	-	-
trans-1,3-Dichloropropene	132	-	0.2	-	-
Trichloroethene	132	-	0.1	-	-
Trichlorofluoromethane	132	-	0.5	-	-
Tetrachloroethene	132	-	0.2	-	-
Tetrahydrofuran	132	-	10	-	-
Toluene	132	-	0.2	-	-
Vinyl chloride	132	-	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 six 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 Cretaceous aquifers (KRET).

Parameter	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	90th percentile	Min	Max	State Median
		ug/L[5]								
Alkalinity	19	0	normal	352160	382276	352000	440000	214000	509000	356000
Aluminum (Al)	19	4	log-censored	1.4	389	2.1	163	< 0.060	223	1.5
Antimony (Sb)	19	8	log-censored	0.010	0.33	0.0090	0.12	< 0.0080	0.20	0.025
Arsenic (As)	19	1	log-censored	1.4	14	1.7	5.5	< 0.060	8.6	1.3
Barium (Ba)	19	0	normal	17	23	15	38	3.1	47	20
Beryllium (Be)	19	19	ins[1]	ins	ins	< 0.010	ins	< 0.010	< 0.010	< 0.010
Boron (B)	19	0	log-normal	608	946	507	2559	158	4659	410
Bromide (Br)	19	17	log-censored	0.089	0.87	< 0.20	0.44	< 0.20	0.76	< 0.20
Cadmium (Cd)	19	8	log-censored	0.041	0.99	0.050	0.42	< 0.020	0.95	0.05
Calcium (Ca)	19	0	normal	208662	265515	207984	391128	15210	474535	132699
Chloride (Cl)	19	0	log-normal	10899	22470	9540	82000	900	153340	5840
Chromium (Cr)	19	9	log-censored	0.064	11	0.070	2.2	< 0.050	6.5	0.14
Cobalt (Co)	19	1	log-censored	0.52	2.9	0.67	1.3	< 0.0020	1.7	0.6
Copper (Cu)	19	2	log-censored	24	184	24	163	< 5.5	248	13
Dissolved Oxygen	19	7	log-censored	1216	23914	1550	9950	< 300	10500	< 300
Eh	19	0	normal	174	242	144	365	-123	456	144
Fluoride (F)[4]	10	9	ins	ins	ins	545	7056	310	2130	430
Iron (Fe)	19	0	log-normal	746	2061	1514	2031	19	7630	1514
Lead (Pb)	19	2	log-censored	0.47	15	0.63	6.6	< 0.030	8.7	0.45
Lithium (Li)	19	3	log-censored	46	284	72	123	< 4.5	160	35.2
Magnesium (Mg)	19	0	normal	67958	85688	73905	115738	6730	154091	51635
Manganese (Mn)	19	1	log-censored	104	8429	204	1316	< 0.90	3213	112
Mercury (Hg)	18	17	ins	ins	ins	< 0.10	0.12	< 0.10	0.38	< 0.10
Molybdenum (Mo)	19	9	log-censored	6.2	29	6.2	23	< 4.2	25	< 4.2
Nickel (Ni)	19	6	log-censored	13	62	15	42	< 6.0	51	< 6.0
Nitrate-N (NO_3-N)	19	15	log-censored	119	60762	< 500	16450	< 500	23300	< 500
Ortho-phosphate	9	0				40	ins	30	130	40
pH	19	0	[3]	-	-	7.00	7.79	6.30	8.29	7
$Phosphorus_{total}$	19	1	log-censored	142	585	164.3	446	< 14.9	452.6	140
Potassium (K)	19	0				6562	11702	3788	12046	5474
Redox	19	0	normal	-44.3	23.4	-75	146	-341	236	-75
Rubidium (Rb)	19	10	log-censored	597	3318	< 555	2203	< 555	2637	< 555
Selenium (Se)	19	10	log-censored	0.84	12	< 1.0	7.6	< 1.0	7.6	1.5
Silcate (Si)	19	0	normal	10668	13181	11508	15795	3136	22629	10955
Silver (Ag)	19	16	log-censored	0.0021	0.10	< 0.0090	0.053	< 0.0090	0.070	< 0.0090
Sodium (Na)	19	0	log-normal	108168	163795	97066	480882	23376	5076	76187
Specific Conductivity	19	0	normal	1727	2099	1775	2670	10	3290	1436
Strontium (Sr)	19	0	normal	1429	1802	1370	2712	596	2920	754
Sulfate (SO_4)	19	0	normal	677415	835635	640020	1252890	177600	1594860	420390
Sulfur (S)	19	0	normal	245542	307302	228051	454466	62692	613372	162675
Temperature	19	0	normal	10.2	10.6	10.1	11.2	8.5	11.7	10
Thallium (Tl)	19	13	log-censored	0.0038	0.068	< 0.0050	0.029	<0.0050	0.056	< 0.0050
Titanium (Ti)	19	8	log-censored	0.0048	0.041	0.0051	0.025	< 0.0035	0.031	< 0.0035
Total dissolved solids	19	0	log-normal	1467574	1711197	1482000	2576000	856000	3158000	1110000
Total organic carbon	19	0	log-normal	3032	3702	2900	5500	1400	8500	2800
Total phosphate	10	5	log-censored	15	312	15	136	< 20	140	50
Total suspended solids	19	0	log-normal	5042	9288	6000	22000	1000	52000	8000
Vanadium (V)	19	4	log-censored	16	67	17	50	< 4.7	56	7.2
Zinc (Zn)	19	0	log-normal	38	71	26	210	5.0	3224	26

[1] ins = insufficient number of detections to calculate statistics
[2] ns = not sampled
[3] Data did not fit a normal or log-normal distribution
[4] Fluoride was censored at several detection limits. All non-detections were treated as missing data and removed from the data set.
[5] Eh and redox are in mV, Specific Conductance in mmhos/cm, Temperature in ^{o}C, and pH in pH units

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

Parameter	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95th percentile	Min	Max	State Median
		ug/L[2]								
Alkalinity	2	0	ins[1]	ins	ins	ins	ins	345000	468000	211000
Aluminum (Al)	2	0	ins	ins	ins	ins	ins	0.31	1.4	9.4
Antimony (Sb)	2	0	ins	ins	ins	ins	ins	0.013	0.040	0.014
Arsenic (As)	2	1	ins	ins	ins	ins	ins	< 0.060	1.0	0.64
Barium (Ba)	2	0	ins	ins	ins	ins	ins	21	780	39
Beryllium (Be)	2	1	ins	ins	ins	ins	ins	< 0.010	0.020	0.020
Boron (B)	2	0	ins	ins	ins	ins	ins	487	760	55
Bromide (Br)	2	2	ins	ins	ins	ins	ins	< 0.20	0.10	< 0.20
Cadmium (Cd)	2	1	ins	ins	ins	ins	ins	< 0.020	0.15	0.02
Calcium (Ca)	2	0	ins	ins	ins	ins	ins	45418	46410	38909
Chloride (Cl)	2	0	ins	ins	ins	ins	ins	7910	13400	2680
Chromium (Cr)	2	0	ins	ins	ins	ins	ins	1.1	1.3	0.61
Cobalt (Co)	2	0	ins	ins	ins	ins	ins	0.18	0.36	0.37
Copper (Cu)	2	1	ins	ins	ins	ins	ins	< 5.5	20	7.3
Dissolved Oxygen	2	0	ins	ins	ins	ins	ins	< 300	56000	735
Eh	2	0	ins	ins	ins	ins	ins	86	296	223
Fluoride (F)	2	0	ins	ins	ins	ins	ins	610	840	490
Iron (Fe)	2	0	ins	ins	ins	ins	ins	121	1474	205
Lead (Pb)	2	0	ins	ins	ins	ins	ins	0.40	1.1	0.5
Lithium (Li)	2	1	ins	ins	ins	ins	ins	< 4.5	22	6.5
Magnesium (Mg)	2	0	ins	ins	ins	ins	ins	28870	31663	13501
Manganese (Mn)	2	0	ins	ins	ins	ins	ins	18	94	102
Mercury (Hg)	1	1	ins	ins	ins	< 0.10	ins	ins	ins	< 0.10
Molybdenum (Mo)	2	1	ins	ins	ins	ins	ins	< 4.2	5.8	< 4.2
Nickel (Ni)	2	2	ins	ins	ins	ins	ins	< 6.0	< 6.0	< 6.0
Nitrate-N (NO_3-N)	2	2	ns	ns	ns	ns	ns	< 500	< 500	< 500
Ortho-phosphate	0	0	ins	ins	ins	ins	ins	ins	ins	ns
pH	2	0	ins	ins	ins	ins	ins	7.34	7.50	7.38
$Phosphorus_{total}$	2	0	ins	ins	ins	ins	ins	21	326	31
Potassium (K)	2	0	ins	ins	ins	ins	ins	3420	4047	2007
Redox	2	0	ins	ins	ins	ins	ins	-131	78	3
Rubidium (Rb)	2	2	ins	ins	ins	ins	ins	< 555	< 555	< 555
Selenium (Se)	2	0	ins	ins	ins	ins	ins	1.9	9.2	2.0
Silcate (Si)	2	0	ins	ins	ins	ins	ins	9017	13178	8567
Silver (Ag)	2	1	ins	ins	ins	ins	ins	< 0.0090	0.060	0.009
Sodium (Na)	2	0	ins	ins	ins	ins	ins	107124	160995	9821
Specific Conductivity	2	0	ins	ins	ins	ins	ins	745	1111	300
Strontium (Sr)	2	0	ins	ins	ins	ins	ins	498	563	197
Sulfate (SO_4)	2	0	ins	ins	ins	ins	ins	390	183300	13230
Sulfur (S)	2	0	ins	ins	ins	ins	ins	586	70222	3721
Temperature	2	0	ins	ins	ins	ins	ins	10.2	10.8	8.5
Thallium (Tl)	2	2	ins	ins	ins	ins	ins	< 0.0050	< 0.0050	< 0.0050
Titanium (Ti)	2	2	ins	ins	ins	ins	ins	< 0.0035	< 0.0035	< 0.0035
Total dissolved solids	2	0	ins	ins	ins	ins	ins	528000	730000	257000
Total organic carbon	2	0	ins	ins	ins	ins	ins	1600	8600	2100
Total phosphate	2	0	ins	ins	ins	ins	ins	< 20	270	< 20
Total suspended solids	2	0	ins	ins	ins	ins	ins	2000	4000	4000
Vanadium (V)	2	1	ins	ins	ins	ins	ins	< 4.7	6.6	5.1
Zinc (Zn)	2	0	ins	ins	ins	ins	ins	17	734	15

[1] ins = insufficient number of detections to calculate statistics
[2] Eh and redox are in mV, Specific Conductance in mmhos/cm, Temperature in ^{o}C, and pH in pH units

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

Parameter	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95th percentile	Min	Max	State Median
		ug/L								
Alkalinity	1	0	ins[1]	ins	ins	333000	ins	ins	ins	333000
Aluminum (Al)	1	1	ins	ins	ins	< 0.060	ins	ins	ins	< 0.060
Antimony (Sb)	1	0	ins	ins	ins	0.015	ins	ins	ins	< 0.0080
Arsenic (As)	1	0	ins	ins	ins	1.4	ins	ins	ins	1.4
Barium (Ba)	1	0	ins	ins	ins	12	ins	ins	ins	12
Beryllium (Be)	1	0	ins	ins	ins	0.080	ins	ins	ins	< 0.010
Boron (B)	1	0	ins	ins	ins	806	ins	ins	ins	271
Bromide (Br)	1	1	ins	ins	ins	< 0.20	ins	ins	ins	< 0.20
Cadmium (Cd)	1	0	ins	ins	ins	0.060	ins	ins	ins	< 0.020
Calcium (Ca)	1	0	ins	ins	ins	160720	ins	ins	ins	102262
Chloride (Cl)	1	0	ins	ins	ins	9680	ins	ins	ins	2120
Chromium (Cr)	1	1	ins	ins	ins	< 0.050	ins	ins	ins	1.1
Cobalt (Co)	1	0	ins	ins	ins	0.54	ins	ins	ins	0.54
Copper (Cu)	1	0	ins	ins	ins	52	ins	ins	ins	5.9
Dissolved Oxygen	1	1	ins	ins	ins	< 300	ins	ins	ins	1640
Eh	1	0	ins	ins	ins	165	ins	ins	ins	166
Fluoride (F)[4]	1	0	ins	ins	ins	800	ins	ins	ins	410
Iron (Fe)	1	0	ins	ins	ins	1650	ins	ins	ins	1650
Lead (Pb)	1	0	ins	ins	ins	0.050	ins	ins	ins	0.11
Lithium (Li)	1	0	ins	ins	ins	41	ins	ins	ins	20
Magnesium (Mg)	1	0	ins	ins	ins	55448	ins	ins	ins	46382
Manganese (Mn)	1	0	ins	ins	ins	241	ins	ins	ins	241
Mercury (Hg)	1	1	ins	ins	ins	< 0.10	ins	ins	ins	< 0.10
Molybdenum (Mo)	1	0	ins	ins	ins	16	ins	ins	ins	< 4.2
Nickel (Ni)	1	0	ins	ins	ins	16	ins	ins	ins	< 6.0
Nitrate-N (NO_3-N)	1	1	ns	ns	ns	< 500	ins	ns	ns	< 500
Ortho-phosphate	1	1	ins	ins	ins	< 30	ins	ins	ins	20
pH	1	0	ins	ins	ins	7.11	ins	ins	ins	7.2
$Phosphorus_{total}$	1	0	ins	ins	ins	70	ins	ins	ins	70
Potassium (K)	1	0	ins	ins	ins	5629	ins	ins	ins	5629
Redox	1	0	ins	ins	ins	-53	ins	ins	ins	-53
Rubidium (Rb)	1	0	ins	ins	ins	885	ins	ins	ins	< 555
Selenium (Se)	1	1	ins	ins	ins	< 1.0	ins	ins	ins	2
Silcate (Si)	1	0	ins	ins	ins	8621	ins	ins	ins	8621
Silver (Ag)	1	1	ins	ins	ins	< 0.0090	ins	ins	ins	< 0.0090
Sodium (Na)	1	0	ins	ins	ins	125967	ins	ins	ins	63903
Specific Conductivity	1	0	ins	ins	ins	14	ins	ins	ins	162
Strontium (Sr)	1	0	ins	ins	ins	1682	ins	ins	ins	743
Sulfate (SO_4)	1	0	ins	ins	ins	547230	ins	ins	ins	174030
Sulfur (S)	1	0	ins	ins	ins	182680	ins	ins	ins	60092
Temperature	1	0	ins	ins	ins	10.1	ins	ins	ins	9.6
Thallium (Tl)	1	1	ins	ins	ins	< 0.0050	ins	ins	ins	< 0.0050
Titanium (Ti)	1	0	ins	ins	ins	0.011	ins	ins	ins	< 0.0035
Total dissolved solids	1	0	ins	ins	ins	1230000	ins	ins	ins	666000
Total organic carbon	1	0	ins	ins	ins	3000	ins	ins	ins	3000
Total phosphate	0	0	ins	ins	ins	ins	ins	ins	ins	25
Total suspended solids	1	0	ins	ins	ins	4000	ins	ins	ins	4000
Vanadium (V)	1	0	ins	ins	ins	19	ins	ins	ins	5.5
Zinc (Zn)	1	0	ins	ins	ins	7.6	ins	ins	ins	8

[1] Insufficient number of detections to calculate statistics

[5] Eh and redox are in mV, Specific Conductance in mmhos/cm, Temperature in ^{o}C, and pH in pH units

Table A.6: Descriptive statistics for the Sioux Quartzite (PMSX).

Parameter	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95th percentile	Min	Max	State Median
		ug/L[4]								
Alkalinity	4	0	ins[1]	ins	ins	244000	ins	161000	427000	244000
Aluminum (Al)	4	1	ins	ins	ins	0.11	ins	< 0.060	3.1	0.11
Antimony (Sb)	4	0	ins	ins	ins	0.054	ins	0.025	0.20	0.054
Arsenic (As)	4	0	ins	ins	ins	3.2	ins	1.1	4.3	3.2
Barium (Ba)	4	0	ins	ins	ins	40	ins	9.9	470	40
Beryllium (Be)	4	3	ins	ins	ins	< 0.010	ins	< 0.010	0.080	< 0.010
Boron (B)	4	0	ins	ins	ins	315	ins	14	763	315
Bromide (Br)	4	4	ins	ins	ins	< 0.20	ins	< 0.20	< 0.20	< 0.20
Cadmium (Cd)	4	1	ins	ins	ins	0.040	ins	< 0.020	0.35	0.04
Calcium (Ca)	4	0	ins	ins	ins	215512	ins	61694	420429	215512
Chloride (Cl)	4	0	ins	ins	ins	3780	ins	2010	42070	3780
Chromium (Cr)	4	1	ins	ins	ins	0.15	ins	< 0.050	0.17	0.15
Cobalt (Co)	4	0	ins	ins	ins	1.1	ins	0.24	3.4	1.1
Copper (Cu)	4	0	ins	ins	ins	28	ins	5.4	39	28
Dissolved Oxygen	4	1	ins	ins	ins	3305	ins	< 300	11330	3305
Eh	4	0	ins	ins	ins	407	ins	233	534	407
Fluoride (F)[3]	4	3	ins	ins	ins	200	ins	200	200	200
Iron (Fe)	4	1	ins	ins	ins	67	ins	< 3.2	782	67
Lead (Pb)	4	0	ins	ins	ins	0.62	ins	0.31	0.71	0.62
Lithium (Li)	4	1	ins	ins	ins	71	ins	< 4.5	125	71
Magnesium (Mg)	4	0	ins	ins	ins	68360	ins	18758	150542	68360
Manganese (Mn)	4	1	ins	ins	ins	1062	ins	< 0.90	2364	1062
Mercury (Hg)	4	4	ins	ins	ins	< 0.10	ins	< 0.10	< 0.10	< 0.10
Molybdenum (Mo)	4	1	ins	ins	ins	6.2	ins	< 4.2	11	6.2
Nickel (Ni)	4	1	ins	ins	ins	16	ins	< 6.0	25	16
Nitrate-N (NO_3-N)	4	1	ins	ins	ins	1030	ins	< 500	12220	1030
Ortho-phosphate	1	0	ns	ns	ns	20	ins	20	20	20
pH	4	0	ins	ins	ins	6.63	ins	6.10	6.91	6.63
$\text{Phosphorus}_{total}$	4	0	ins	ins	ins	124	ins	45	247	124
Potassium (K)	4	0	ins	ins	ins	3846	ins	758	9560	3846
Redox	4	0	ins	ins	ins	188	ins	13	318	188
Rubidium (Rb)	4	2	ins	ins	ins	663	ins	< 555	1009	663
Selenium (Se)	4	2	ins	ins	ins	1.0	ins	< 1.0	2.6	1
Silcate (Si)	4	0	ins	ins	ins	12707	ins	7706	14527	12707
Silver (Ag)	4	4	ins	ins	ins	< 0.0090	ins	< 0.0090	< 0.0090	< 0.0090
Sodium (Na)	4	0	ins	ins	ins	73459	ins	13522	134398	73459
Specific Conductivity	4	0	ins	ins	ins	1414.000	ins	552	2550.000	1414
Strontium (Sr)	4	0	ins	ins	ins	741	ins	234	2214	741
Sulfate (SO_4)	4	0	ins	ins	ins	592440	ins	25950	1299690	592440
Sulfur (S)	4	0	ins	ins	ins	235986	ins	8695	522112	235986
Temperature	4	0	ins	ins	ins	9.9	ins	9.1	11.8	9.9
Thallium (Tl)	4	1	ins	ins	ins	0.014	ins	< 0.0050	0.37	0.014
Titanium (Ti)	4	1	ins	ins	ins	0.0055	ins	< 0.0035	0.0099	0.0055
Total dissolved solids	4	0	ins	ins	ins	1368500	ins	364000	2577000	1368500
Total organic carbon	4	0	ins	ins	ins	2050	ins	700	3300	2050
Total phosphate	3	0	ins	ins	ins	40	ins	30	50	40
Total suspended solids	4	0	ins	ins	ins	1500	ins	1000	2000	1500
Vanadium (V)	4	1	ins	ins	ins	19	ins	< 4.7	29	19
Zinc (Zn)	4	0	ins	ins	ins	8.0	ins	3.3	29	8

[1] ins = insufficient number of detections to calculate statistics
[2] ns=not sampled
[3] Fluoride was censored at several detection limits. All non-detections were treated as missing data and removed from the data set.
[4] Eh and redox are in mV, Specific Conductance in mmhos/cm, Temperature in ^oC, and pH in pH units

Table A.7: Descriptive statistics for buried Quaternary artesian aquifers (QBAA).

Parameter	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95th percentile	Min	Max	State Median
		ug/L[4]								
Alkalinity	78	0	normal	372513	387324	372000	483350	202000	513000	328000
Aluminum (Al)	78	14	log-censored	0.79	57	0.83	49	< 0.060	174	0.88
Antimony (Sb)	78	22	log-censored	0.016	0.28	0.018	0.17	< 0.0090	6.8	0.011
Arsenic (As)	78	6	log-censored	3.8	97	4.3	37	< 0.060	48	2.6
Barium (Ba)	78	0	normal	81	111		466	7.1	642	61
Beryllium (Be)	78	65	log-censored	0.004	0.028	< 0.010	0.030	< 0.010	0.030	< 0.010
Boron (B)	78	0	log-normal	330	424	342	2073	28	4763	98
Bromide (Br)	77	75	ins	ins	ins	< 0.20	< 0.20	< 0.20	0.82	< 0.20
Cadmium (Cd)	78	26	log-censored	0.042	0.64	0.040	0.41	< 0.020	0.87	< 0.020
Calcium (Ca)	78	0	log-normal	144444	167996	151702	379342	11841	435901	79537
Chloride (Cl)	78	1	log-censored	3936	81644	3370	47969	< 200	719700	2320
Chromium (Cr)	78	24	log-censored	0.4	5.3	0.57	2.8	< 0.050	8.3	0.49
Cobalt (Co)	78	0	log-normal	0.65	0.77	0.66	2.4	0.12	3.1	0.46
Copper (Cu)	78	33	log-censored	8.9	58	7.7	40	< 5.5	58	< 5.5
Dissolved Oxygen	78	41	log-censored	437	11833	< 300	5986	< 300	16550	< 300
Eh	78	0	[2]	-	-	143.89	453	-76	582	164
Fluoride (F)[3]	52	26				485	1466	210	3960	380
Iron (Fe)	78	1	log-censored	1507	23252	2018	8864	< 3.2	16889	1179
Lead (Pb)	78	10	log-censored	0.22	4.6	0.20	2.4	< 0.030	210	0.18
Lithium (Li)	78	3	log-censored	40	244	43	190	< 4.4	224	14
Magnesium (Mg)	78	0	log-normal	52529	59772	54188	137160	10504	182044	30515
Manganese (Mn)	78	1	log-censored	212	3212	280	1667	< 0.90	2939	131
Mercury (Hg)	61	57	log-censored	0.015	0.14	< 0.10	0.11	< 0.10	0.24	< 0.10
Molybdenum (Mo)	78	31	log-censored	6.1	21	5.3	16	< 4.2	21	< 4.2
Nickel (Ni)	78	44	log-censored	7.1	34	< 6.0	28	< 6.0	37	< 6.0
Nitrate-N (NO_3-N)	78	61	log-censored	30	25904	< 500	23875	< 500	33240	< 500
Ortho-phosphate	17	4	log-censored	29	581	40	ins	< 4.0	260	50
pH	78	0	[2]	-	-	7.02	7.52	6.20	8.10	7.29
Phosphorus$_{total}$	78	0	log-normal	129	153	123	446	32	1514	102
Potassium (K)	78	0	log-normal	5644	6555	5239	17100	1308	128473	3068
Redox	78	0	[2]	-	-	-75.5	233	-295	365	-56
Rubidium (Rb)	78	57	log-censored	436	1254	< 555	1040	< 555	1581	< 555
Selenium (Se)	78	18	log-censored	3.3	21	3.5	11	< 1.0	16	2.4
Silcate (Si)	78	0	[2]	-	-	13537	15546	3490	15657	11914
Silver (Ag)	78	60	log-censored	0.0062	0.098	< 0.0090	0.070	< 0.0090	0.13	< 0.0090
Sodium (Na)	78	0	log-normal	48854	62878	57134	298730	3404	1095280	18812
Specific Conductivity	78	0	normal	1345	1513	1203	2752	16	4030	619
Strontium (Sr)	78	0	log-normal	748	869	741	1956	130	2274	304
Sulfate (SO_4)	78	0	[2]	-	-	362760	1305453	5790	1482900	21900
Sulfur (S)	78	0	[2]	-	-	123667	464866	250	509432	8110
Temperature	78	0	[2]	-	-	9.5	11.1	7.9	12.4	8.9
Thallium (Tl)	78	41	log-censored	0.007	0.12	< 0.0050	0.072	< 0.0050	0.14	< 0.0050
Titanium (Ti)	78	55	ns	0.003	0.016	< 0.0035	0.014	< 0.0035	0.017	< 0.0035
Total dissolved solids	78	0	log-normal	983332	1126160	1026000	2494000	292000	3394000	430000
Total organic carbon	78	1	log-censored	3551	11692	3600	8620	< 500	25600	2600
Total phosphate	61	9	log-censored	68	593	60	399	< 20	540	60
Total suspended solids	78	0	normal	9111	15326	4000	28300	1000	50000	5000
Vanadium (V)	78	33	log-censored	8.2	40	8.2	29	< 4.7	36	< 4.7
Zinc (Zn)	78	5	log-censored	16	126	19	89	< 2.7	765	13

[1] ns = not sampled
[2] Data did not fit a normal or log-normal distribution.
[3] Fluoride was censored at several detection limits. All non-detections were treated as missing data and removed from the data set.
[4] Eh and redox are in mV, Specific Conductance in mmhos/cm, Temperature in ^{o}C, and pH in pH units

Table A.8: Descriptive statistics for unconfined buried Quaternary aquifers (QBUA).

Parameter	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95th percentile	Min	Max	State Median
		ug/L[4]								
Alkalinity	9	0	normal	367889	420121	404000	ins	257000	441000	281000
Aluminum (Al)	9	1	log-censored	1.8	57	1.8	ins	< 0.060	21	0.91
Antimony (Sb)	9	1	log-censored	0.051	0.39	0.067	ins	< 0.0080	0.18	0.016
Arsenic (As)	9	0	normal	7.4	13	5.7	ins	0.30	26	1.9
Barium (Ba)	9	0	log-normal	60	140	58	ins	17	657	71
Beryllium (Be)	9	8	ins	ins	ins	< 0.010	ins	< 0.010	0.010	< 0.010
Boron (B)	9	0	normal	296	519	250	ins	42	993	23
Bromide (Br)	7	7	ins	ins	ins	< 0.20	ins	< 0.20	< 0.10	< 0.20
Cadmium (Cd)	9	5	log-censored	0.054	0.48	< 0.020	ins	< 0.020	0.31	< 0.020
Calcium (Ca)	9	0	normal	180014	260617	148635	ins	88950.3	436238	78821
Chloride (Cl)	9	0	normal	51548	102004	18940	ins	550	180580	3625
Chromium (Cr)	9	0	normal	0.99	1.6	0.87	ins	0.070	2.8	0.69
Cobalt (Co)	9	0	normal	1.0	1.6	0.71	ins	0.42	2.4	0.46
Copper (Cu)	9	3	log-censored	21	96	30	ins	< 5.5	58	< 5.5
Dissolved Oxygen	9	3	log-censored	979	41301	830	ins	< 300	12730	< 500
Eh	9	0	normal	253	342	215	ins	137	454	225
Fluoride (F)[3]	6	3				720	ins	430	1500	305
Iron (Fe)	9	0	normal	2210	4274	722	ins	20	7733	367
Lead (Pb)	9	0	log-normal	0.23	0.54	0.64	ins	0.12	18	0.19
Lithium (Li)	9	0	normal	69	96	75	ins	19	115	7.1
Magnesium (Mg)	9	0	normal	71295	98837	69245	ins	28732	139936	26539
Manganese (Mn)	9	0	normal	322	578	142	ins	2.4	844	152
Mercury (Hg)	5	4	ins	ins	ins	< 0.10	ins	< 0.10	0.11	< 0.10
Molybdenum (Mo)	9	5	log-censored	3.9	36	< 4.2	ins	< 4.2	21	< 4.2
Nickel (Ni)	9	6	log-censored	13	39	< 6.0	ins	< 6.0	28	< 6.0
Nitrate-N (NO_3-N)	9	5	log-censored	2014	428737	< 500	ins	< 500	98020	< 500
Ortho-phosphate	2	0	ins	ins	ins	7.0	ins	< 5.0	10	10
pH	9	0	normal	7.05	7.21	7.00	ins	6.8	7.5	7.2
$Phosphorus_{total}$	9	0	normal	116	192	58	ins	25	286	57
Potassium (K)	9	0	log-normal	6105	12092	669	ins	1262	31205	1796
Redox	9	0	normal	33	122	-2	ins	-82	234	5
Rubidium (Rb)	9	6	log-censored	664	1325	< 555	ins	< 555	1140	< 555
Selenium (Se)	9	0				7.6	ins	1.1	17	3.2
Silcate (Si)	9	0	normal	13165	14706	13899	ins	8534.1	15381.5	10867
Silver (Ag)	9	4	log-censored	0.033	0.067	0.029	ins	< 0.0090	0.050	< 0.0090
Sodium (Na)	9	0	log-normal	31739	72094	26444	ins	7721	239924	5906
Specific Conductivity	9	0	log-normal	1236	1852	990	ins	781	3160	533
Strontium (Sr)	9	0	normal	978	1525	810	ins	312	2543	112
Sulfate (SO_4)	9	0	normal	365082	638676	209400	ins	51990	51990	984390
Sulfur (S)	9	0	normal	127482	224195	67269	ins	16008	366990	5406
Temperature	9	0	normal	9.59	10.3	9.3	ins	8.5	11.4	8.8
Thallium (Tl)	9	3	log-censored	0.014	0.20	0.010	ins	< 0.0050	0.080	< 0.0050
Titanium (Ti)	9	5	log-censored	0.0063	0.014	< 0.0035	ins	< 0.0035	0.0112	< 0.0035
Total dissolved solids	9	0	normal	1169000	1765279	766000	ins	530000	2737000	350000
Total organic carbon	9	0	normal	3667	5563	2900	ins	1600	9700	1900
Total phosphate	7	2	log-censored	40	967	30	ins	< 20	250	40
Total suspended solids	9	0	normal	9111	15326	4000	ins	1000	22000	2000
Vanadium (V)	9	3	log-censored	10	48	11	ins	< 4.7	29	< 4.7
Zinc (Zn)	9	0	log-normal	40	98	26	ins	11	420	12

[1] ins = insufficient number of detections to calculate statistics
[2] ns = not sampled
[3] Fluoride was censored at several detection limits. All non-detections were treated as missing data and removed from the data set.
[4] Eh and redox are in mV, Specific Conductance in mmhos/cm, Temperature in ^{o}C, and pH in pH units

Table A.9: Descriptive statistics for buried undifferentiated Quaternary aquifers (QBUU).

Parameter	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95th percentile	Min	Max	State Median
		ug/L								
Alkalinity	3	0	ins[1]	ins	ins	353000	ins	339000	389000	385000
Aluminum (Al)	3	0	ins	ins	ins	2.1	ins	0.97	3.7	0.36
Antimony (Sb)	3	0	ins	ins	ins	0.062	ins	0.018	0.093	0.056
Arsenic (As)	3	0	ins	ins	ins	3.4	ins	1.3	47	2.8
Barium (Ba)	3	0	ins	ins	ins	40	ins	12	200	52
Beryllium (Be)	3	3	ins	ins	ins	< 0.010	ins	< 0.010	< 0.010	< 0.010
Boron (B)	3	0	ins	ins	ins	297	ins	24	770	279
Bromide (Br)	3	3	ins	ins	ins	< 0.20	ins	< 0.20	< 0.20	< 0.20
Cadmium (Cd)	3	0	ins	ins	ins	0.07	ins	0.06	0.36	0.13
Calcium (Ca)	3	0	ins	ins	ins	150546	ins	90905	330219	114917
Chloride (Cl)	3	0	ins	ins	ins	4370	ins	410	10280	2185
Chromium (Cr)	3	2	ins	ins	ins	< 0.050	ins	< 0.050	0.17	0.06
Cobalt (Co)	3	0	ins	ins	ins	0.34	ins	0.32	3.2	0.99
Copper (Cu)	3	1	ins	ins	ins	< 5.5	ins	< 5.5	18	< 5.5
Dissolved Oxygen	3	1	ins	ins	ins	< 300	ins	< 300	18400	< 500
Eh	3	0	ins	ins	ins	317	ins	144	532	267
Fluoride (F)[3]	3	0	ins	ins	ins	360	ins	320	400	330
Iron (Fe)	3	0	ins	ins	ins	2312	ins	7.0	6457	2080
Lead (Pb)	3	0	ins	ins	ins	0.21	ins	0.18	0.70	0.27
Lithium (Li)	3	0	ins	ins	ins	100	ins	20	182	36
Magnesium (Mg)	3	0	ins	ins	ins	51434	ins	43264	107828	42087
Manganese (Mn)	3	0	ins	ins	ins	115	ins	5.8	693	205
Mercury (Hg)	3	3	ins	ins	ins	< 0.10	ins	< 0.10	< 0.10	< 0.10
Molybdenum (Mo)	3	2	ins	ins	ins	< 4.2	ins	< 4.2	12.40	< 4.2
Nickel (Ni)	3	3	ins	ins	ins	< 6.0	ins	< 6.0	< 6.0	< 6.0
Nitrate-N (NO_3-N)	3	1	ins	ins	ins	780	ins	< 500	10870	< 500
Ortho-phosphate	0	0	ns	ns	ns	ns	ns	ns	ns	ns
pH	3	0	ins	ins	ins	6.80	ins	6.59	7.05	7.1
$Phosphorus_{total}$	3	0	ins	ins	ins	71	ins	15	85	80
Potassium (K)	3	0	ins	ins	ins	8373	ins	467	14311	4960
Redox	3	0	ins	ins	ins	100	ins	-75	312	49
Rubidium (Rb)	3	3	ins	ins	ins	< 555	ins	< 555	< 555	< 555
Selenium (Se)	3	0	ins	ins	ins	1.6	ins	1.0	11	1.8
Silcate (Si)	3	0	ins	ins	ins	14928	ins	12261	15475	13548
Silver (Ag)	3	3	ins	ins	ins	< 0.0090	ins	< 0.0090	< 0.0090	< 0.0090
Sodium (Na)	3	0	ins	ins	ins	47271	ins	7186	58708	47568
Specific Conductivity	3	0	ins	ins	ins	1230	ins	390	1.98	955
Strontium (Sr)	3	0	ins	ins	ins	1013	ins	277	2052	561
Sulfate (SO_4)	3	0	ins	ins	ins	331740	ins	35280	851400	127170
Sulfur (S)	3	0	ins	ins	ins	114994	ins	12382	352026	43256
Temperature	3	0	ins	ins	ins	9.80	ins	8.70	11.00	10.1
Thallium (Tl)	3	3	ns	ns	ns	< 0.0050	ns	< 0.0050	< 0.0050	0.011
Titanium (Ti)	3	3	ins	ins	ins	< 0.0035	ins	< 0.0035	< 0.0035	< 0.0035
Total dissolved solids	3	0	ins	ins	ins	856000	ins	499000	1920000	608000
Total organic carbon	3	0	ins	ins	ins	2800	ins	2300	7700	3400
Total phosphate	3	1	ins	ins	ins	20	ins	< 20	70	50
Total suspended solids	3	0	ins	ins	ins	6000	ins	1000	18000	7000
Vanadium (V)	3	1	ins	ins	ins	< 4.7	ins	< 4.7	16.6	5.1
Zinc (Zn)	3	0	ins	ins	ins	25	ns	25	40	25

[1] ins = insufficient number of detections to conduct statistical analysis
[2] ns=not sampled
[3] Fluoride was censored at several detection limits. All non-detections were treated as missing data and removed from the data set.
[5] Eh and redox are in mV, Specific Conductance in mmhos/cm, Temperature in ^{o}C, and pH in pH units

Table A.10: Descriptive statistics for unconfined, undifferentiated Quaternary aquifers (QUUU).

Parameter	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	95th percentile	Min	Max	State Median
		ug/L[4]								
Alkalinity	4	0	ins[1]	ins	ins	326000	ins	297000	342000	326000
Aluminum (Al)	4	1	ins	ins	ins	0.74	ins	< 0.060	43	0.74
Antimony (Sb)	4	0	ins	ins	ins	0.049	ins	0.030	0.16	0.049
Arsenic (As)	4	0	ins	ins	ins	1.2	ins	0.35	2.8	1.2
Barium (Ba)	4	0	ins	ins	ins	15	ins	11	48	15
Beryllium (Be)	4	4	ins	ins	ins	< 0.010	ins	< 0.010	< 0.010	< 0.010
Boron (B)	4	1	ins	ins	ins	165	ins	< 13	682	165
Bromide (Br)	4	4	ins	ins	ins	< 0.20	ins	< 0.20	< 0.20	< 0.20
Cadmium (Cd)	4	1	ins	ins	ins	0.050	ins	< 0.020	0.15	0.05
Calcium (Ca)	4	0	ins	ins	ins	265785	ins	88108	404766	265785
Chloride (Cl)	4	0	ins	ins	ins	15715	ins	3840	44620	15715
Chromium (Cr)	4	1	ins	ins	ins	0.17	ins	< 0.050	0.56	0.17
Cobalt (Co)	4	0	ins	ins	ins	0.84	ins	0.18	1.4	0.84
Copper (Cu)	4	1	ins	ins	ins	27	ins	< 5.5	41	27
Dissolved Oxygen	4	0	ins	ins	ins	11305	ins	1000	17300	11305
Eh	4	0	ins	ins	ins	468	ins	300	525	468
Fluoride (F)[3]	4	2	ins	ins	ins	1375	ins	510	2240	1375
Iron (Fe)	4	1	ins	ins	ins	50	ins	< 3.2	3943	50
Lead (Pb)	4	0	ins	ins	ins	0.40	ins	0.13	0.76	0.4
Lithium (Li)	4	1	ins	ins	ins	86	ins	< 4.5	133	86
Magnesium (Mg)	4	0	ins	ins	ins	73278	ins	28445	86159	73278
Manganese (Mn)	4	0	ins	ins	ins	143	ins	3.8	1039	143
Mercury (Hg)	4	3	ins	ins	ins	< 0.10	ins	< 0.10	0.11	< 0.10
Molybdenum (Mo)	4	1	ins	ins	ins	8.5	ins	< 4.2	14	8.5
Nickel (Ni)	4	1	ins	ins	ins	19	ins	< 6.0	27	19
Nitrate-N (NO_3-N)	4	1	ins	ins	ins	5080	ins	< 500	10550	5080
Ortho-phosphate	3	1	ins	ins	ins	5.0	ins	< 5.0	10	5
pH	4	0	ins	ins	ins	6.83	ins	6.60	7.14	6.83
$Phosphorus_{total}$	4	1	ins	ins	ins	55	ins	< 15	157	55
Potassium (K)	4	1	ins	ins	ins	6757	ins	< 118.5	10582	6757
Redox	4	0	ins	ins	ins	249	ins	80	306	249
Rubidium (Rb)	4	2	ins	ins	ins	779	ins	< 555	1459	779
Selenium (Se)	4	1	ins	ins	ins	2.2	ins	< 1.0	6.0	2.2
Silcate (Si)	4	0	ins	ins	ins	12463	ins	11894	15930	12463
Silver (Ag)	4	4	ins	ins	ins	< 0.0090	ins	< 0.0090	< 0.0090	< 0.0090
Sodium (Na)	4	0	ins	ins	ins	29180	ins	4185	75062	29180
Specific Conductivity	4	0	ins	ins	ins	1817	ins	666	2230	1817
Strontium (Sr)	4	0	ins	ins	ins	1005	ins	135	1415	1005
Sulfate (SO_4)	4	0	ins	ins	ins	681195	ins	18210	923310	681195
Sulfur (S)	4	0	ins	ins	ins	232842	ins	6051	334352	232842
Temperature	4	0	ins	ins	ins	9.3	ins	8.9	9.4	9.3
Thallium (Tl)	4	2	ins	ins	ins	0.0065	ins	< 0.0050	0.026	0.0065
Titanium (Ti)	4	1	ins	ins	ins	0.0090	ins	< 0.0035	0.016	0.009
Total dissolved solids	4	0	ins	ins	ins	1466000	ins	383000	1971000	1466000
Total organic carbon	4	0	ins	ins	ins	3200	ins	2100	6500	3200
Total phosphate	1	1	ins	ins	ins	< 20	ins	< 20	< 20	< 20
Total suspended solids	4	0	ins	ins	ins	4000	ins	1000	10000	4000
Vanadium (V)	4	1	ins	ins	ins	20	ins	< 4.7	33	20
Zinc (Zn)	4	0	ins	ins	ins	30	ins	21	329	30

[1] ins = insufficient number of detections to conduct statistics
[2] ns = not sampled
[3] Fluoride was censored at several detection limits. All non-detections were treated as missing data and removed from the data set.
[4] Eh and redox are in mV, Specific Conductance in mmhos/cm, Temperature in ^{o}C, and pH in pH units

Table A.11: Descriptive statistics for Quaternary water table aquifers (QWTA).

Parameter	No. of samples	No. values censored	Distribution	Mean	UCL mean	Median	90th percentile	Min	Max	State Median
		ug/L[5]								
Alkalinity	12	0	normal	343167	403526	339000	518400	222000	528000	237500
Aluminum (Al)	12	5	log-censored	0.37	93	0.33	19	< 0.060	25	1.2
Antimony (Sb)	12	1	log-censored	0.049	0.61	0.070	0.34	< 0.0070	0.37	0.017
Arsenic (As)	12	0	log-normal	1.9	3.9	1.6	18	0.27	21	1.3
Barium (Ba)	12	0	normal	113	172	85	308	22	260	85
Beryllium (Be)	12	10	ins	ins	ins	< 0.0010	0.024	< 0.0010	0.030	< 0.010
Boron (B)	12	0	[2]	-	-	77	552	17	747	24
Bromide (Br)	12	12	ins	ins	ins	< 0.20	ins	< 0.20	< 0.20	< 0.20
Cadmium (Cd)	12	6	log-censored	0.025	0.16	0.030	0.10	< 0.020	0.11	< 0.020
Calcium (Ca)	12	0	log-normal	124968	162256	104960	262669	78798	278470	74237
Chloride (Cl)	12	0	log-normal	12291	24199	11920	70363	1790	74380	5810
Chromium (Cr)	12	2	log-censored	0.28	2	0.25	1.2	< 0.050	1.4	0.55
Cobalt (Co)	12	0	[2]	-	-	0.44	1.7	0.26	1.7	0.48
Copper (Cu)	12	5	log-censored	9.8	39	12	31	< 5.5	35	6.3
Dissolved Oxygen	12	6	log-censored	924	55244	680	15578	< 300	17000	< 500
Eh	12	0	normal	245	342	269	470	-56	485	196
Fluoride (F)[3]	10	2				410	756	210	780	300
Iron (Fe)	12	1	log-censored	285	19917	811	2726	< 3.2	2793	811
Lead (Pb)	12	0	log-normal			0.23	1.7	< 0.030	1.9	0.18
Lithium (Li)	12	1	log-censored	26	79	29	58	< 4.5	61	5.7
Magnesium (Mg)	12	0	normal	48455	63270	35983	96904	32325	104892	22224
Manganese (Mn)	12	1	log-censored	72	7997	135	1863	< 0.90	2474	176
Mercury (Hg)	12	10	ins	ins	ins	< 0.10	0.11	< 0.10	0.11	< 0.10
Molybdenum (Mo)	12	7	log-censored	3.5	10	< 4.2	8.3	< 4.2	9.4	< 4.2
Nickel (Ni)	12	8	log-censored	5.3	24	< 6.0	17	< 6.0	18.9	< 6.0
Nitrate-N (NO_3-N)	12	6	log-censored	1656	67928	520	17593	< 500	18130	< 500
Ortho-phosphate	3	0	ins	ins	ins	20	ins	10	40	20
pH	12	0	normal	6.94	7.11	6.88	7.31	6.52	7.31	7.21
$Phosphorus_{total}$	12	1	log-censored	63	256	58	336	< 15	443.5	56
Potassium (K)	12	0	normal	3544	5241	3039	9054	1036.9	10434	1766
Redox	12	0	normal	27	123	52	248	-274	264	-24
Rubidium (Rb)	12	11	ins	ins	ins	< 555	633	< 555	666	< 555
Selenium (Se)	12	2	log-censored	3.2	26	2.3	12	< 1.0	13	2.1
Silcate (Si)	12	0	normal	12956	14298	12790	17071	10140	18052	10819
Silver (Ag)	12	9	log-censored	0.0092	0.053	< 0.0090	0.035	< 0.0090	0.04	< 0.0090
Sodium (Na)	12	0	log-normal	12880	23741	9674	103896	2899	138028	4986
Specific Conductivity	12	0	normal	943	1253	916	1956	363	2160	465
Strontium (Sr)	12	0	normal	444	625	409	1036	126	1157	105
Sulfate (SO_4)	12	0	log-normal	102329	220343	103500	768420	11190	891900	12750
Sulfur (S)	12	0	log-normal	33908	73756	32057	275426	3872	320531	4603
Temperature	12	0	normal	10.1	11.1	9.9	12.9	7.7	13.2	8.8
Thallium (Tl)	12	6	log-censored	0.016	0.14	< 0.0050	0.070	< 0.0050	0.076	< 0.0050
Titanium (Ti)	12	9	log-censored	0.003	0.0091	< 0.0035	0.0070	< 0.0035	0.0076	< 0.0035
Total dissolved solids	12	0	normal	755000	1062573	582000	1811200	400000	1978000	340000
Total organic carbon	12	0	normal	3742	5299	2900	8560	1400	9700	2400
Total phosphate	9	2	log-censored	42	382	40	ins	< 20	410	40
Total suspended solids	12	0	normal	4833	7065	4000	9400	1000	10000	4000
Vanadium (V)	12	5	log-censored	8.4	22	9.5	16	< 4.7	17	5.4
Zinc (Zn)	12	0	log-normal	11	20	15	55	3.0	69	12

[1] ins = insufficient number of detections to conduct statistics
[2] Data did not fit a normal or log-normal distribution
[3] Fluoride was censored at several detection limits. All non-detections were treated as missing data and removed from the data set.
[4] ns = not sampled
[5] Eh and redox are in mV, Specific Conductance in mmhos/cm, Temperature in ^oC, and pH in pH units

Table A.12: 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	KRET		QBAA		QWTA		QBUA	
	a	b	a	b	a	b	a	b
Aluminum (Al)	0.329	2.875	-0.242	2.188	-0.992	2.821	0.559	1.78
Antimony (Sb)	-4.582	1.776	-4.145	1.467	-3.013	1.286	-2.985	1.036
Arsenic (As)	0.302	1.179	1.326	1.656	-	-	-	-
Beryllium (Be)	-	-	-5.52	0.994	-	-	-	-
Bromide (Br)	-2.422	1.163	-9.006	3.662	-	-	-	-
Cadmium (Cd)	-3.198	1.628	-3.17	1.392	-3.693	0.961	-2.916	1.108
Chloride (Cl)	-	-	8.278	1.547	-	-	-	-
Chromium (Cr)	-2.742	2.633	-0.913	1.314	-1.269	1.013	-	-
Cobalt (Co)	-0.647	0.876	-	-	-	-	-	-
Copper (Cu)	3.165	1.045	2.181	0.962	2.284	0.71	3.044	0.778
Dissolved Oxygen	7.103	1.52	6.08	1.683	6.829	2.087	6.887	1.909
Iron (Fe)	-	-	7.318	1.396	5.652	2.167	-	-
Lead (Pb)	-0.755	1.753	-1.506	1.552	-	-	-	-
Lithium (Li)	3.835	0.926	3.679	0.928	3.268	0.564	-	-
Manganese (Mn)	4.649	2.24	5.356	1.387	4.271	2.406	-	-
Mercury (Hg)	-	-	-4.197	1.147				
Molybdenum (Mo)	1.822	0.797	1.812	0.63	1.261	0.549	1.356	1.132
Nickel (Ni)	2.589	0.785	1.955	0.804	1.665	0.769	2.536	0.57
Nitrate (NO3)	4.778	3.182	3.408	3.446	7.412	1.895	7.608	2.735
Ortho-phosphate	-	-	3.35	1.538	-	-	-	-
Phosphorustotal	4.959	0.721	-	-	4.146	0.714	-	-
Rubidium (Rb)	6.392	0.875	6.078	0.539	-	-	6.499	0.352
Selenium (Se)	-0.173	1.345	1.191	0.952	1.165	1.061	-	-
Silver (Ag)	-6.148	1.986	-5.081	1.406	-4.689	0.891	-3.423	0.369
Thallium (Tl)	-5.567	1.465	-4.955	1.435	-4.132	1.088	-4.3	1.37
Titanium (Ti)	-5.333	1.097	-5.808	0.869	-5.816	0.571	-5.075	0.428
Total organic carbon	-	-	8.175	0.608	-	-	-	-
Total phosphate	2.694	1.556	4.224	1.103	3.749	1.12	3.679	1.63
Vanadium (V)	2.757	0.739	2.11	0.803	2.127	0.5	2.331	0.788
Zinc (Zn)	-	-	2.757	1.062	-	-	-	-

Table A.13: Coefficients for log-normal data from analysis of descriptive statistics, for each aquifer and chemical. See MPCA, 1998a, for application of these coefficients.

Chemical Parameter	KRET		QBAA		QWTA		QBUA	
	std. dev.	n	std. dev.	n	std. dev.	n	std. dev.	n
Arsenic (As)	-	-	-	-	0.483	12	-	-
Barium (Ba)	-	-	-	-	-	-	0.483	9
Boron (B)	0.398	19	0.457	78	-	-	-	-
Calcium (Ca)	-	-	0.280	78	0.179	12	-	-
Chloride (Cl)	0.650	19	-	-	0.463	12	-	-
Cobalt (Co)	-	-	0.295	78	-	-	-	-
Iron (Fe)	0.915	19	-	-	-	-	-	-
Lead (Pb)	-	-	-	-	0.563	12	0.747	9
Magnesium (Mg)	-	-	0.238	78	-	-	-	-
Phosphorustotal	-	-	0.319	78	-	-	-	-
Potassium (K)	-	-	0.274	78	-	-	0.386	9
Sodium (Na)	0.374	19	0.467	78	0.418	12	0.464	9
Specific Conductivity	-	-	-	-	-	-	0.229	9
Sulfate (SO4)	-	-	-	-	0.524	12	-	-
Sulfur (S)	-	-	-	-	0.531	12	-	-
Total dissolved solids	0.138	19	0.254	78	-	-	-	-
Total organic carbon	0.180	19	-	-	-	-	-	-
Zinc (Zn)	0.680	19	-	-	0.411	12	0.514	9

Table A.14: Median concentrations, in ug/L, of sampled parameters for each of the major aquifers. Different letters within a row indicate median concentrations which differed at a significance level of 0.05.

Parameter	KRET	PMSX	QBAA	QBUA	QBUU	QUUU	QWTA
				ug/L			
Alkalinity	352000	244000	372000	404000	353000	326000	339000
Aluminum (Al)	2.1	0.11	0.83	1.8	2.1	0.74	0.33
Antimony (Sb)	0.0090 a	0.054 bc	0.018 ab	0.067 abc	0.062 bc	0.049 c	0.070 abc
Arsenic (As)	1.7	3.2	4.3	5.7	3.4	1.2	1.6
Barium (Ba)	15 a	40 bc	bc	58 cd	40 cd	15 ab	85 d
Beryllium (Be)	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Boron (B)	507 c	315 b	342 bc	250 b	297 b	165 ab	77 a
Bromide (Br)	< 0.20	< 0.20	< 0.20	< 0.20	< 0.20	< 0.20	< 0.20
Cadmium (Cd)	0.050	0.040	0.040	< 0.020	0.07	0.050	0.030
Calcium (Ca)	207984	215512	151702	148635	150546	265785	104960
Chloride (Cl)	9540 ab	3780 ab	3370 ab	18940 ab	4370 a	15715 b	11920 ab
Chromium (Cr)	0.070	0.15	0.57	0.87	< 0.050	0.17	0.25
Cobalt (Co)	0.67	1.1	0.66	0.71	0.34	0.84	0.44
Copper (Cu)	24 b	28 b	7.7 ab	30 ab	< 5.5 a	27 b	12 ab
Dissolved Oxygen	1550	3305	< 300	830	< 300	11305	680
Eh	144 ab	407 ab	144 a	215 ab	317 a	468 b	269 ab
Fluoride (F)	545	200	485	720	360	1375	410
Iron (Fe)	1514 cd	67 a	2018 d	722 bcd	2312 cd	50 ab	811 abc
Lead (Pb)	0.63	0.62	0.20	0.64	0.21	0.40	0.23
Lithium (Li)	72	71	43	75	100	86	29
Magnesium (Mg)	73905	68360	54188	69245	51434	73278	35983
Manganese (Mn)	204	1062	280	142	115	143	135
Mercury (Hg)	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Molybdenum (Mo)	6.2	6.2	5.3	< 4.2	< 4.2	8.5	< 4.2
Nickel (Ni)	15 b	16 b	< 6.0 ab	< 6.0 ab	< 6.0 a	19 b	< 6.0 ab
Nitrate-N (NO_3-N)	< 500 a	1030 b	< 500 a	< 500 ab	780 ab	5080 b	520 ab
Ortho-phosphate	40	20	40	7.0	ns	5.0	20
pH	7.00	6.63	7.02	7.00	6.80	6.83	6.88
$Phosphorus_{total}$	164.3 c	124 bc	123 c	58 abc	71 a	55 a	58 ab
Potassium (K)	6562 b	3846 ab	5239 ab	669 b	8373 b	6757 b	3039 a
Rubidium (Rb)	< 555	663	< 555	< 555	< 555	779	< 555
Selenium (Se)	< 1.0 ab	1.0 a	3.5 bcd	7.6 d	1.6 bcd	2.2 abc	2.3 cd
Silcate (Si)	11508	12707	13537	13899	14928	12463	12790
Silver (Ag)	< 0.0090	< 0.0090	< 0.0090	0.029	< 0.0090	< 0.0090	< 0.0090
Sodium (Na)	97066 d	73459 bcd	57134 cd	26444 bc	47271 abc	29180 ab	9674 a
Specific Conductivity	1775	1414	1203	990	1.23	1817	916
Strontium (Sr)	1370 c	741 ab	741 bc	810 bc	1013 bc	1005 bc	409 a
Sulfate (SO_4)	684153 b	707958 ab	371001 ab	201807 ab	344982 ab	698526 ab	96171 a
Sulfur (S)	228051 b	235986 ab	123667 ab	67269 ab	114994 ab	232842 b	32057 a
Temperature	10.1 c	9.9 bc	9.5 ab	9.3 ab	9.80 bc	9.3 a	9.9 bc
Thallium (Tl)	< 0.0050	0.014	< 0.0050	0.010	< 0.0050	0.0065	< 0.0050
Titanium (Ti)	0.0051 ab	0.0055 b	< 0.0035 ab	< 0.0035 ab	< 0.0035 a	0.0090 b	< 0.0035 ab
Total dissolved solids	1482000 b	1368500 ab	1026000 ab	766000 ab	856000 ab	1466000 ab	582000 a
Total organic carbon	2900	2050	3600	2900	2800	3200	2900
Total phosphate	< 20	40	60	30	20	< 20	40
Total suspended solids	6000	1500	4000	4000	6000	4000	4000
Vanadium (V)	17	19	8.2	11	< 4.7	20	9.5
Zinc (Zn)	26 ab	8.0 a	19 ab	26 b	25 b	30 b	15 a

[1] Eh and redox are in mV, Specific Conductance in mmhos/cm, Temperature in ^{o}C, and pH in pH units

Table A.15: Median concentrations (ug/L) of sampled parameters for different well diameters[1].

Parameter	4 inch	5 inch	6 to 8 inch	12 to 16 inch	24 inch	30 inch	36 inch
No. samples	46	58	10	2	4	5	7
Alkalinity	372000	357500	348000	307000	306500	305000	342000
Aluminum	0.85	0.80	1.7	4.4	1.9	2.3	2.2
Antimony	0.023 a	0.015 a	0.016 a	0.060 a	0.045 b	0.091 c	0.11 bc
Arsenic	5.1	2.7	1.2	3.5	1.4	1.5	1.3
Barium	37 b	20 a	20 a	22 a	18 a	48 b	47 b
Beryllium	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Boron	319 b	413 c	603 d	167 a	360 b	78 a	95 a
Bromide	< 0.20	< 0.20	< 0.20	< 0.20	< 0.20	< 0.20	< 0.20
Cadmium	0.050	0.030	0.060	0.070	0.050	< 0.020	0.050
Calcium	116105	176792	277207	180657	245926	119010	179829
Chloride	3440 a	4570 a	4190 a	20335 b	15825 b	17310 b	22530 b
Chromium	1.1 d	0.12 c	0.090 c	0.040 a	0.080 b	0.13 b	0.13 bc
Cobalt	0.62	0.65	0.79	0.60	0.94	1.3	0.57
Copper	5.7 ab	12 bc	27 d	8.8 a	19 cd	21 cd	25 d
Dissolved oxygen	290 a	375 ab	3305 b	1465 ab	1000 bc	9600 c	2120 c
Eh	146 b	145 b	155 b	119 a	388 c	435 c	450 c
Fluoride	600 d	410 b	680 d	380 a	390 ab	865 d	495 c
Iron	1939 e	1973 e	1562 d	3725 f	600 c	37 b	20 a
Lead	0.24	0.24	0.50	0.13	0.13	0.30	0.43
Lithium	37	46	80	7.5	64	35	41
Magnesium	49494	60741	83849	60844	61071	40966	54611
Manganese	139 c	323 e	281 c	579 f	284 d	5.3 b	12 a
Mercury	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Molybdenum	5.0	4.9	9.4	4.1	6.3	5.4	4.6
Nickel	5.9 a	6.0 b	16 c	8.7 ab	15 c	19 c	5.9 a
Nitrate-N	490 a	490 a	545 b	615 b	6100 c	9600 c	16340 c
Ortho-phosphate-P	< 5.0	40	20	-	13	10	20
Ortho-phosphate	12	120	60	-	38	30	60
Oxidation-reduction potential	-73 b	-74 b	-64 b	-100 a	169 c	215 c	230 c
pH	7.10 e	6.99 d	6.95 c	6.62 a	6.71 b	6.88 cd	6.94 cd
Phosphorus	118 d	125 d	152 d	56 a	85 b	57 c	41 a
Potassium	5071	5415	5976	4998	9035	5833	3054
Rubidium	555	555	761	555	608	555	555
Selenium	7.1 d	1.5 bc	0.95 a	1.4 b	1.9 c	3.2 d	1.7 c
Silicate	13648	13042	13347	9032	12256	12863	11667
Silver	0.015 c	< 0.0090 a	< 0.0090 a	< 0.0090 a	< 0.0090 a	< 0.0090 b	< 0.0090 a
Sodium	42312 c	71467 d	108063 e	40609 b	54508 c	10042 a	22491 a
Specific Conductance	1130	1427	1084	1351	1973	878	947
Strontium	585 b	915 c	1306 c	1156 c	1235 c	307 a	570 a
Sulfate	202410 a	467970 bc	656070 cd	429300 b	726000 d	158880 a	164040 a
Sulfur	74339	163166	233580	151624	271228	52513	51980
Temperature	9.60	9.80	9.75	9.30	9.85	8.90	9.00
Thallium	< 0.0041	0.0045	0.0065	0.017	< 0.0041	0.028	< 0.0041
Titanium	< 0.0035	< 0.0035	0.0061	< 0.0035	0.0075	0.0056	< 0.0035
Total dissolved solids	773000	1188500	1608500	1042000	1591000	598000	930000
Total organic carbon	2950	3250	3950	3250	3250	2200	3600
Total phosphate-P	80	50	40	25	10	210	20
Total phosphate	240	150	120	75	30	630	60
Total suspended solids	7000 e	6000 d	4000 d	9000 f	2000 c	2000 b	1000 a
Vanadium	5.3	10	21	10	17	17	13
Zinc	20	16	18	5.2	12	24	22

[1] Eh and redox are in mV, Specific Conductance in mmhos/cm, Temperature in ^{o}C, and pH in pH units

Table A.16: Summary of water quality criteria, basis of criteria, and endpoints, by chemical parameter.

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

Table A.16 continued

Parameter	Criteria (ug/L)	Basis of criteria	Endpoint
1,1,1-trichloroethane	600	HRL	gi/liv
1,1-dichloroethane	70	HRL	kid
1,1-dichloroethene	6	HRL	gi/liv
1,2-dichloroethane	4	HRL	cancer
1,2-dichloropropane	5	HRL	cancer
acetone	700	HRL	cv/bld; liv
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	cns/pns
methyl ethyl ketone	4000	HRL	repro
methylene chloride	50	HRL	cancer
naphthalene	300	HRL	cv/bld
tetrachloroethene	7	HRL	cancer
tetrahydrofuran	100	HRL	gi/liv
toluene	1000	HRL	kid; gi/liv
trichloroethene	30	HRL	cancer
1,2,4-trimethylbenzene	-	-	-
1,3,5-trimethylbenzene	-	-	-
cis-1,2 dichloroethene	70	HRL	cv/bld
ethyl benzene	700	HRL	kid; gi/liv
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.17: Number of samples exceeding health-based water quality criteria, by aquifer.

Parameter	No. exceedances of criteria								
	KRET	PCCR	PCUU	PMSX	QBAA	QBUA	QBUU	QUUU	QWTA
Antimony (Sb)	0	0	0	0	1	0	0	0	0
Barium (Ba)	0	0	0	0	0	0	0	0	0
Beryllium (Be)	0	0	1	1	0	0	0	0	0
Boron (B)	8	1	1	1	24	1	1	1	1
Cadmium (Cd)	0	0	0	0	0	0	0	0	0
Chromium (Cr)	0	0	0	0	0	0	0	0	0
Cobalt (Co)	0	0	0	0	0	0	0	0	0
Copper (Cu)	0	0	0	0	0	0	0	0	0
Manganese (Mn)	2	0	0	2	9	0	0	1	1
Molybdenum (Mo)	0	0	0	0	0	0	0	0	0
Nickel (Ni)	0	0	0	0	0	0	0	0	0
Nitrate (NO3)	3	0	0	1	5	3	1	1	3
Selenium (Se)	0	0	0	0	0	0	0	0	0
Silver (Ag)	0	0	0	0	0	0	0	0	0
Strontium (Sr)	0	0	0	0	0	0	0	0	0
Thallium (Tl)	0	0	0	0	0	0	0	0	0
Vanadium (V)	1	0	0	0	0	0	0	0	0
Zinc (Zn)	1	0	0	0	0	0	0	0	0

Table A.18: Percentage of samples exceeding health-based water quality criteria, by aquifer.

Parameter	No. exceedances of criteria								
	KRET	PCCR	PCUU	PMSX	QBAA	QBUA	QBUU	QUUU	QWTA
Antimony (Sb)	0	0	0	0	1	0	0	0	0
Barium (Ba)	0	0	0	0	0	0	0	0	0
Beryllium (Be)	0	0	100	25	0	0	0	0	0
Boron (B)	42	100	100	25	31	11	33	25	8
Cadmium (Cd)	0	0	0	0	0	0	0	0	0
Chromium (Cr)	0	0	0	0	0	0	0	0	0
Cobalt (Co)	0	0	0	0	0	0	0	0	0
Copper (Cu)	0	0	0	0	0	0	0	0	0
Manganese (Mn)	11	0	0	50	12	0	0	25	8
Molybdenum (Mo)	0	0	0	0	0	0	0	0	0
Nickel (Ni)	0	0	0	0	0	0	0	0	0
Nitrate (NO3)	16	0	0	25	6	33	33	25	25
Selenium (Se)	0	0	0	0	0	0	0	0	0
Silver (Ag)	0	0	0	0	0	0	0	0	0
Strontium (Sr)	0	0	0	0	0	0	0	0	0
Thallium (Tl)	0	0	0	0	0	0	0	0	0
Vanadium (V)	5	0	0	0	0	0	0	0	0
Zinc (Zn)	5	0	0	0	0	0	0	0	0

Table A.19: Number of samples exceeding non-health-based water quality criteria, by aquifer.

Parameter	No. exceedances of criteria								
	KRET	PCCR	PCUU	PMSX	QBAA	QBUA	QBUU	QUUU	QWTA
Aluminum (Al)	3	0	0	0	3	0	0	0	0
Arsenic (As)	0	0	0	0	0	0	0	0	0
Chloride (Cl)	0	0	0	0	1	0	0	0	0
Fluoride (F)[4]	0	0	0	0	0	0	0	0	0
Iron (Fe)	14	1	1	1	78	6	2	1	8
Lead (Pb)	0	0	0	0	1	1	0	0	0
Mercury (Hg)	0	0	0	0	0	0	0	0	0
Sodium (Na)	4	0	0	0	5	0	0	0	0
Sulfate (SO_4)	13	0	1	2	28	2	1	2	1

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

Parameter	No. exceedances of criteria								
	KRET	PCCR	PCUU	PMSX	QBAA	QBUA	QBUU	QUUU	QWTA
Aluminum (Al)	16	0	0	0	4	0	0	0	0
Arsenic (As)	0	0	0	0	0	0	0	0	0
Chloride (Cl)	0	0	0	0	1	0	0	0	0
Fluoride (F)[4]	0	0	0	0	0	0	0	0	0
Iron (Fe)	74	50	100	25	100	67	67	25	67
Lead (Pb)	0	0	0	0	1	11	0	0	0
Mercury (Hg)	0	0	0	0	0	0	0	0	0
Sodium (Na)	21	0	0	0	6	0	0	0	0
Sulfate (SO_4)	68	0	100	50	36	50	33	50	8

Table A.21: Comparison of water quality data for buried drift aquifers from different literature sources for Southwest Minnesota. Concentrations represent median values, in ug/L (ppb)[2].

Parameter	Rock River Watershed	Redwood River Watershed	Cottonwood Watershed	Des Moines River Watershed	SW Regional Assessment	GWMAP Baseline Study
No. samples	7	34	26	6	72 to 75	87
Bicarbonate	ns	424000	383000	ns	333000	375000
Boron	ns	440	330	ns	257[1]	340
Calcium	ns	82000	170000	ns	294000	150674
Chloride	ns	2700	9200	ns	3000	3610
Conductivity	ns	ns	ns	ns	1524	1195
Fluoride	ns	300	300	ns	ns	490
Hardness (as $CaCO_3$)	ns	811000	690000	780000	1084000	607000
Iron	2500	5100	1100	4400	3710	1996
Magnesium	ns	20000	58000	ns	85100	56089
Manganese	95	430	140	440	796	278
Nitrate	622	978	2889	< 978	< 10	< 500
pH	ns	ns	7.6	ns	7.11	7.01
Potassium	ns	7600	7500	ns	8170	5260
Redox	ns	ns	ns	ns	49	-73
Silica	ns	24000	29000	ns	14280	13591
Sodium	ns	45000	59000	ns	52400	48624
Strontium	ns	ns	ns	ns	1490	744
Sulfate	ns	450000	460000	ns	847000	343350
Temperature	ns	ns	ns	ns	9.7	9.50
Total dissolved solids	1070000	1105000	981000	970000	1543000	1026000

[1] 18 samples
[2] Redox is in mV, Temperature in ^{o}C, and pH in pH units

Table A.22: Summary of correlation coefficients between chemicals of concern and sampled parameters for buried drift aquifers (QBAA and QBUA).

Chemical	Alkalinity	Barium	Calcium	Chloride	Magnesium	Potassium	Sodium	Strontium
Boron	ns	-0.684	0.298	0.180[1]	0.260	0.621	0.888	0.621
Iron	ns	-0.329	0.431	-0.298	0.451	0.306	ns	0.428
Manganese	ns	-0.325	0.595	ns	0.396	0.209[1]	ns	0.420
Molybdenum	-0.223	-0.363	0.272	ns	0.238	0.448	0.348	0.426
Nitrate	ns	ns	ns	0.378	ns	ns	ns	ns
Sulfate	ns	-0.832	0.820	ns	0.754	0.663	0.679	0.875
	Dissolved Oxygen	**Eh**	**TDS**	**Tritium**	**UTM-e**	**UTM-n**	**Well depth**	**Well diameter**
Boron	ns	ns	0.628	negative	-0.313	ns	0.350	ns
Iron	ns	-0.427	0.333	negative[1]	ns	ns	ns	ns
Manganese	ns	ns	0.420	ns	ns	-0.358	ns	0.201[1]
Molybdenum	ns	ns	0.368	ns	ns	-0.186[1]	ns	ns
Nitrate	0.288	0.262	ns	ns	-0.251	-0.438	ns	0.395
Sulfate	ns	ns	0.979	negative	-0.375	-0.486	0.231	0.276

[1] Significant at the 0.10 level but not at the 0.05 level.
[2] ns = Not significant at the 0.10 level.

Table A.23: Comparison of water quality data for surficial drift aquifers from different literature sources for Southwest Minnesota. Concentrations represent median values, in ug/L (ppb).

Parameter	Adolphson	Rock River Watershed	GWMAP
No. of Samples	26	3	11
Bicarbonate	330000	ns	327500
Boron	50	ns	74
Calcium	120000	ns	103642
Chloride	8500	ns	11145
Dissolved Oxygen	ns	ns	485
Hardness (as $CaCO_3$)	ns	360000	414557
Iron	5200	1200	902
Magnesium	40500	ns	35754
Manganese	ns	ns	169
Nitrate	2700	700	505
pH	7.3	7.1	6.9
Potassium	1700	ns	3046
Sodium	11000	ns	9632
Sulfate	170000	ns	97440
Total dissolved solids	558000	552000	538000

Table A.24: Summary of correlation coefficients between chemicals of concern and sampled parameters for water-table drift aquifers (QWTA).

Chemical	Alkalinity	Barium	Calcium	Chloride	Magnesium	Potassium	Sodium	Strontium
Boron	ns	-0.664	0.734	ns	0.546	ns	0.601	0.734
Iron	ns	ns	ns	ns	ns	ns	ns	ns
Manganese	ns	ns	ns	-0.587	ns	ns	ns	ns
Nitrate	ns	ns	ns	0.560[1]	ns	ns	ns	ns
Sulfate	ns	-0.664	0.839	ns	0.748	ns	0.552[1]	0.748
Vanadium	ns	-0.508[1]	0.595	ns	ns	ns	ns	0.551[1]
	Dissolved Oxygen	**Eh**	**TDS**	**Tritium[3]**	**UTM-e**	**UTM-n**	**Well depth**	**Well diameter**
Boron	ns	ns	0.634	-	ns	ns	ns	ns
Iron	ns	-0.839	ns	-	0.559[1]	0.664	ns	-0.686
Manganese	ns	ns	ns	-	ns	ns	ns	-0.503[1]
Nitrate	ns	0.735	ns	-	-0.526[1]	-0.608	ns	0.689
Sulfate	ns	ns	0.816	-	ns	ns	ns	ns
Vanadium	ns	0.609	0.563[1]	-	nd	ns	ns	0.541[1]

[1] Significant at the 0.10 level but not at the 0.05 level.
[2] ns = Not significant at the 0.10 level.
[3] Tritium was not sampled in water table aquifers

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

Parameter	Rock River Watershed	Redwood River Watershed	Des Moines River Watershed	SW Regional Assessment	Woodward and Anderson	GWMAP
No. of Samples	3	12	3	26 to 27	52 to 154	19
Bicarbonate		328000		290000	430000	352000
Boron		3000		637		507
Calcium		82000		128000	94000	207984
Chloride		84000		12380	10000	9540
Dissolved oxygen				< 10		1550
Fluoride		800	802			545
Hardness	770000	226000	1400000		320000	841286
Iron	4700	860	3700	960		1514
Magnesium		20000		37300	38000	73905
Manganese	250	110	520	73		204
Nitrate	500	900	300	200		< 500
pH				7.65		7
Potassium		7100		8590	7000	6562
Redox				2		-75
Silica		8700		4740	14000	11508
Sodium		207000		256900	120000	97066
Specific conductivity				1725	1490	1775
Strontium				1837		1370
Sulfate		589000			380000	640020
Temperature				10.5		10.1
Total dissolved solids	1210000	130000	2500000	1522000	961000	1482000

[1] Redox is in mV, Specific Conductance in mmhos/cm, Temperature in ^{o}C, and pH in pH units

Table A.26: Summary of correlation coefficients between chemicals of concern and sampled parameters for Cretaceous aquifers (KRET).

Chemical	Alkalinity	Barium	Calcium	Chloride	Magnesium	Potassium	Sodium	Strontium
Boron	ns	ns	-0.395[1]	ns	-0.419[1]	0.493	0.770	ns
Aluminum	ns	ns	ns	ns	ns	-0.445	ns	ns
Zinc	ns	ns	0.433[1]	ns	0.437[1]	ns	ns	0.516
Molybdenum	ns	ns	0.688	ns	0.616	0.392[1]	ns	0.426[1]
Strontium	ns	ns	0.707	ns	0.690	ns	ns	-
Iron	ns	ns	0.446	ns	ns	ns	ns	0.414[1]
Manganese	ns	ns	0.605	-0.721	0.459	0.420[1]	ns	0.521
Nitrate	ns	0.411[1]	ns	0.499	ns	ns	ns	ns
Sulfate	ns	ns	0.570	ns	0.483	0.581	0.504	0.786
Vanadium	ns	ns	0.907	ns	0.877	ns	ns	0.688
	Dissolved Oxygen	**Eh**	**TDS**	**Tritium[3]**	**UTM-e**	**UTM-n**	**Well depth**	**Well diameter**
Boron	ns	-0.528	ns	-	ns	ns	ns	ns
Aluminum	ns	ns	0.420[1]	-	ns	-0.427[1]	ns	ns
Zinc	ns	ns	0.532	-	ns	-0.539	ns	ns
Molybdenum	ns	ns	0.392[1]	-	ns	-0.464[1]	ns	ns
Strontium	ns	ns	0.707	-	ns	ns	0.390	ns
Iron	ns	ns	ns	-	ns	-0.498	0.470	ns
Manganese	ns	ns	ns	-	ns	-0.509	0.482	ns
Nitrate	ns	0.504	ns	-	ns	ns	-0.595	ns
Sulfate	ns	ns	0.881	-	ns	ns	ns	ns
Vanadium	ns	ns	0.624	-	ns	-0.396	ns	ns

[1] Significant at the 0.10 level but not at the 0.05 level.
[2] ns = Not significant at the 0.10 level.
[3] Tritium was not sampled in Cretaceous aquifers

Table A.27: Comparison of water quality data for Precambrian aquifers from different literature sources for Southwest Minnesota. Concentrations represent median values, in ug/L (ppb)[1].

Parameter	Rock River Watershed	Redwood River Watershed	SW Regional Assessment	GWMAP
No. of Samples	4	7	9 to 11	7
Bicarbonate	-	347000	216000	333000
Boron	-	760	104	573
Calcium	-	78000	216000	70920
Chloride	-	28000	3190	7910
Dissolved oxygen	-	-	80	2250
Fluoride	-	1200	-	705
Hardness	500000	270000	-	-
Iron	1410	310	2700	123
Magnesium	-	22000	62100	31663
Manganese	110	80	501	94
Nitrate	3800	3000	300	< 500
pH	-	-	7.1	6.91
Potassium	-	7000	5690	4047
Redox	-	-	70	78
Silica	-	16000	10540	11897
Sodium	-	146000	36000	125967
Specific conductivity	-	-	1059	745
Strontium	-	-	910	563
Sulfate	-	205000	534000	183300
Temperature	-	-	9.6	10.1
Total dissolved solids	644000	718000	1094000	730000

[1] Redox is in mV, Specific Conductance in mmhos/cm, Temperature in ^{o}C, and pH in pH units

Table A.28: Summary statistics for different nitrate stability groups.

Nitrate stability	No. samples	Minimum (ug/L)	Q25 (ug/L)	Median (ug/L)	Q75 (ug/L)	Maximum (ug/L)
Stable	25	< 500	520	9600	17290	33240
Not stable	74	< 500	< 500	< 500	< 500	98020
Unknown	33	< 500	< 500	< 500	< 500	23510

Table A.29: Summary information for VOCs detected in Region 4. Wells have been assigned arbitrary values to replace CWI unique numbers.

Unique No.	PARAMETER	Concentration (ug/L)	Chemical Class
1	chlorodibromomethane	0.8	Trihalomethane
2	chloroform	1.3	Trihalomethane
2	bromodichloromethane	3.2	Trihalomethane
2	chlorodibromomethane	3.8	Trihalomethane
3	1,2-dichloropropane	0.3	Halogenated aliphatic
4	chloroform	0.1	Trihalomethane
5	benzene	0.6	BTEX
5	chloroform	0.3	Trihalomethane
6	chloroform	0.1	Trihalomethane
7	acetone	21	Ketone
8	ethyl ether	9.5	Ether
9	chloroform	0.7	Trihalomethane
10	bromodichloromethane	1.3	Trihalomethane
10	chloroform	8.3	Trihalomethane
11	chloroform	0.4	Trihalomethane
12	chloroform	0.3	Trihalomethane
13	chloroform	0.1	Trihalomethane
14	chloroform	0.3	Trihalomethane
14	tetrahydrofuran	23	Ether
15	tetrahydrofuran	14	Ether
16	chloroform	0.3	Trihalomethane
17	tetrahydrofuran	58	Ether
18	methylene chloride	1.6	Halogenated aliphatic
19	methylene chloride	13	Halogenated aliphatic
19	chloroform	0.1	Trihalomethane

APPENDIX B - FIGURES

1. Location of Region 4.
2. Location of sampled wells from Quaternary (drift) aquifers.
3. Location of sampled wells from bedrock aquifers.
4. Distribution of boron concentrations in Quaternary and Cretaceous aquifers.
5. Distribution of dissolved oxygen concentrations and Eh in buried Quaternary aquifers.
6. Schematic representation of ground water movement within the Region 4 aquifers system.
7. Distribution of nitrate concentrations in large and small diameter wells from samples in which nitrate was considered to be stable.
8. Distribution of VOCs, chloride, and dissolved oxygen in samples from Region 4.
9. Illustration of redox boundaries for some chemicals of concern. Also illustrated are chemicals which are likely to interact with the redox-sensitive chemicals.

Figure B.1: Location of Region 4.

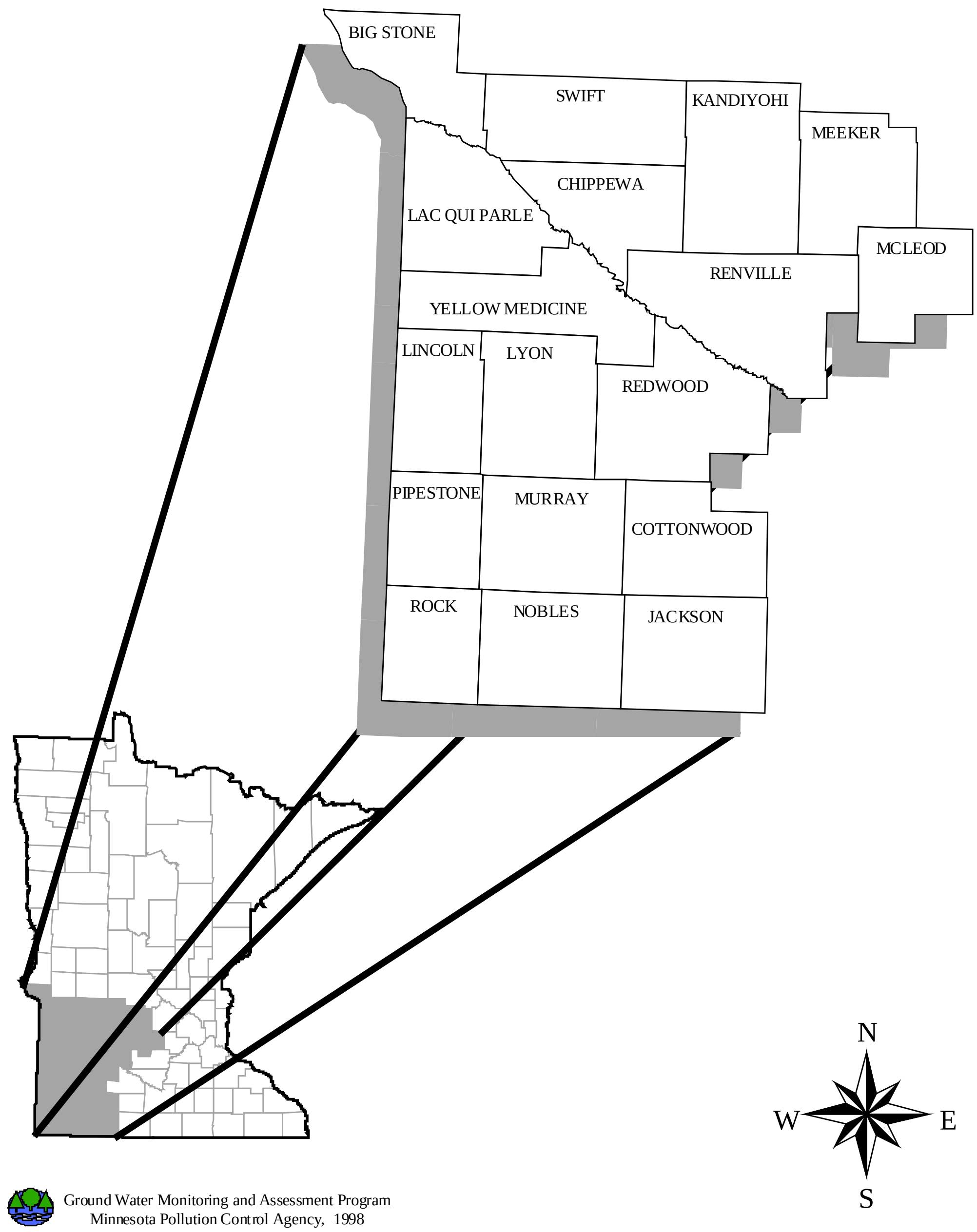
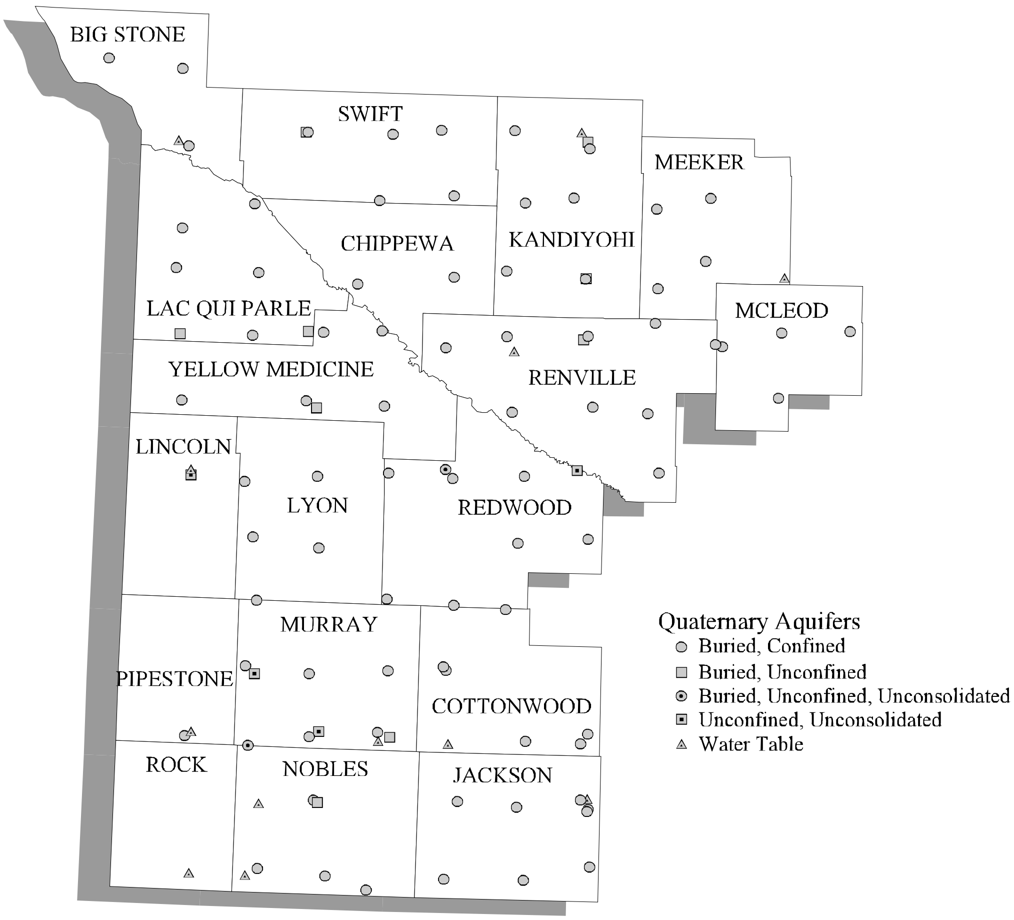


Figure B.2: Location of sampled wells from Quaternary (drift) aquifers.



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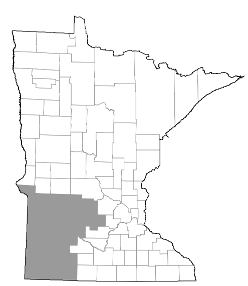


Ground Water Monitoring and Assessment Program
Minnesota Pollution Control Agency, 1998

Figure B.3: Location of sampled wells from bedrock aquifers.

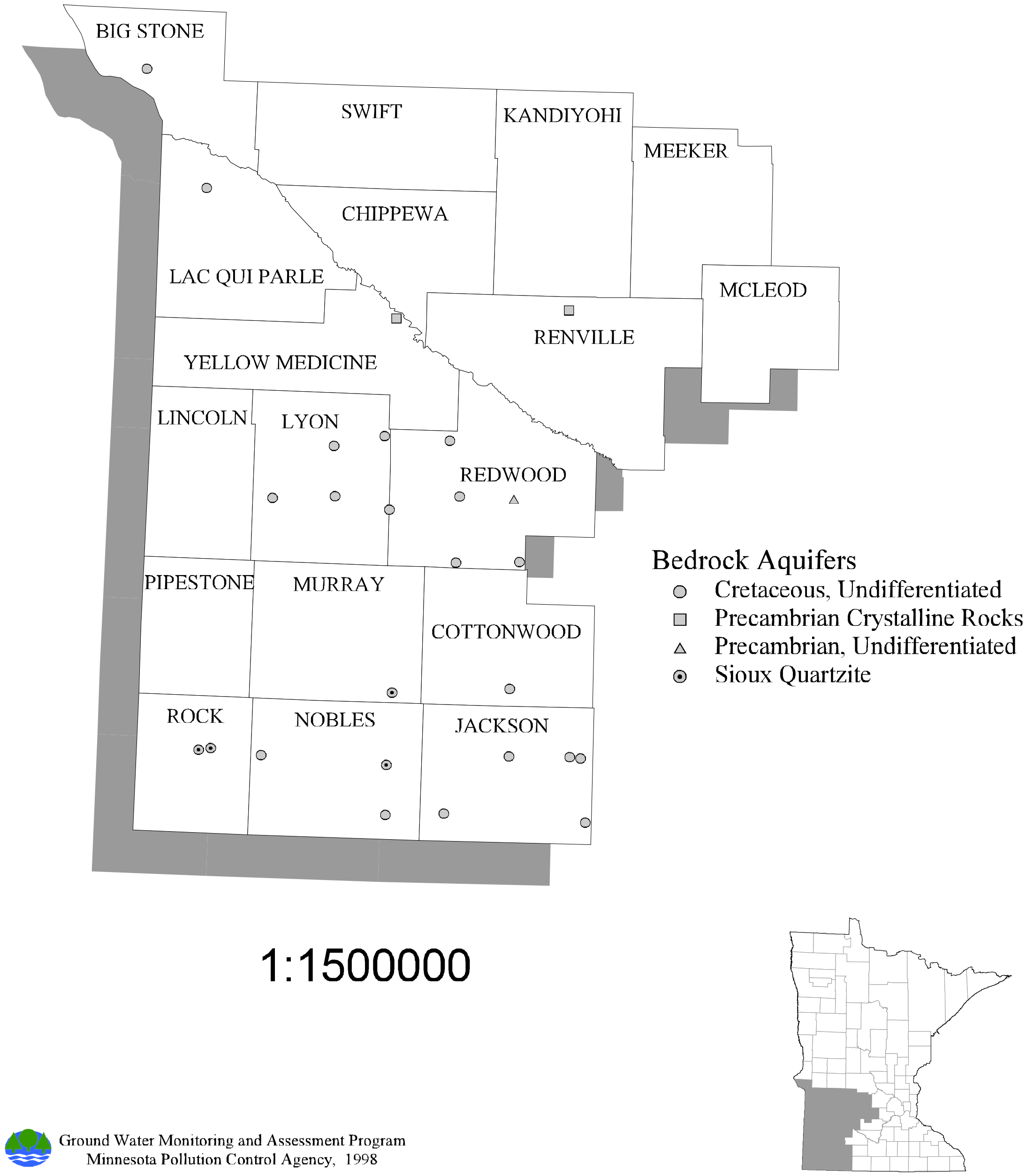


Figure B.4: Distribution of boron concentrations in Quaternary and Cretaceous aquifers.

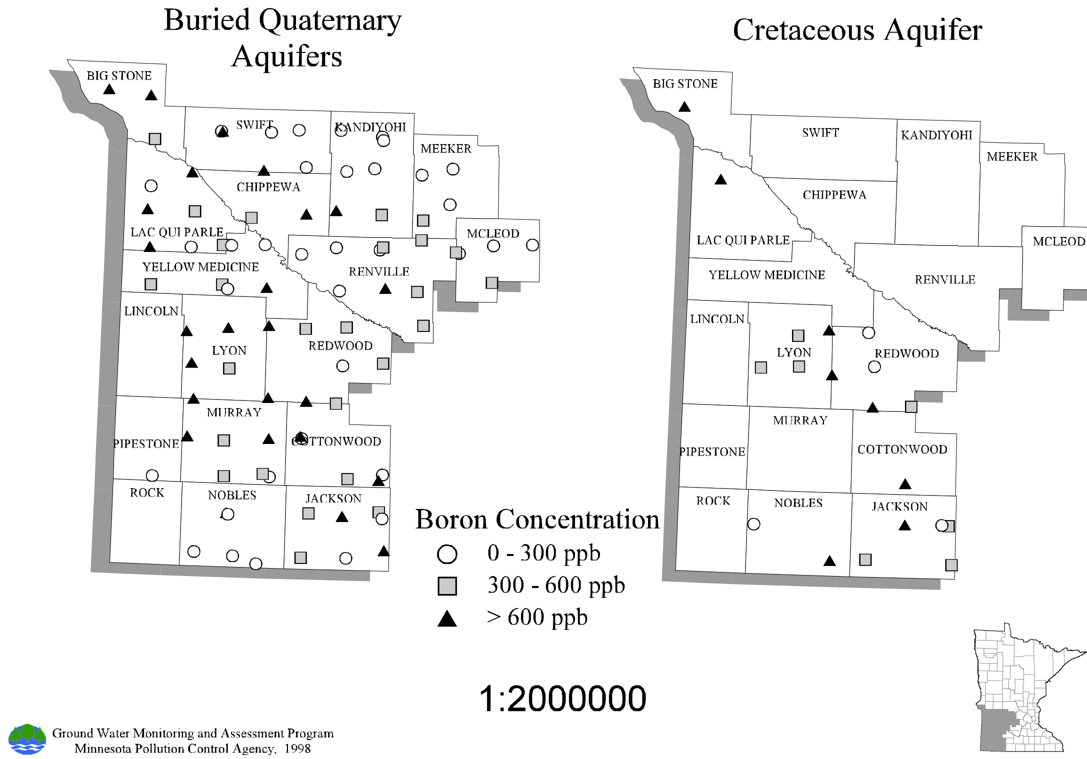
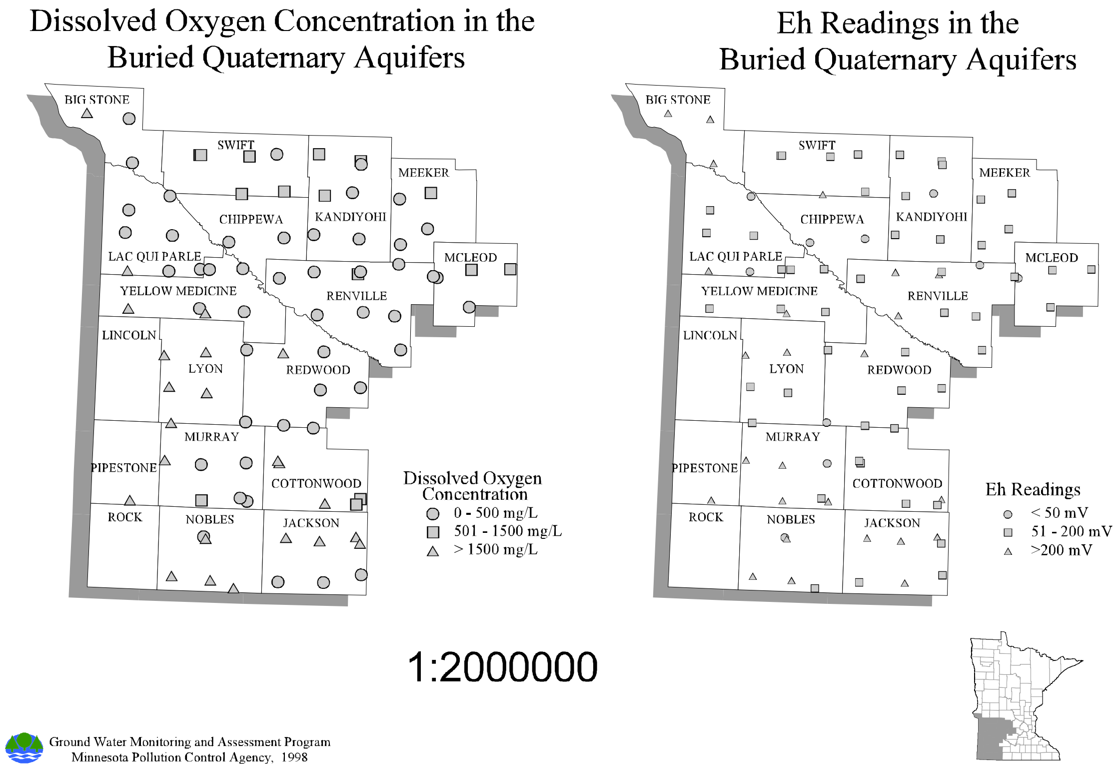


Figure B.5: Distribution of dissolved oxygen concentrations and Eh in buried Quaternary aquifers.



B.6: Schematic representation of ground water movement within the Region 4 aquifer system.

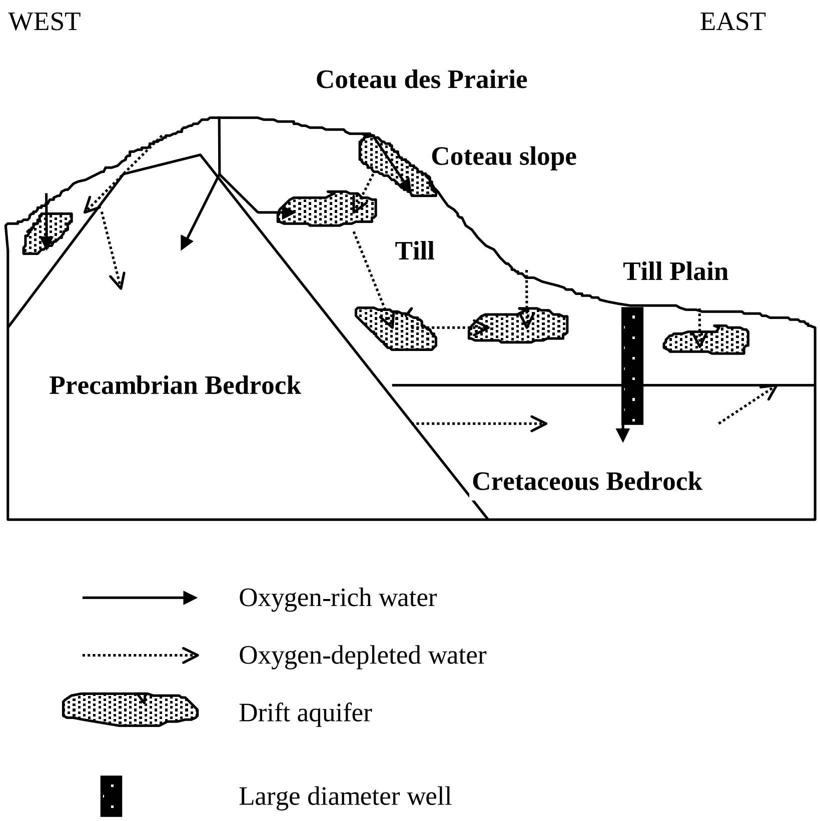


Figure B.7: Distribution of nitrate concentrations in large and small diameter wells from samples in which nitrate was considered to be stable.

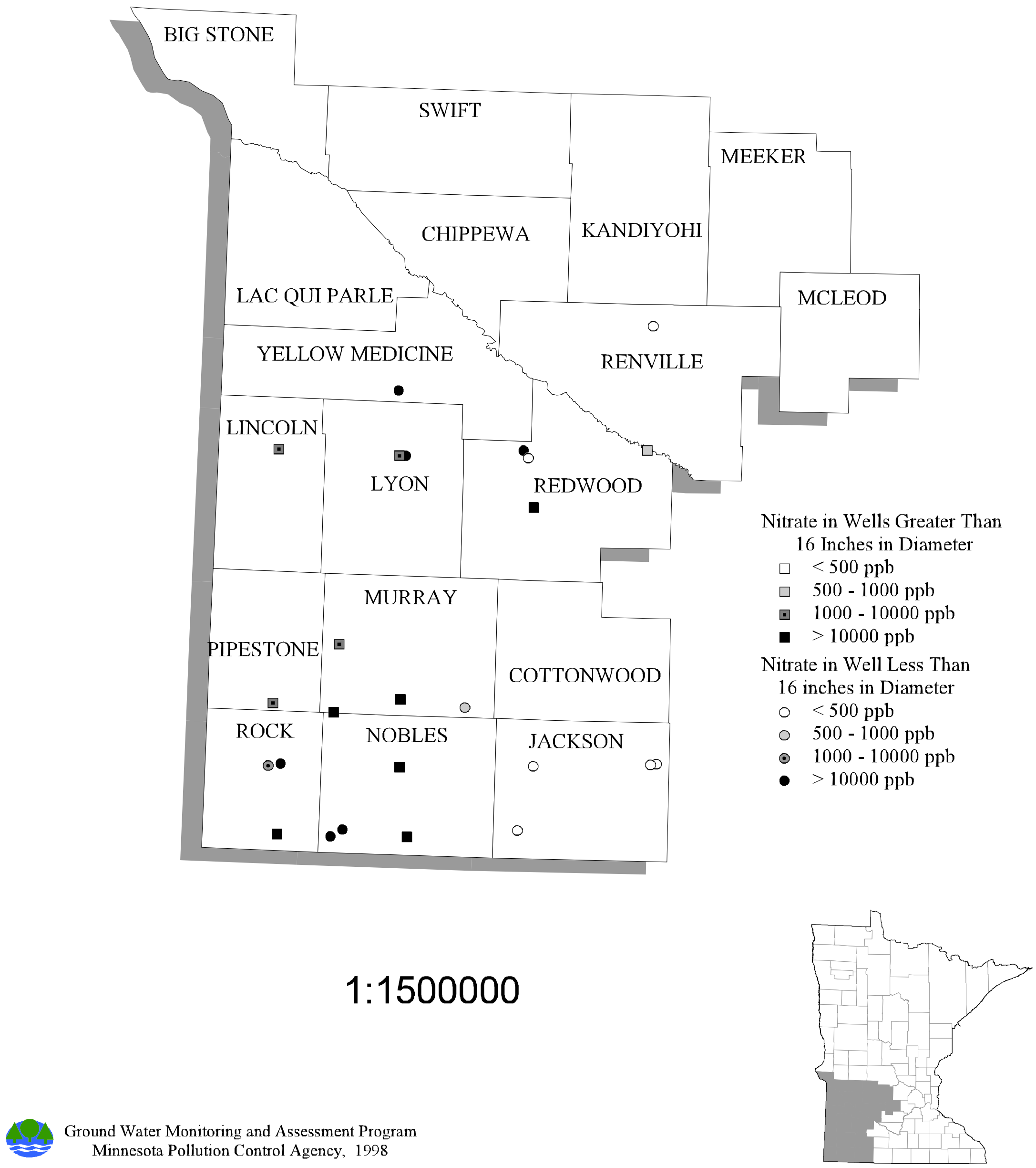


Figure B.8: Distribution of VOCs, chloride, and dissolved oxygen in samples from Region 4.

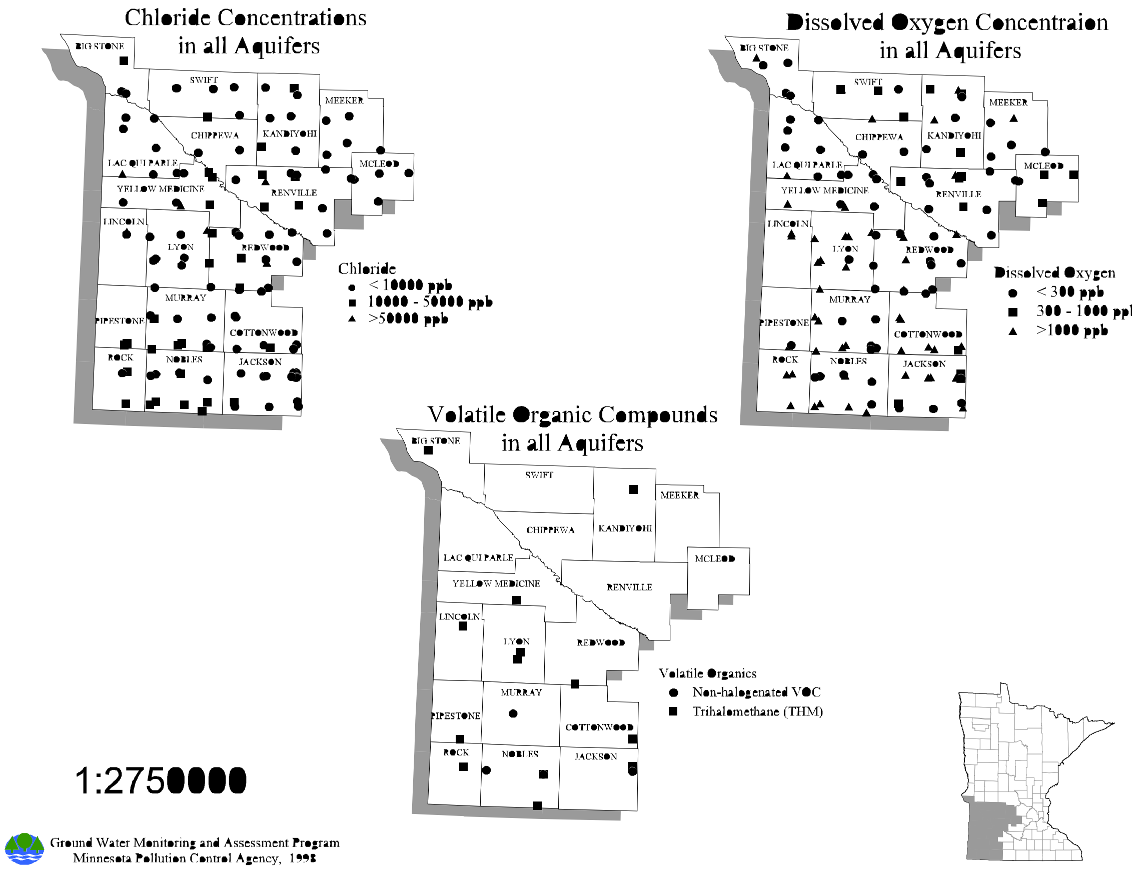
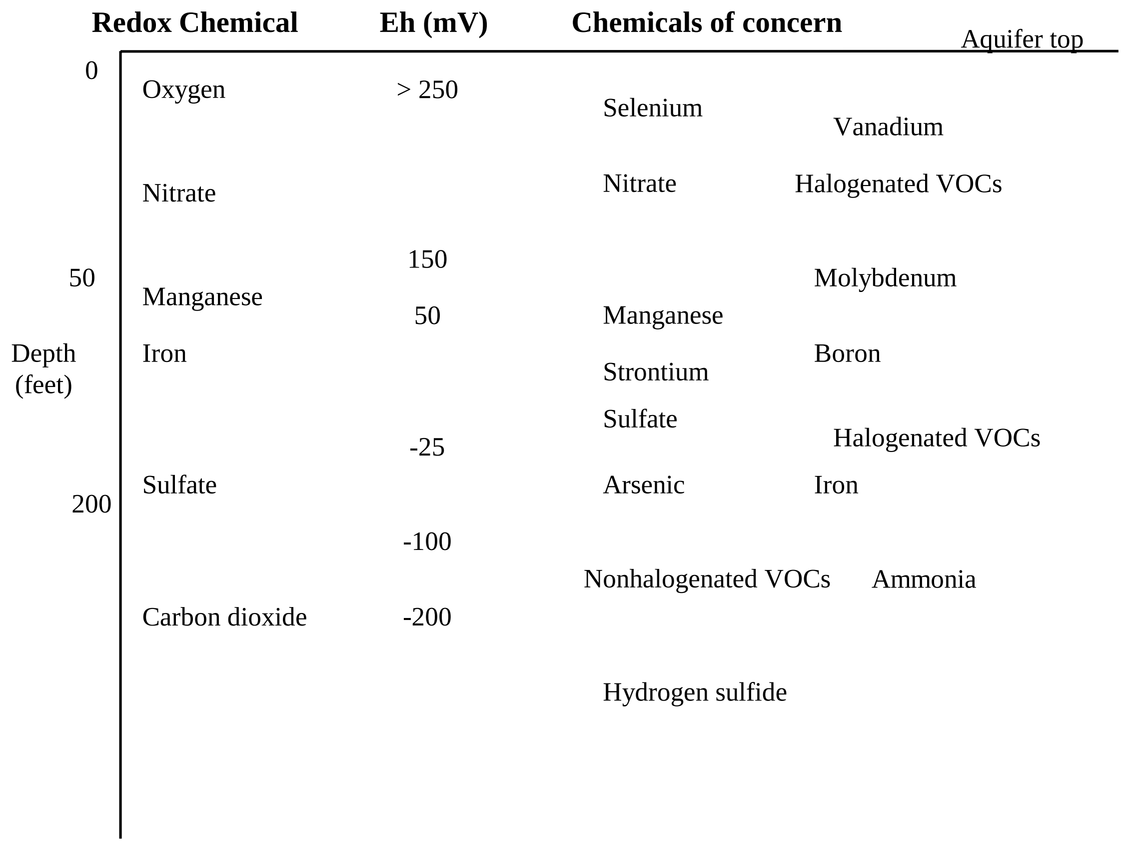


Figure B.9: Illustration of redox boundaries for some chemicals of concern. Also illustrated are chemicals which are likely to interact with the redox-sensitive chemicals.



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