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Delineation of High Salinity Conditions in the Cambro-Ordovician Aquifer of Eastern Wisconsin

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Abstract

The salinity and major ion content of the water contained within the Cambro-Ordovician aquifer of eastern Wisconsin was investigated. Data obtained from the Wisconsin Department of Natural Resources Drinking Water Database in conjunction with stratigraphic data obtained from the Wisconsin Geologic and Natural History Survey was used to compile an overall view of the geochemical conditions within the aquifer. All data was entered into GIS format (ArcView 3.2). Salinity of water pumped from the aquifer averages 473 ppm and is more saline to the north and east. The spatial variance in salinity is almost entirely due to a 1:1 molar increase in calcium and sulfate, probably due to dissolution of gypsum. In spite of this increase in calcium-sulfate character, the aquifer is dominated by calcium-bicarbonate water except in isolated locations within Calumet and Outagamie Counties where the water is calcium-sulfate in character. An attempt was made to correlate the percentage of the well open to a particular stratigraphic interval and salinity, however no correlation was found. Most wells within the study area do not exhibit large changes in salinity over time. Only 10 wells have salinity changes that exceed 10 ppm/year and of these, 5 exhibit decreasing salinities. Stratigraphic data are used to show the usage pattern of the Cambro-Ordovician aquifer. Maps are presented that show, on a relative basis, from which stratigraphic unit water is being pumped.

Introduction

The Cambro-Ordovician aquifer system extends over large portions of the upper Midwestern United States. In eastern Wisconsin, the Cambro-Ordovician aquifer serves as the primary source of drinking water for all of those urban areas that do not have access to Lake Michigan water. There is a growing recognition that geochemical conditions within the aquifer directly affect its usefulness. In some portions of eastern Wisconsin, total dissolved solids (TDS) content of the water is quite high; in other portions sulfate, arsenic, radium or gross alpha is anomalously high. This is of immediate concern to the affected municipalities because it effectively limits the amount of water that can be drawn from the aquifer. Two areas that are known to be particularly affected are in Waukesha County and in the lower Fox River Valley (Calumet, Fond du Lac and Brown Counties). Both of these areas are experiencing rapid growth thereby causing an ever-increasing pumping stress to the Cambro-Ordovician aquifer. In some areas of Waukesha County, TDS and gross alpha levels have been continuously climbing for years.

In order to effectively manage this critical water resource, the extent of these problems must be known. In addition, the underlying geochemical processes that give rise to these anomalies must be understood. Once the processes and the geographical extent of the problem are known, proper management strategies can be developed. The literature is full of research into the regional scale hydrogeology and overall geochemistry of the Cambro-Ordovician aquifer in various portions of the upper Midwest. The USGS has published an excellent overview of the Cambro-Ordovician aquifer system in the entire upper Midwest (Mandle and Kontis, 1992; Siegel, 1990). Smaller scale studies have been published in the Lake Michigan region, both in Illinois and Wisconsin (eg. Kammerer, et al., 1998; Perry, et al., 1982; Siegel, 1992; Weaver and Bahr, 1991a, 1991b). Evidence published in other than the open literature exists concerning the nature of various anomalous areas within eastern Wisconsin itself (eg. Grundl, et al., 2000; Layne Northwest, 1999; Taylor and Jansen, 2000; Simo, 1996). These data represent individual, unconnected lines of evidence that have been collected from a variety of sources including well water analyses, mineralogic analysis, downhole geophysical logs, and surface geophysical techniques (principally time domain electromagnetic induction).

These data have been used to suggest that high salinity zones are:

1) a function of depth with in the aquifer. Deep zones within the aquifer presumably have less groundwater movement and originally saline water and/or evaporite minerals have not been flushed out.

2) a function of the topography of the bottom boundary at the Precambrian/Cambrian interface. In this scenario, Precambrian basement highs isolate immediately down gradient groundwater from the main flow of groundwater.

3) a function of the confined/unconfined boundary beneath the Makoqueta Shale subcrop. This theory holds that glacial advances in the Pleistocene reversed groundwater flow out of the Michigan Basin and transported deep saline water up to shallow levels.

4) solely a function of Ca^{2+} and SO_4^{2-} ions.

5) getting worse over time.

Each of these trends suggests a distinct way to manage the resource. Each trend may hold true for the specific area in which it was developed, however it is not known if any of these trends holds true over a regional scale. No clear regional study has been performed in eastern Wisconsin that coalesces all the available data into a cohesive picture.

There is a general agreement in the scientific community that one of the primary obstacles to the full understanding of the Cambro-Ordovician system is the lack of vertically discrete water quality data. A full understanding of the Cambro-Ordovician system requires three-dimensional information on both the groundwater flow regime and water chemistry. The collection of vertically discrete water quality information is problematic because water supply wells are typically open to large portions of the Cambro-Ordovician aquifer and vertically discrete water samples are virtually non-existent. Collection of vertically discrete samples requires either packer testing or the collection of vertically averaged samples taken from sampling containers opened at varying depths beneath the pump of actively pumped wells. The necessity for geophysical and flowmeter logging, along with long pumping times (on the order of weeks) prior to sample collection means that these techniques are very expensive and disruptive to the water supply system of the municipalities involved. To date, only three sets of vertically averaged samples have been collected. Clearly additional vertically discrete samples must be collected before an adequate understanding of the Cambro-Ordovician system is achieved.

Any future collection of such expensive and critical water samples should be guided by as clear an understanding of the problem as possible. With this in mind, the objective of this study is to use existing data to delineate, in a cohesive manner, the extent of high salinity conditions within the Cambro-Ordovician aquifer system in the whole of eastern Wisconsin. The lateral extent of high salinity will be delineated by use of the Wisconsin Department of Natural Resources (WDNR) drinking water database. The entire WDNR database is posted on the Internet in a manner that allows for efficient searching for water quality constituents. The usefulness of the WDNR drinking water database is not limited to the simple delineation of high salinity. Hints as to temporal trends and the geochemical processes in operation are possible by the study of major ion analyses taken from individual wells. The database does not explicitly contain any vertically discrete data, therefore estimation of vertical extent will be limited to performing a correlation between the stratigraphic intervals intersected by specific wells and TDS.

This study provides an overall view of the geochemical conditions in the Cambro-Ordovician aquifer system in eastern Wisconsin. It has discounted some theories surrounding the relation between TDS and stratigraphy as well as brought to light other patterns in eastern Wisconsin. It will become especially powerful when combined with the hydrologic picture that is beginning to emerge from modeling studies such as the SE Wisconsin Regional Flow Model. This synthesized hydrologic/geochemical view of the aquifer can also form a framework against which specific geochemical problems (such as the provenance of high radium and arsenic) can be studied.

Methods

The WDNR Drinking Water database, the Wisconsin Geologic and Natural History Survey (WGNHS) stratigraphic well logs, and the stratigraphy contained within the SE Regional Model served as the primary sources of data for this project. The counties contained in the study area include Brown, Calumet, Dodge, *Door*, Fond du Lac, Jefferson, Kenosha, *Kewaunee, Manitowoc, Marinette*, Milwaukee, *Oconto*, Outagamie, Ozaukee, Racine, Rock, *Shawano, Sheboygan*, Walworth, Washington, Waukesha, and Winnebago. No usable data existed for the counties in listed in italics. Figure 1 shows the location of the counties with usable data. Chemical constituents extracted from the database include alkalinity, calcium, chloride, magnesium, sodium, and sulfate. If samples also included information on measured total dissolved solids (TDS), nitrate, pH, iron, or potassium, the respective information was kept, but not directly used in subsequent analysis.

Only those wells open exclusively to the Cambro-Ordovician aquifer were included. Geologic well logs obtained from the WGNHS and the SE Regional Model's stratigraphic database were used to determine the depth and stratigraphy of the wells. Well construction logs from the drinking water database were used to confirm the depth of the wells. Those wells that were not open to the Cambro-Ordovician aquifer or did not reach the Cambro-Ordovician aquifer were eliminated from the study.

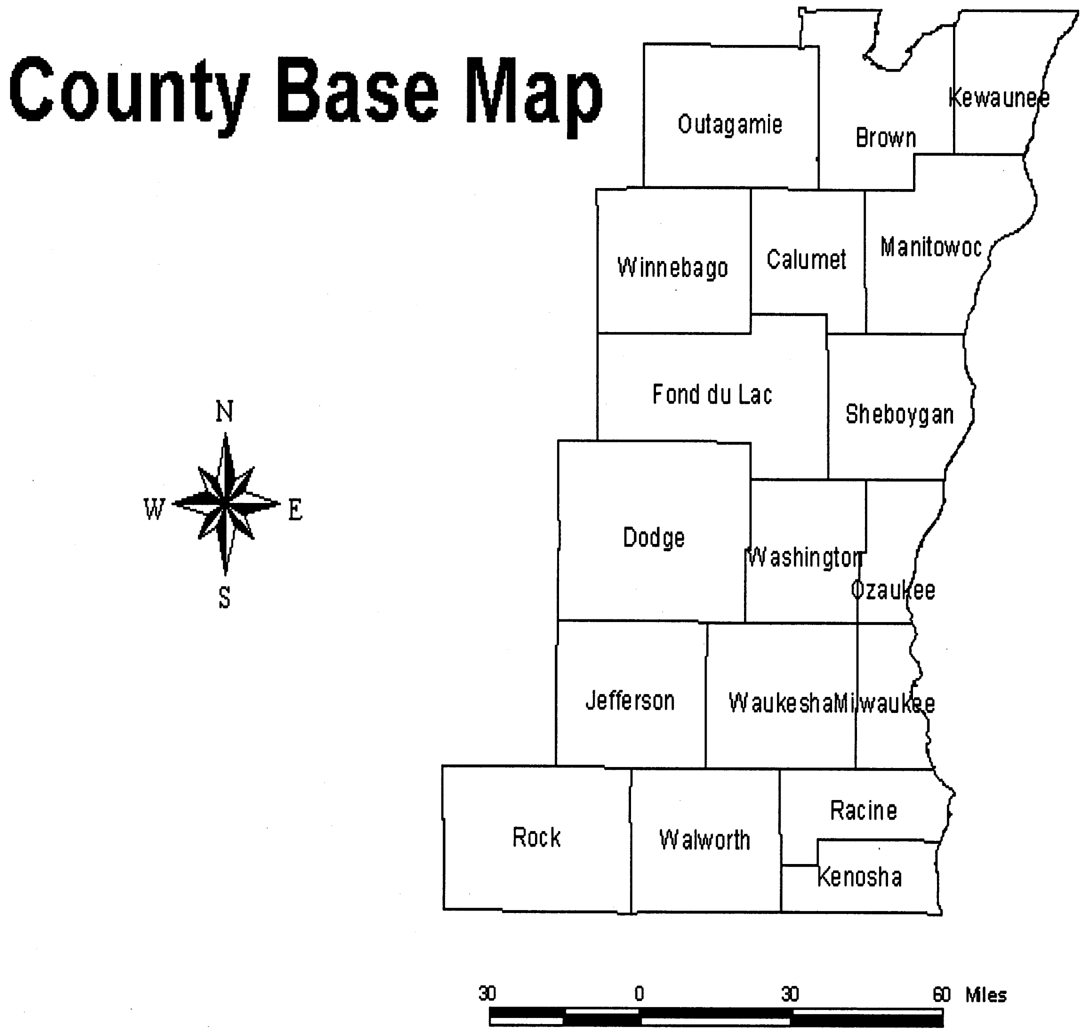


Figure 1: Base map showing the location of all counties in eastern Wisconsin that were included as a part of the study area.

The stratigraphic units used in this study follow WGNHS nomenclature for the Cambro-Ordovician aquifer. From top to bottom the units are: Sinnipee, St. Peter, Trempeleau/Tunnel City, Wonewoc, Eau Claire, Mt. Simon, and Precambrian bedrock. From approximately Fond du Lac county northward, very few stratigraphic logs distinguish between the Wonewoc, the Eau Claire, and the Mt. Simon, instead collectively calling all three the Elk Mound. Therefore, the Elk Mound is used to the north of Fond du Lac county to represent the deeper portions of the aquifer.

All chemical data was checked for accuracy. Each sample had the sum of anions, the sum of cations, the ionic strength, the electrical balance, the mass balance (difference between the measured TDS and the TDS calculated from the sum of all ions) calculated. All samples with an electrical balance error greater than 15% were rejected. All but twenty-seven of the remaining samples had a mass balance error of less than 10%. These twenty-seven samples remained in the database but were denoted as having a larger mass balance error.

The database contains water quality information from 1977 to the present. Over 259 separate analyses from a total of 188 wells are included in the study. Of these, 51 have multiple samples collected over a time span greater than one year. Complete stratigraphic data have been obtained for 112 wells. The remaining 76 wells have well construction reports confirming that they are open to the Cambro-Ordovican aquifer.

Well location, in degrees of latitude and longitude, was obtained from either the WDNR database itself, or by use of www.topozone and Yahoo! Maps in conjunction with the address of the well or city. All locations were converted to decimal degrees for input into the internal project database.

All data was saved in spreadsheet format (Excel), in database format (DBF IV format) for inclusion into the GIS program ArcView 3.2, and in text format for inclusion in the geochemical program AquaChem 3.70. Multiple samples from a single well were averaged before inclusion into the AquaChem program. AquaChem output (Figure 10 and 18) therefore represents a single, time-averaged water quality analysis for each well.

Results

Throughout this section and in the Appendices, contour maps are presented. These maps were generated by ArcView 3.2 using the inverse distance weighted method of interpolation and 20 nearest neighbors. The method assumes that each point has a local influence that diminishes with distance. This contouring routine is subject to certain limitations. In particular, the routine tends to draw "bulls-eyes" around data points and in addition, contouring trends get carried to the edge of the domain. This can be misleading in areas with little or no data control near the edges. It is for this reason that the contouring domain has been clipped in parts of the study area. These program limitations must be kept in mind when interpreting the data.

Stratigraphic Relations

The stratigraphic data collected during the course of this study provide an excellent way to gain an overall insight of the usage patterns of the Cambro-Ordovician aquifer. Figures 2 through 8 are contour maps showing, on a relative basis, from where the water is being pumped throughout eastern Wisconsin. For a given well, the percent of open interval that is assigned to a particular stratigraphic interval is a function of the relative thickness of the interval itself as well as the total depth of the well. Since few wells penetrate the entire Cambro-Ordovician section, Figures 2 through 8 are not isopach maps, but rather reflect what stratigraphic units are actually being pumped in a given location.

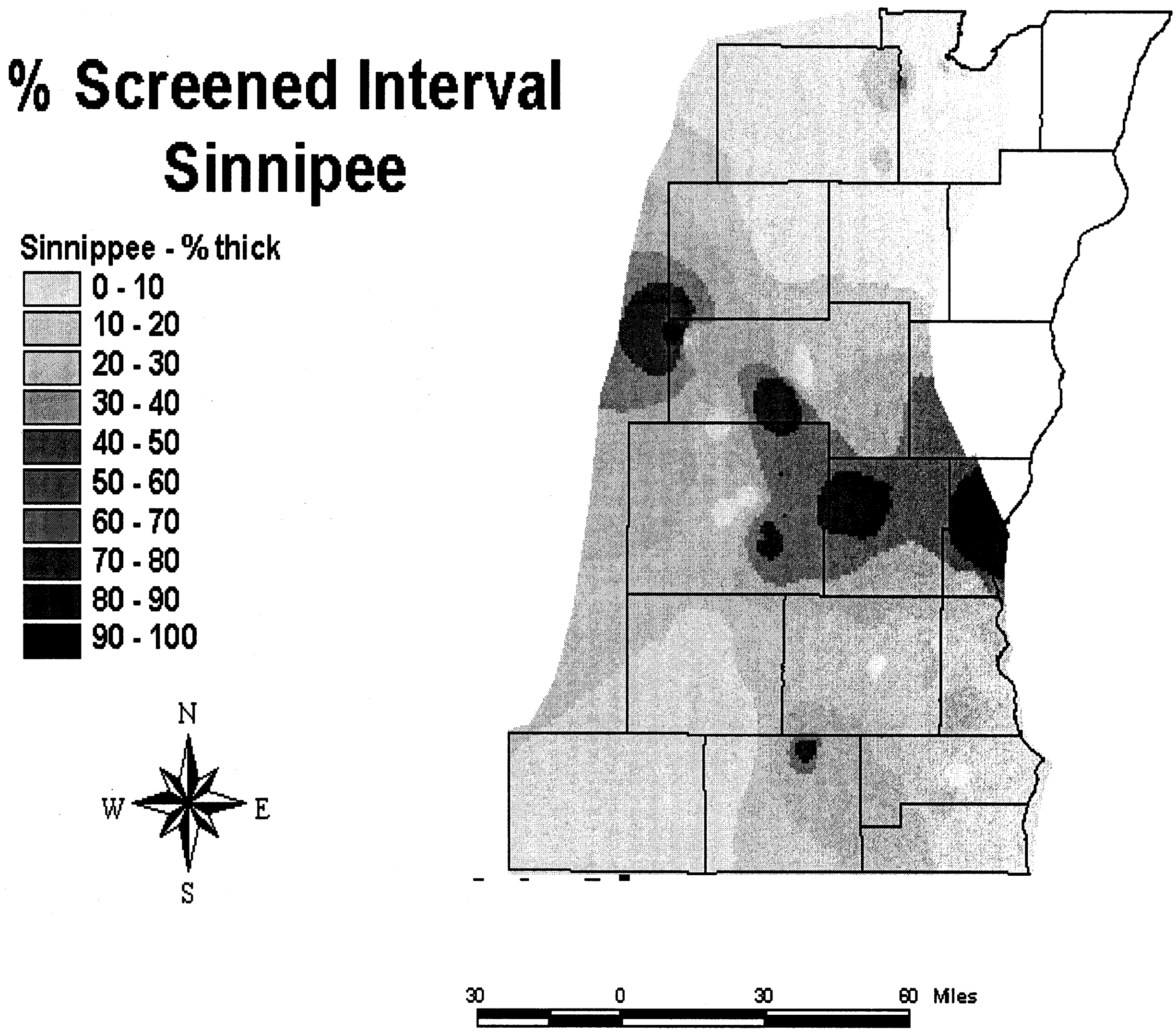


Figure 2: Percent of the screened interval of wells in the Cambro-Ordovician aquifer of eastern Wisconsin that is open to the Sinippee Formation.

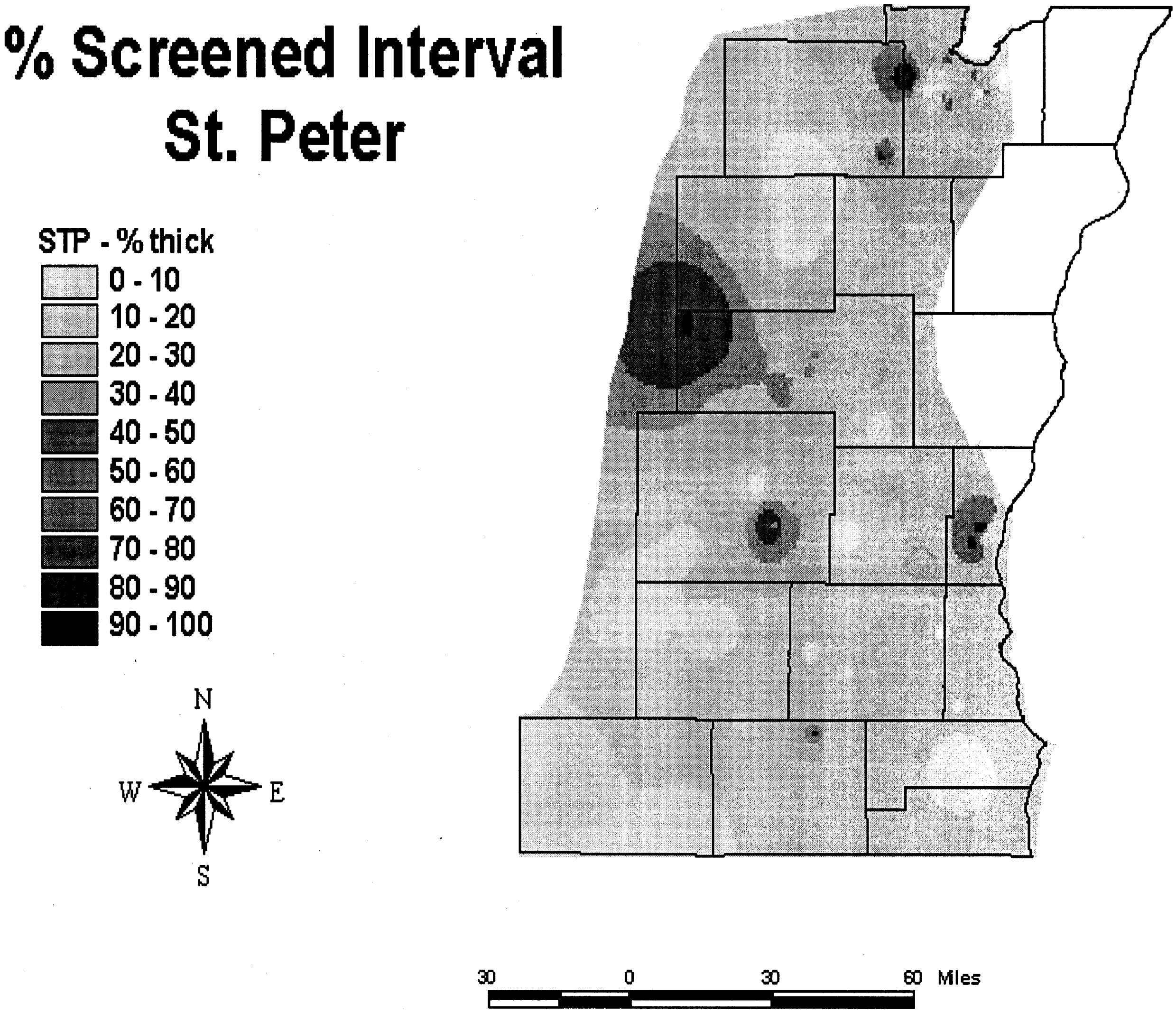


Figure 3: Percent of the screened interval of wells in the Cambro-Ordovician aquifer of eastern Wisconsin that is open to the St Peter Formation Formation.

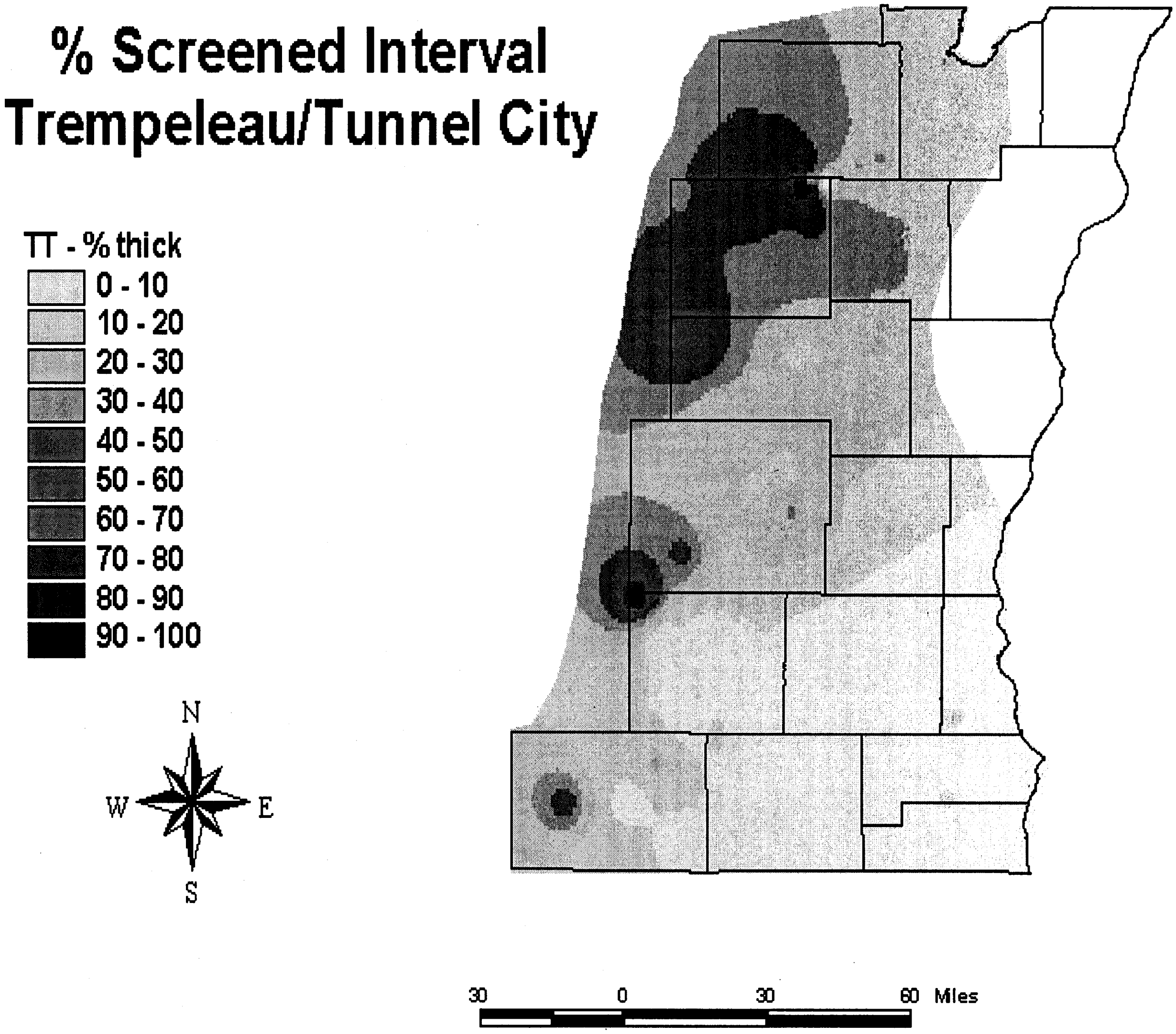


Figure 4: Percent of the screened interval of wells in the Cambro-Ordovician aquifer of eastern Wisconsin that is open to the Trempeleau/Tunnel City Formations.

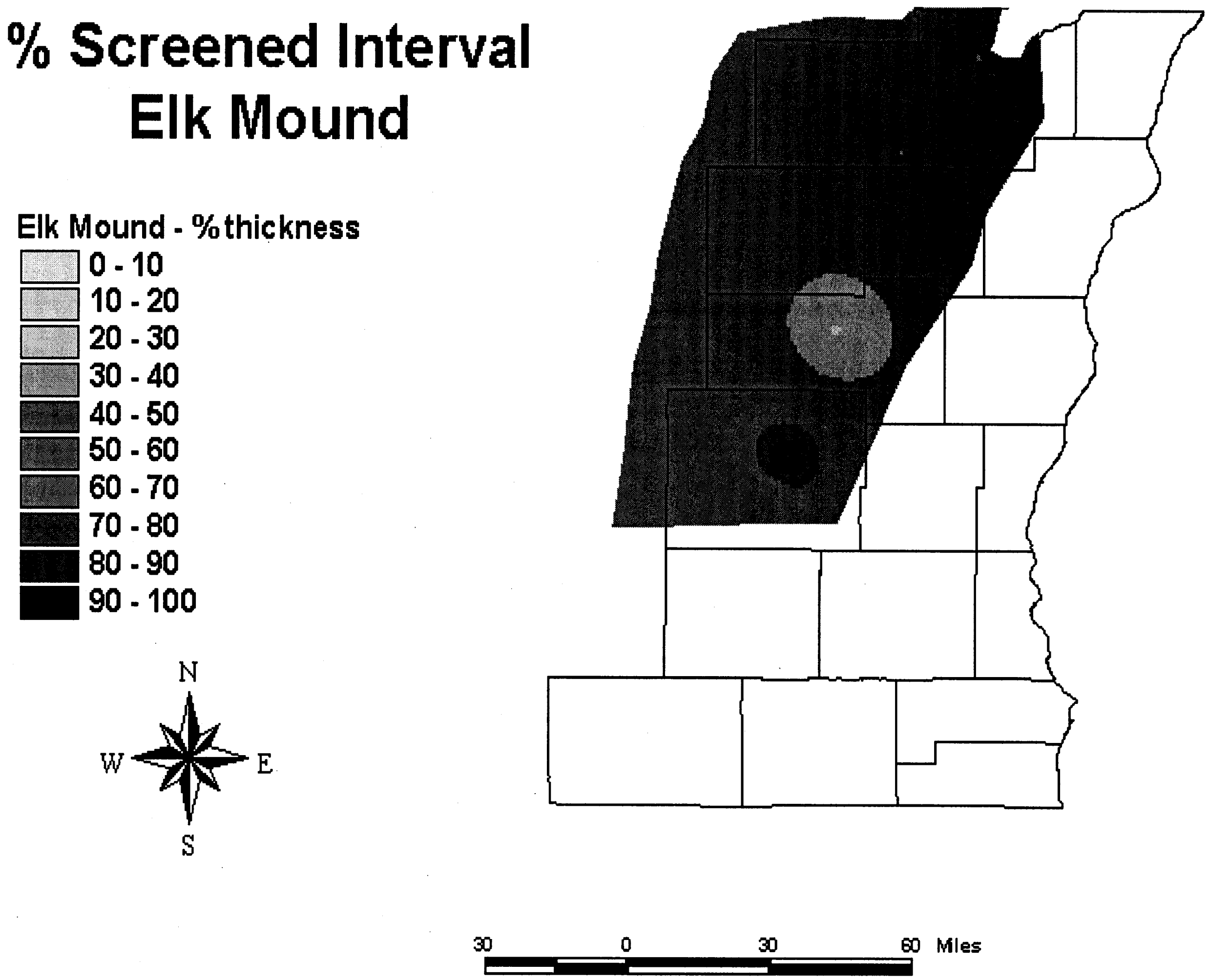


Figure 5: Percent of the screened interval of wells in the Cambro-Ordovician aquifer of eastern Wisconsin that is open to the Elk Mound Formation. The Elk Mound Formation is defined only in the northern half of the study area.

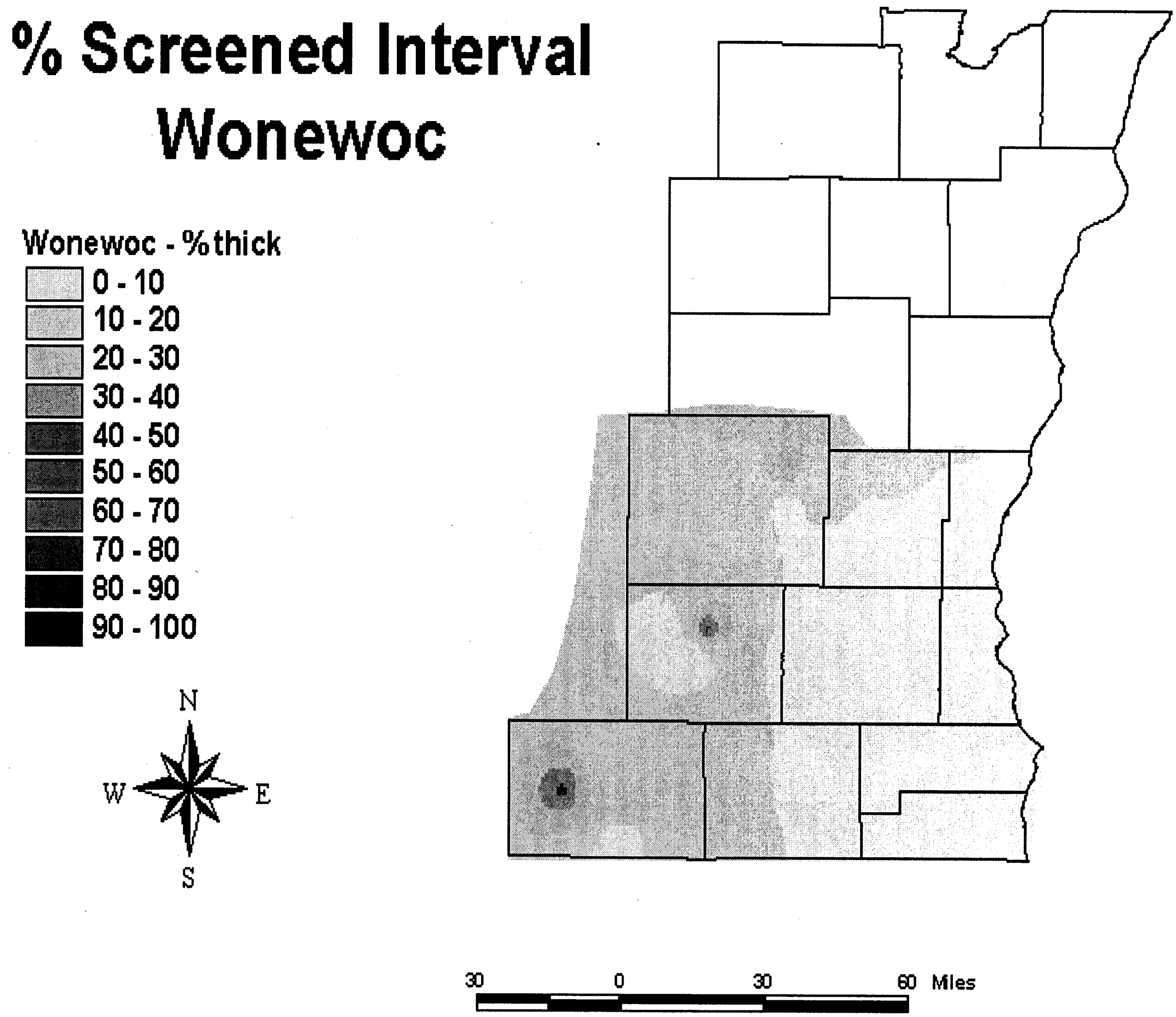


Figure 6: Percent of the screened interval of wells in the Cambro-Ordovician aquifer of eastern Wisconsin that is open to the Wonewoc Formation. The Wonewoc Formation is defined only in the southern half of the study area.

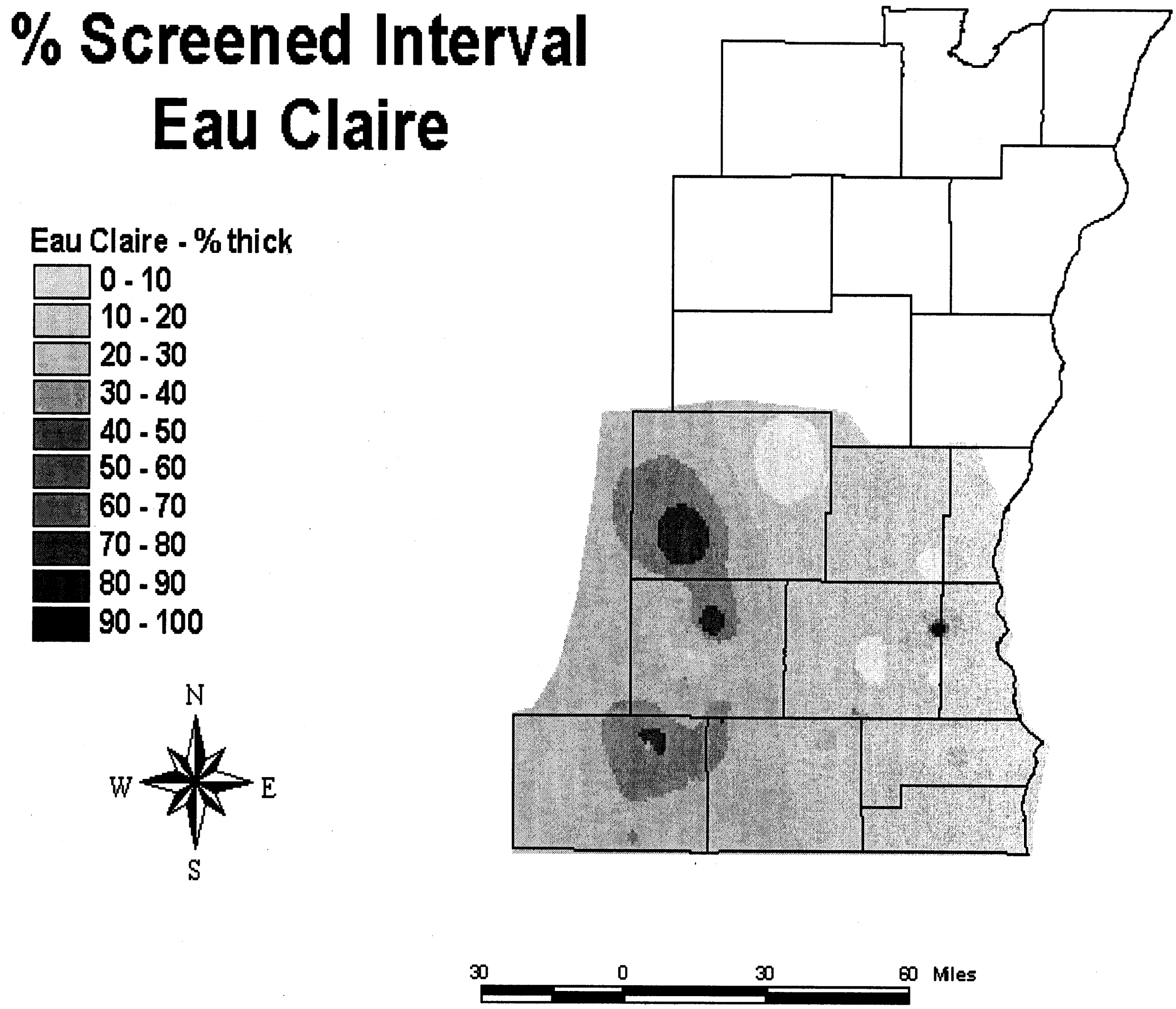


Figure 7: Percent of the screened interval of wells in the Cambro-Ordovician aquifer of eastern Wisconsin that is open to the Eau Claire Formation. The Eau Claire Formation is defined only in the southern half of the study area.

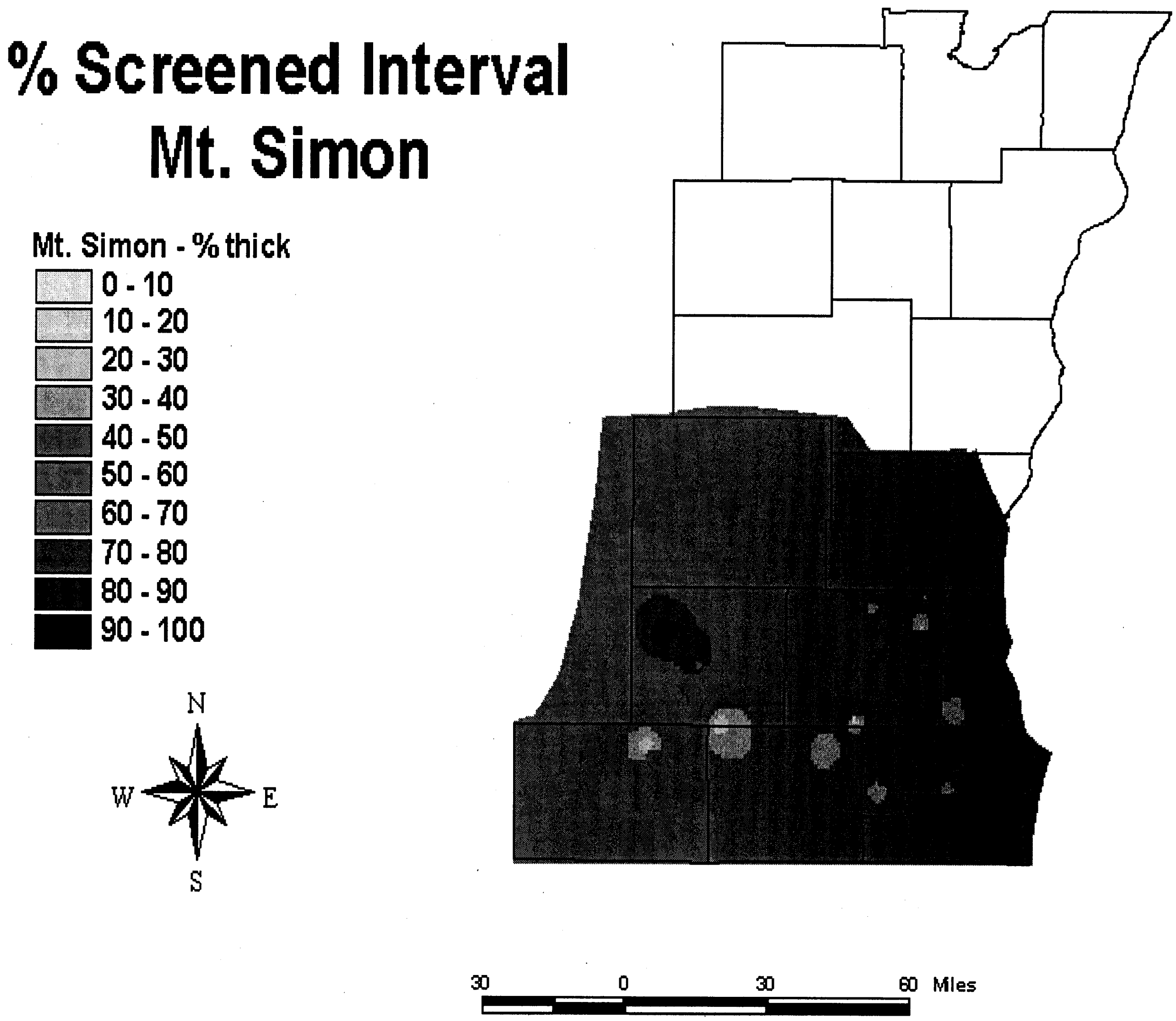


Figure 8: Percent of the screened interval of wells in the Cambro-Ordovician aquifer of eastern Wisconsin that is open to the Mt Simon Formation. The Mt Simon Formation is defined only in the southern half of the study area.

These figures are arranged in order from the shallowest to the deepest units. It is clear that widely different portions of the stratigraphic section are being used for water supply throughout the study area. The Sinnipee seems to be utilized more in the center portion of the study area, in a broad northwest to southeast trend (Figure 2). On the other hand, the St. Peter exhibits a generally uniform usage of about 20-30% saturated thickness (Figure 3). The deeper Trempeleau/Tunnel City tends to occupy the wells located in the western part of the study area where it occurs at shallow enough depths to be readily accessible. The Elk Mound stratigraphic unit is defined only in the northern half of the study area and represents a combination the Wonewoc, Eau Claire and Mt. Simon units. The Elk Mound map (Figure 5) depicts the stratigraphically defined Elk Mound unit in the northern half of the study area. No wells penetrated the Elk Mound in the eastern portion of the study area and this is the reason that Figure 5 is not contoured in this area. Figures 6 through 8 depict theWonewoc, Eau Claire and Mt. Simon units individually in the southern portion of the study area. Where the Wonewoc and Eau Claire are mapped separately, these deeper formations are used preferentially in the western part of the study area. The Mt. Simon unit is the predominant formation used throughout the entire the southern portion of the study area (Figure 8).

To the west of the study area, the lower units are much more accessible since the entire stratigraphic interval dips to the east. On the eastern side of the study area, it was much harder to obtain data for the Cambro-Ordovician aquifer because the units were very deep. Note that no data results were found in Manitowoc, Kewaunee, or Door counties and very little data were found in Ozaukee, Milwaukee, and Kenosha counties. The few bedrock wells that are located in these areas produce sufficient water from the overlying Silurian dolomite and do not reach the Cambro-Ordovician aquifer.

Total Dissolved Solids

The total dissolved solids (TDS) content of the Cambro-Ordovician aquifer was examined as a function of time, spatial extent and in relation to the stratigraphic intervals intercepted by each well. An isopleth map of the entire 18 county area shows a general increase in TDS values to the north and east (Figure 9). A distinct increase can be seen across a NW/SE trending line that extends from Kenosha County to the western side of Fond Du Lac County. The TDS values reach a maximum value of 4912 ppm and a minimum value of 204 ppm. One well in Calumet County (Calumet County Park - Showers, WDNR unique well ID # EQ020) exhibits a TDS value (4912 ppm) that is significantly higher than all other wells. Exclusive of this well, the maximum TDS content within the aquifer is 1245 ppm and the average TDS is 473 ppm. For clarity, this well is not included in any of the subsequent data plots or Piper diagrams. Data from this well is included in all Arc View maps. Fifty-two wells are producing water with TDS values in excess of Wisconsin's drinking water standard of 500 ppm. The highest salinities are observed in Calumet and southern Outagamie counties. A general increase in salinity is observed to the north and east that is in general accord with previous studies (Kammerer, 1998; Ryling, 1961). Ryling (1961) reports very high salinities in extreme eastern Manitowoc and Sheboygan counties, however his data included wells that were open to Silurian units above the Makoqueta Shale.

Although the WDNR database does not explicitly contain vertical information, hints as to vertical trends can be obtained by comparing salinity with the percentage of the well that is open to a particular stratigraphic unit. Stratigraphic intervals were obtained from the WGNHS for 100 wells. Comparison of the TDS map (Figure 9) with any of the percent thickness maps (Figures 2 through 8) shows no relation between the preponderance of a particular stratigraphic interval and the resultant TDS. A plot of TDS versus the percent of the well that is open to each stratigraphic unit is given in Figure 10. This plot also shows no evident relation between salinity and stratigraphy. If TDS were related to a particular stratigraphic unit, the colors would be coordinated in a rainbow effect as TDS increased. There is no trend in this data to indicate increasing salinity with increasing depth. Similar plots of the individual ions versus percent of the well open to each stratigraphic units also show no relationship (data not shown). This lack of stratigraphic correlation agrees with data collected on the three wells in eastern

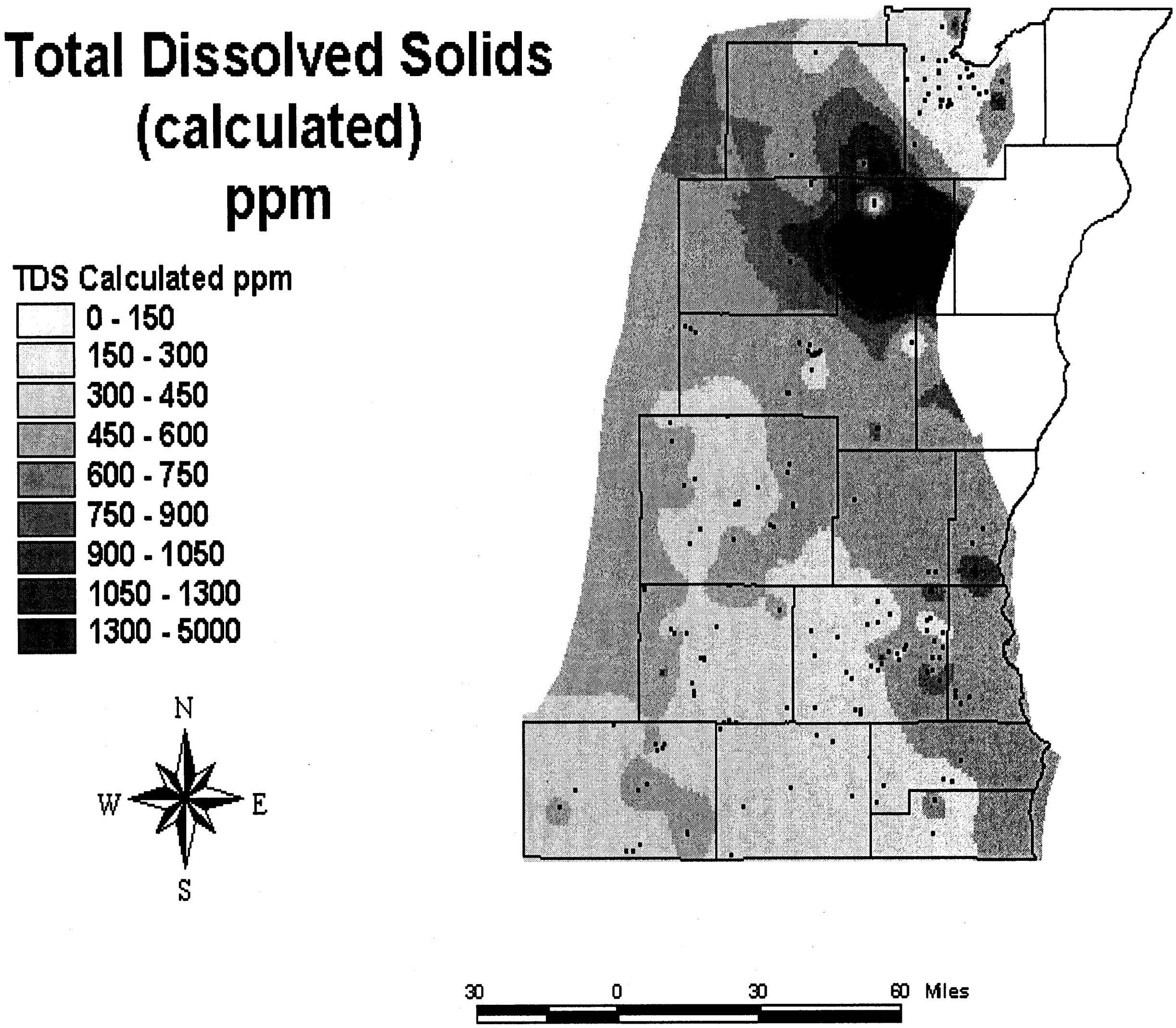


Figure 9: Isopleth map of the total dissolved solids content of the Cambro-Ordovician aquifer of eastern Wisconsin. Total dissolved solids (calculated ppm) are based on the summation of the concentrations of the major ions expressed in parts per million. Black spots indicate individual wells.

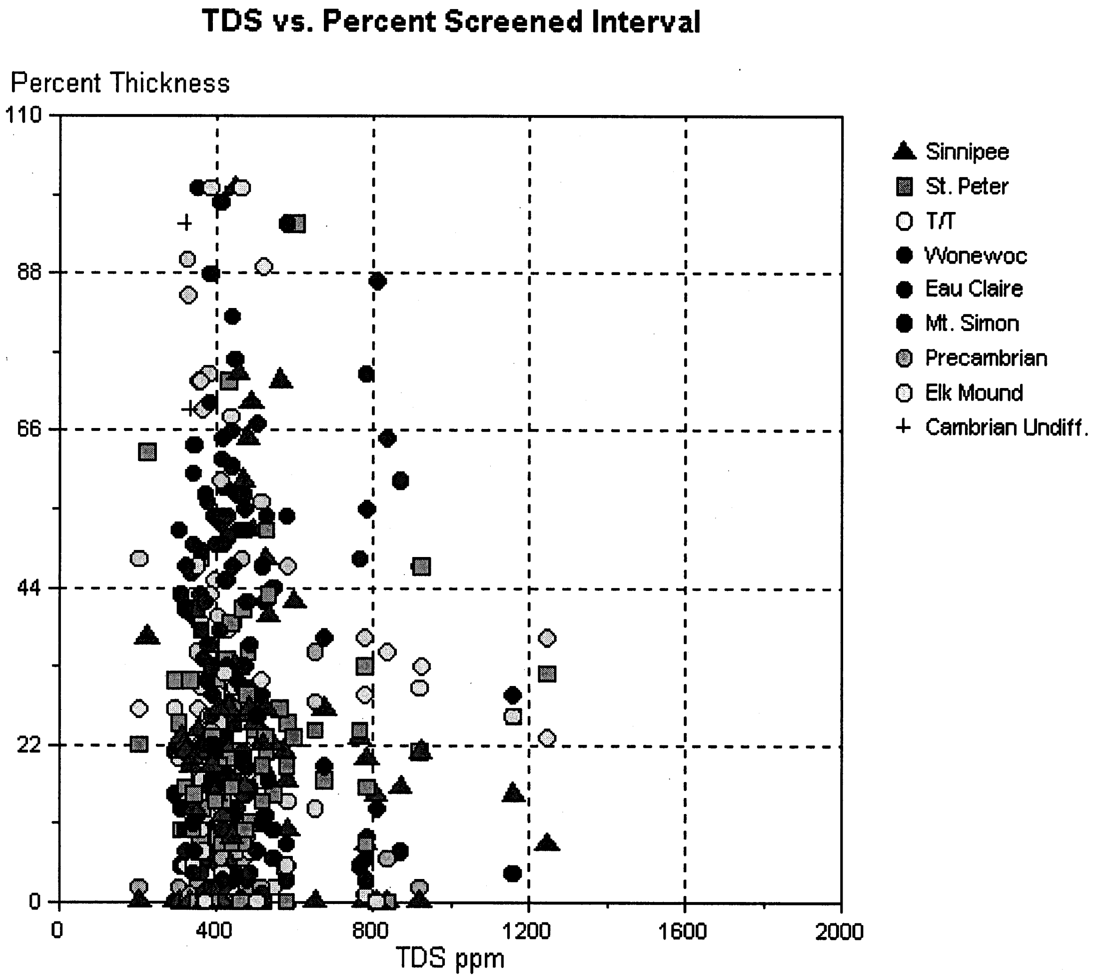


Figure 10: Plot of the total dissolved solids content (ppm calculated) of a well versus percent of the well that is open to each stratigraphic interval.

Wisconsin that have been sampled in a vertically averaged manner (Waukesha #9, New Berlin #8, Sussex #5). In none of these wells is an increase in salinity with depth observed (data contained in Aquifer Science and Technology, 2001a,b). In contrast, static logs of Waukesha #9 show a marked increase in specific conductance and temperature with depth (Jansen, et al., 2002). The relationships between produced water and stratigraphic interval as done in the present study do not provide sufficiently accurate information to rectify this dichotomy.

Although no relationship between salinity or chemical character and stratigraphy is seen, numerous complicating factors may exist. One important complication is that lateral facies changes within a given stratigraphic interval are certain to occur. Lateral variations in salinity that are a result of these facies changes are contained in the data and cannot be factored out. This can be especially problematic where hydrostratigraphic units cross pure stratigraphic units that are defined in terms of lithology alone. The flow regime of the Cambro-Ordovician aquifer is not well enough understood at this time to define hydrostratigraphic units.

The data was also examined for temporal variation. Fifty-one wells were found with chemical data that was separated by a minimum of one year. All of the analyses were separated by at least 1.8 years with an average time separation of 8.2 years. These data indicate that, in general, the water produced from the Cambro-Ordovician aquifer is remaining relatively constant over time. A frequency plot of the time rate of change (Figure 11) shows this trend very clearly. Forty-one of the 51 wells (80%) exhibit a change of less than 10 ppm per year and 29 wells (57%) change less than 5 ppm per year. Equally evident is the fact that the number of wells exhibiting an increase and decrease salinity are equal. In some cases, individual wells within a well field will exhibit an increase in salinity while the surrounding wells remain constant. The location of those wells with rates of salinity change larger than 10 ppm per year (either increasing or decreasing) are shown in Figure 12. No correlation with spatial location, depth of well, or overall pumpage can be seen.

Chemical Character

Throughout much of the study area, a rise in TDS is strongly correlated with a rise in the Ca-SO_4 content of the water. The molar ratio of calcium to sulfate approximates

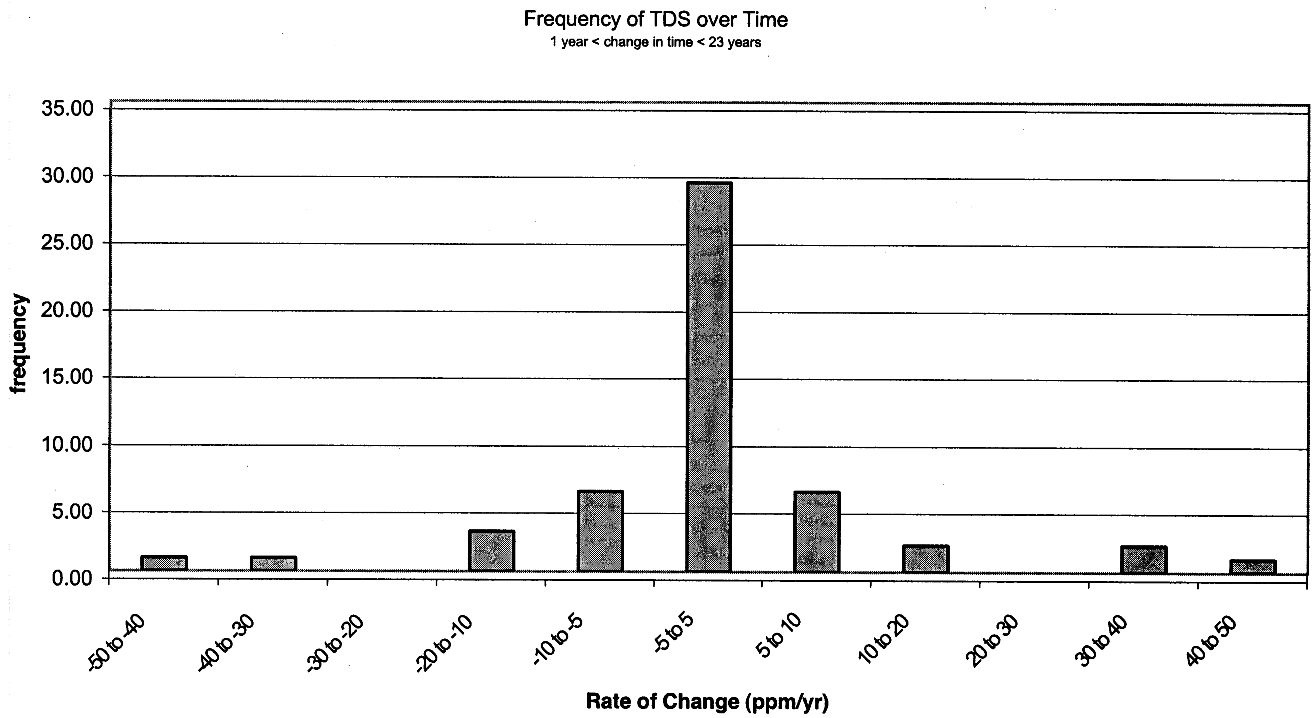


Figure 11: Frequency plot of the rate of change in total dissolved solids content over time. Minimum time period for which rate of change is calculated is 1.8 years.

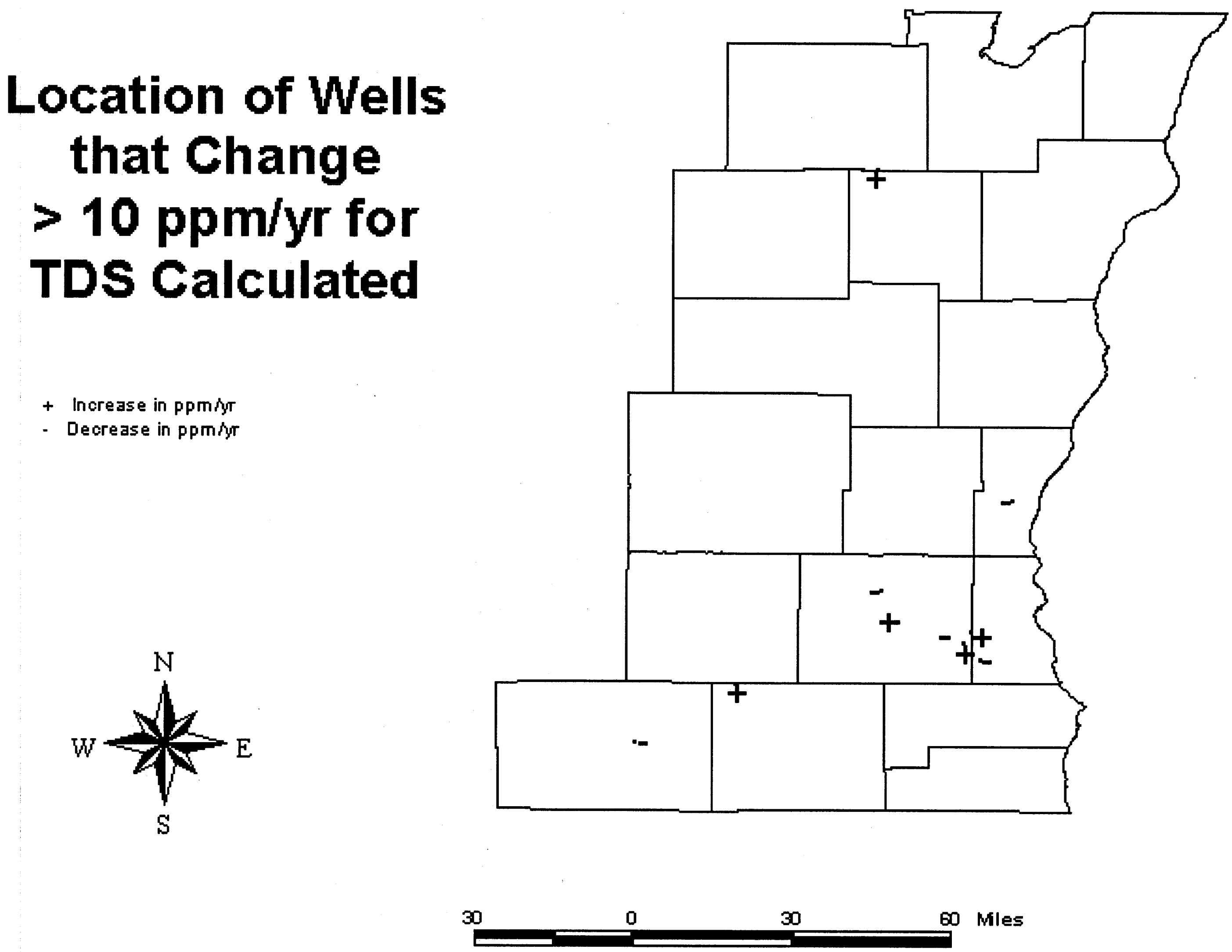


Figure 12: Location of wells that exhibit a salinity rate of change. Wells that exhibit a decrease in salinity greater than 10 ppm/year are indicated by - . Wells that exhibit an increase in salinity greater than 10 ppm/year are indicated by + .

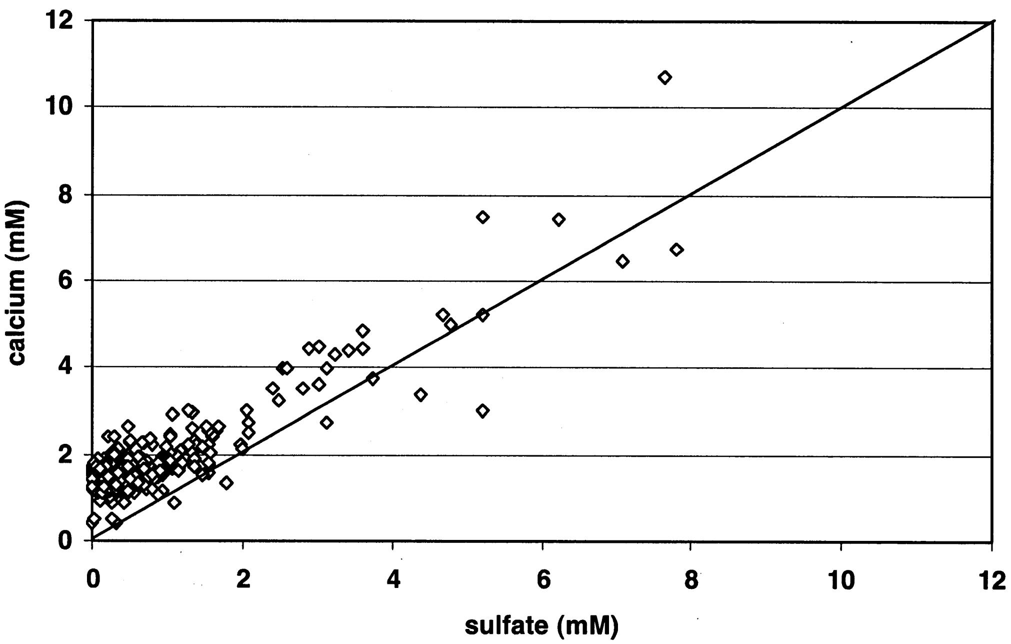


Figure 13: Molar relationship between calcium and sulfate in Cambro-Ordovician wells of eastern Wisconsin. Line indicates the 1:1 molar ratio.

1:1 as concentrations rise (Figure 13). An increase in calcium is matched by an increase in sulfate except at low concentrations at which point calcium is in excess. At these lower concentrations dissolution of calcite and dolomite becomes an important contributor to the total calcium content of the water. A 1:1 molar increase in calcium and sulfate as the overall TDS rises is an indication that gypsum dissolution is the primary source of high salinity. This is further supported by the observation that the dS isotopic signature of sulfate reflects seawater composition over much of the study area as would be expected from gypsum that has precipitated from seawater (Siegel, 1990).

The relationship between TDS and sulfate content is further exemplified in Figure 14. A linear least squares regression shows a good correlation between sulfate and TDS content. The equation relating TDS and sulfate is:

$$SO_4^{2-}(ppm) = 0.64[TDS(ppm)] - 218. \qquad r^2 = 0.73$$

This relation indicates that 73% of the increase in salinity can be accounted for by an increase in sulfate.

The spatial relation between sulfate and TDS are also strongly correlated. This can be seen by comparing Figures 16 and 9. In general, both the salinity and Ca-SO_4 nature of the water is lowest in the southeast portion of the study area and rises to the northeast. Sulfate and bicarbonate show an inverse relation as would be expected from the two primary anions in the water. This relation can be seen by comparing Figures 16 and 17. In spite of rising sulfate to the north and east, most of the aquifer is dominated by bicarbonate-rich water. Figure 16 indicates that a small portion of Brown and Outagamie counties and two individual wells in Ozaukee county are the only portions of the aquifer that are dominated by sulfate (ie. greater than 50% sulfate). Calcium is the dominant cation throughout the entire study area (Figure 15).

Waukesha and Brown counties are illustrative of the chemical trends in the aquifer at large because they both contain large numbers of wells and both are located in

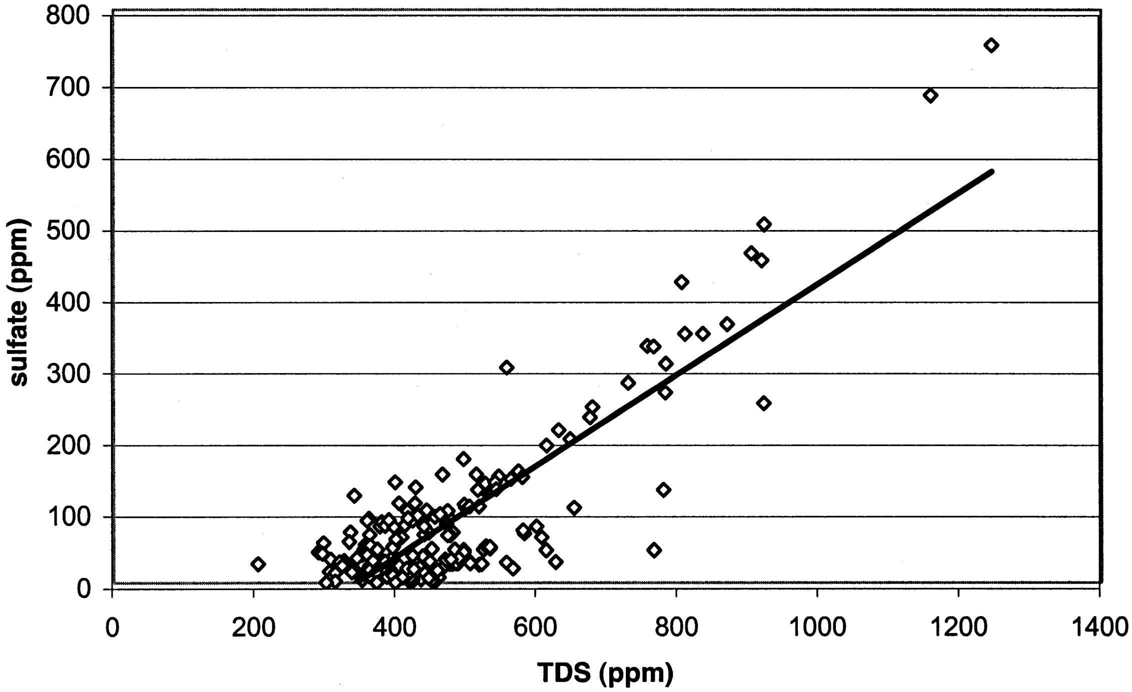


Figure 14: Relationship between sulfate content and total dissolved solids in Cambro-Ordovician wells of eastern Wisconsin. Solid line is the linear regression best-fit line.

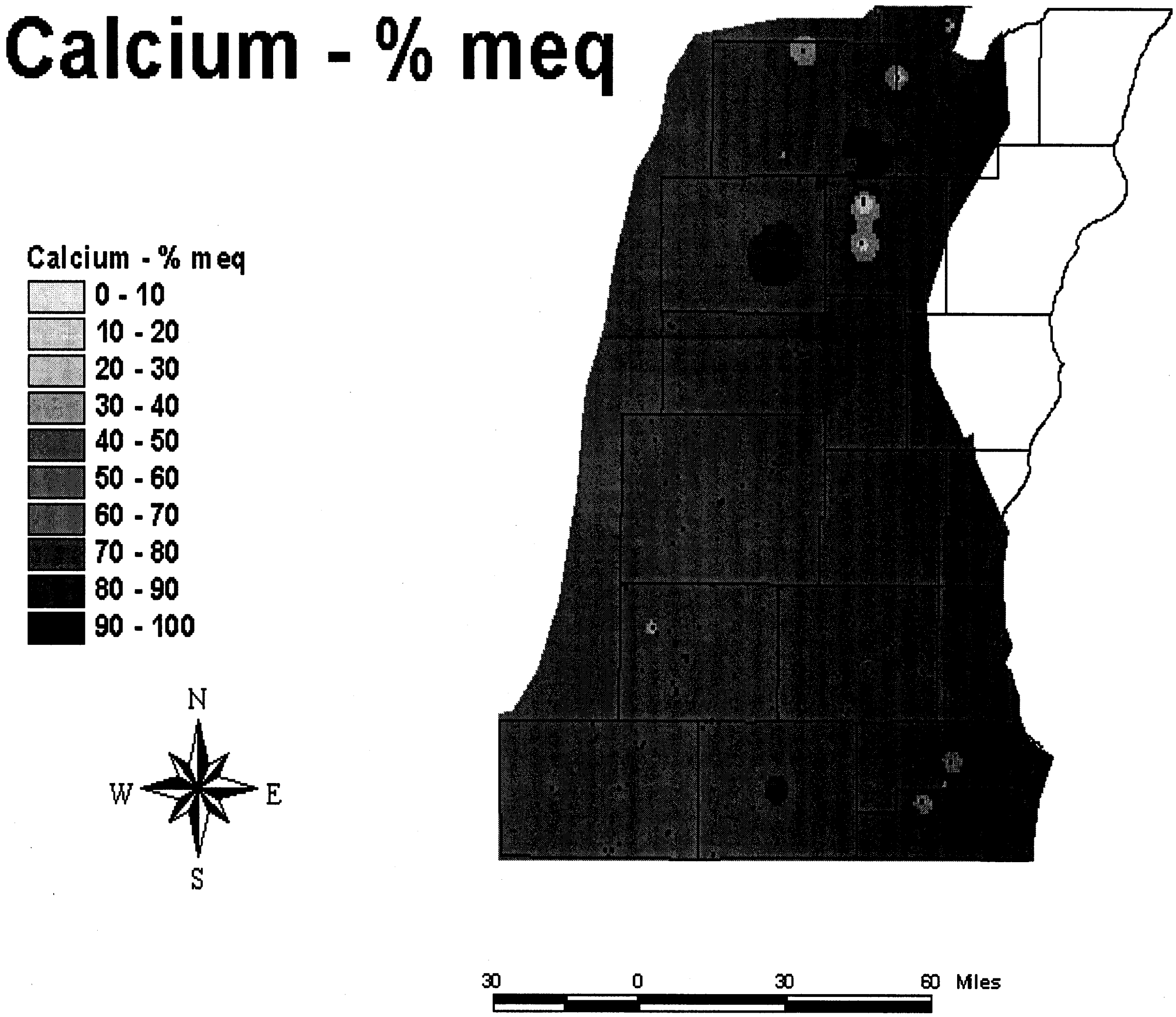


Figure 15: The percent of total cations in water produced from wells in the Cambro-Ordovician aquifer of eastern Wisconsin that is attributable to calcium. Expressed as % milliequivalents. Black spots indicate individual wells.

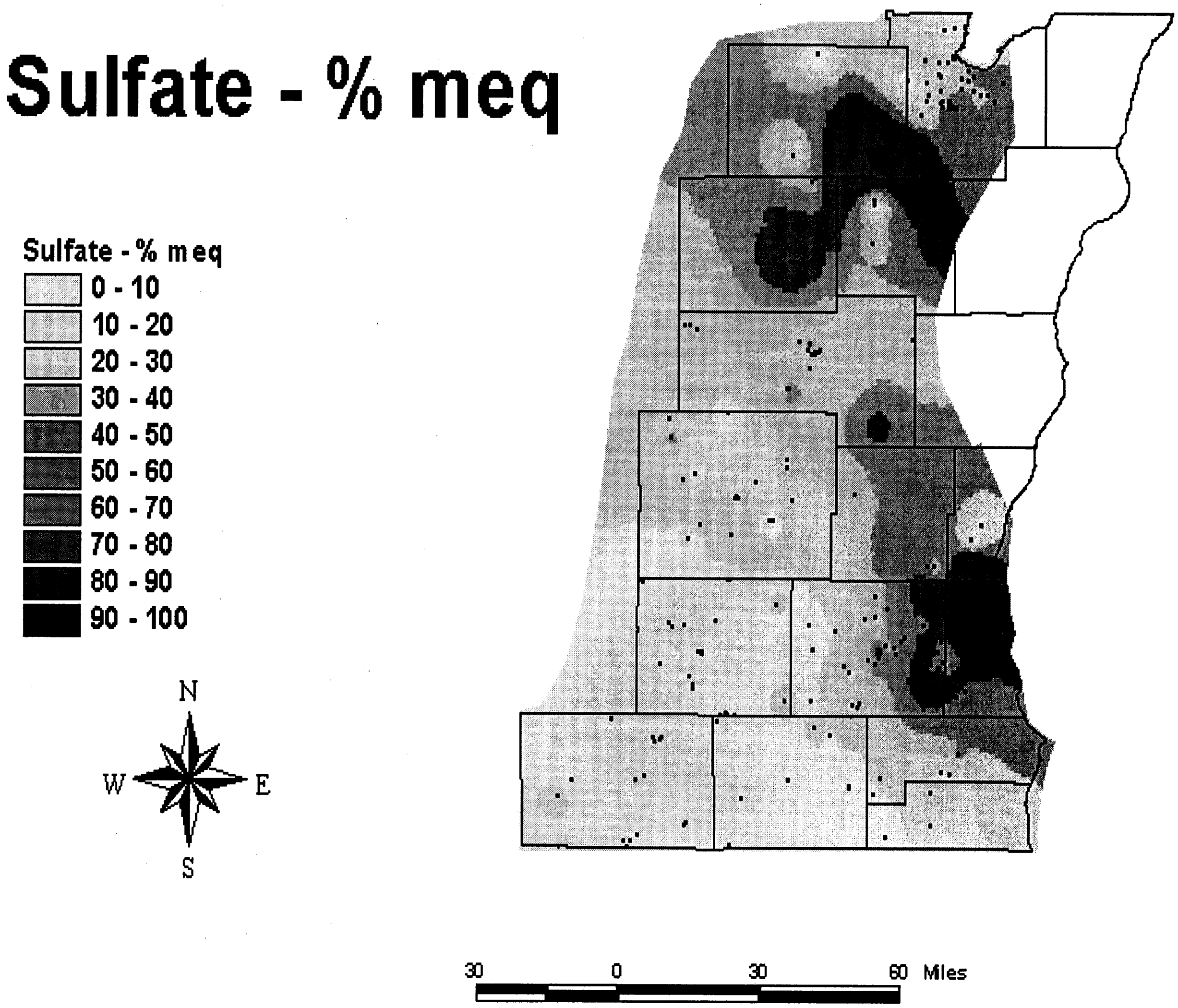


Figure 16: The percent of total cations in water produced from wells in the Cambro-Ordovician aquifer of eastern Wisconsin that is attributable to sulfate. Expressed as % milliequivalents. Black spots indicate individual wells.

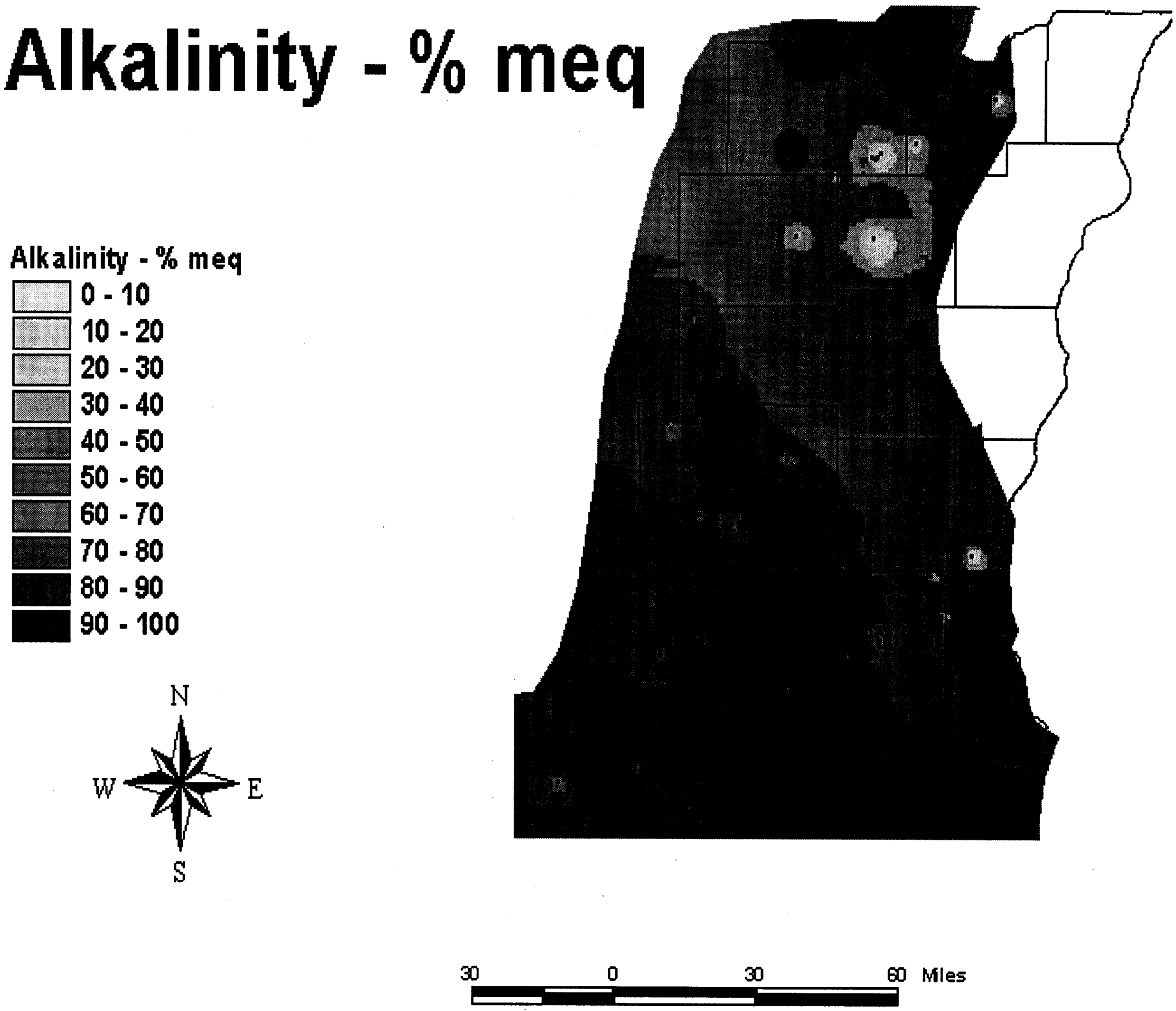
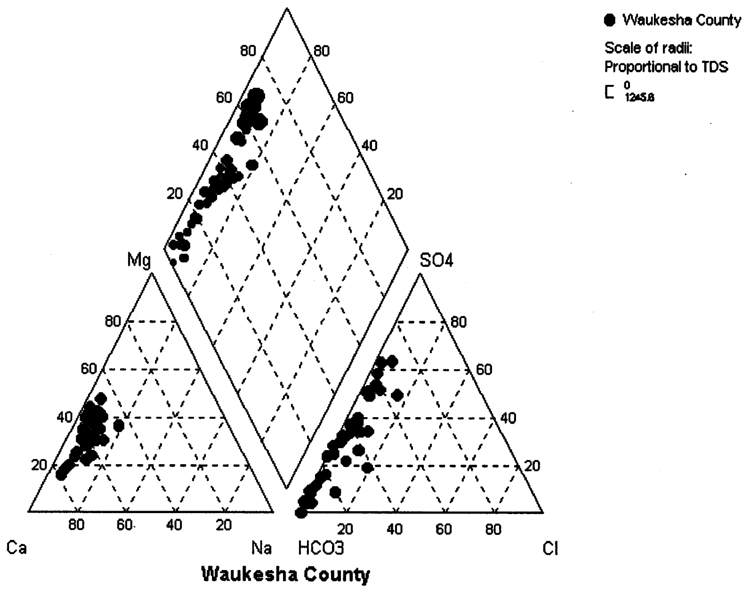


Figure 17: The percent of total cations in water produced from wells in the Cambro-Ordovician aquifer of eastern Wisconsin that is attributable to bicarbonate alkalinity. Expressed as % milliequivalents. Black spots indicate individual wells.

areas that straddle the boundary between relatively saline Ca-SO_4 water and relatively fresh Ca-HCO3 water. Piper diagrams for both counties are shown in Figure 18. Symbol size in the upper diamond shaped field is proportional to the TDS. Maximum TDS differs slightly (870 ppm in Waukesha county and 922 in Brown county) however the trend with increasing salinity is the same. More saline water (larger symbols) occurs near the top apex as the relative proportion of sulfate increases. The cation content exhibits a nearly constant mixture of calcium and magnesium with an excess of calcium. This cationic composition is reasonable for waters in which calcite and dolomite are the primary sources of dissolved solids. A Piper diagram of all the remaining counties shows the same trend (Figure 19). Excess calcium can arise from either the incongruent dissolution of calcite or from the increasing contribution resulting from gypsum dissolution however an examination of wells throughout the entire study area shows that wells with less than 50% sulfate content are less saline (average TDS = 450 ± 87 ppm) and have an approximately equimolar content of calcium and magnesium. High sulfate wells (greater than 50% sulfate content) are more saline (average TDS = 888 ± 175 ppm) and contain significantly more calcium than magnesium. This pattern favors gypsum dissolution as the source of excess calcium.

A sodium signature is observed in several wells within the study area. High sodium wells (greater than 20 mole percent sodium) occur in Brown, Calumet, Fond du Lac counties to the north. In this area, high sodium is matched by a molar equivalent quantity of chloride indicating halite dissolution as the source. A few isolated wells in the southern part of the study area (Kenosha, Racine and Waukesha counties) contain high sodium that is not matched by an equivalent quantity of chloride. The likely source of sodium in these wells is from cation exchange of calcium for sodium within shaley zones.



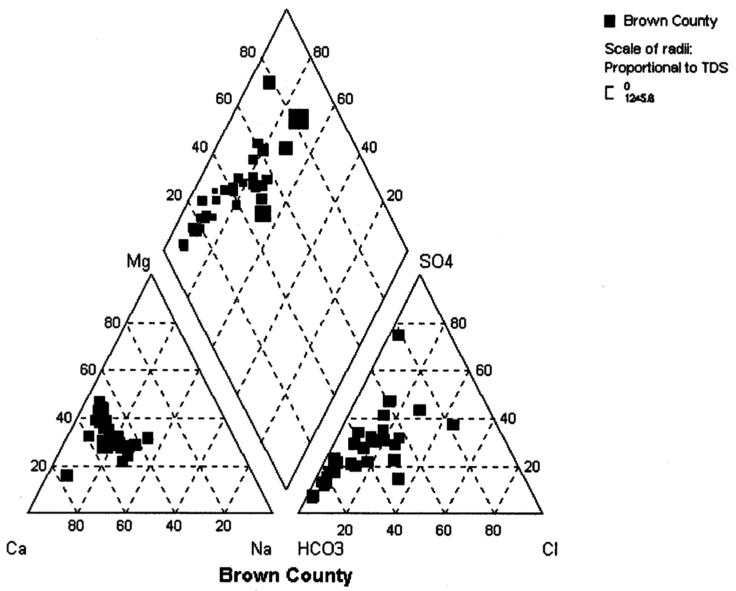


Figure 18: Top) Piper diagram of Waukesha County wells. **Bottom)** Piper diagram of Brown County wells. Size of data symbols is proportional to TDS content of the water. Symbol size is scaled between 0 and 1245 ppm in both diagrams. Each data point is the average value of all samples taken at a given well.

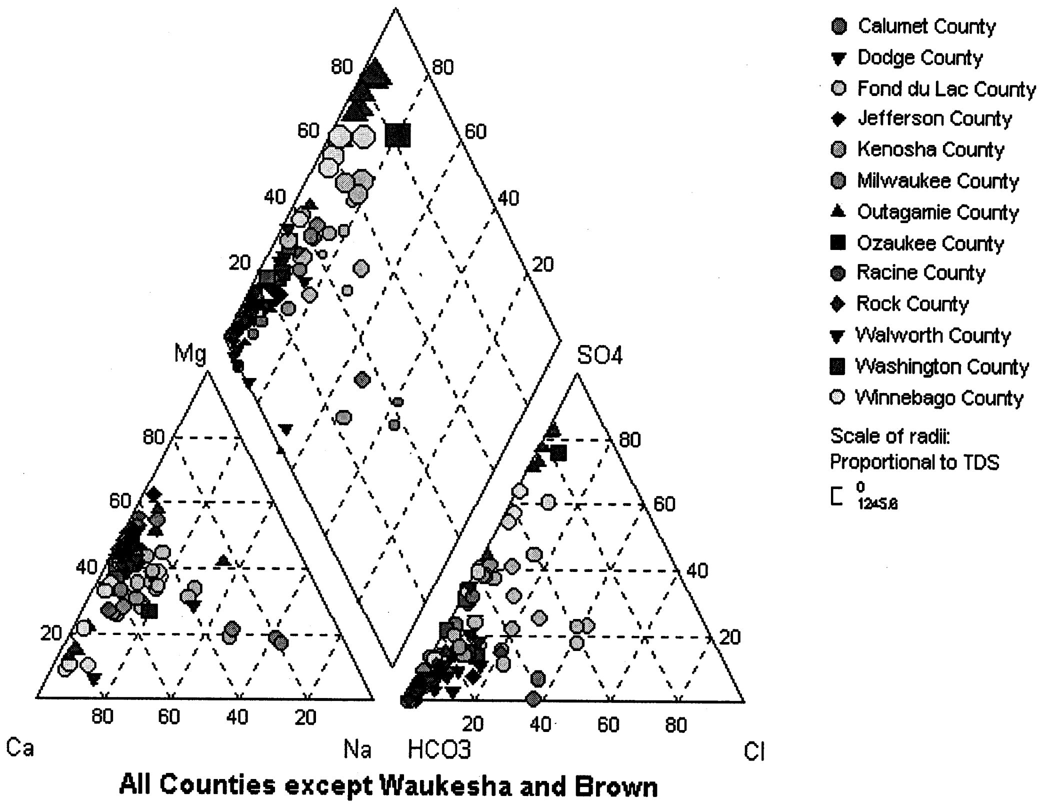


Figure 19: Piper diagram of all counties except Waukesha and Brown. Size of data symbols is proportional to TDS content of the water. Symbol size is scaled between 0 and 1245 ppm. Each data point is the average value of all samples taken at a given well.

Conclusions

This study provides an overall view of the geochemical conditions of the Cambro-Ordovician aquifer in eastern Wisconsin. In general, relatively fresh Ca-HCO_3 rich water is found in the southwest portion of the study area and increasingly saline water is found in the northeast portion of the study area. This increase in salinity is due to an equimolar rise in calcium and sulfate indicating dissolution of gypsum as the probable source. A Na-Cl signature is seen in a localized band centered in Brown, Calumet and western Fond du Lac counties. The probable source is dissolution of halite. Although individual wells may exhibit a rise in TDS over time, the aquifer as a whole produces water that is remarkably constant in TDS. The vast majority of wells are changing less than 10 ppm per year with an equal number exhibiting an increasing and decreasing salinity.

The data examined in this study does not explicitly contain vertically discrete information however an attempt was made to obtain hints as to vertical trends by comparing salinity with the percentage of the well that is open to a particular stratigraphic interval. The data is insufficient to support any relationship between either salinity or chemical character and the occurrence of a particular stratigraphic unit within the well.

This study calls into question the idea that higher salinity is a function of the confined/unconfined boundary beneath the Makoqueta Shale subcrop. Salinity also does not appear to be correlative to depth within the aquifer and, except in localized wells, salinity is not increasing over time. Higher salinity is largely a function of increased calcium and sulfate content. The observed spatial pattern of high salinity that may be due to changes in the amount of sedimentary gypsum that is present and available for dissolution or may be due to portions of the aquifer that have not been adequately flushed. Whether these reasons are a function of changing sedimentary conditions during deposition in Cambrian-Ordovician time, are related to the topography of the Precambrian-Cambrian contact is not clear or are related to current pumpage rates is not clear. The ever increasing understanding of the flow regime in the southeast portion of the aquifer may help to solve these puzzles, at least on a local scale.

References

Aquifer Science and Technology, 2001a. Geophysical Letter Report – Rehabilitation of Well 5 to reduce groundwater radionuclide concentrations, Sussex, Wisconsin. Report to the City of Sussex, WI.

Aquifer Science and Technology, 2001b. Report of the geophysical logging study on well 8. Report to the City of New Berlin, WI.

Grundl, T., Taylor, R.W. and Cherkauer, D. 2000. Makoqueta Shale as radium source to the Cambro-Ordovician Aquifer. Final Project Report to Water Resources Institute.

Jansen, J., Bradbury, K and Powell, T. 2002. Geophysical well-logging studies to identify saline water zones in the Cambro-Ordovician aquifer of southeastern Wisconsin. Proc. Symposium on the Application of Geophysics to Engineering and Environmental Problems, presented at the Environmental and Engineering Geophysical Society Meeting, Las Vegas, NV, February 2002.

Kammerer, P.A., Trotta, L.C., Krabbenhoft, D.P., Lidwin, R.A. 1998. Geology, groundwater flow, and dissolved solids content in groundwater along hydrogeologic sections through Wisconsin aquifers. USGS Hydrologic Investigations Atlas HA 731.

Layne-Northwest Company and Aquifer Science and Technology, Inc. 1999. Report on the time domain electromagnetic induction survey of the sandstone aquifer in Oakfield, WI.

Mandle, R.J. and Kontis, A.L. 1992. Simulation of regional groundwater flow in the Cambro-Ordovician aquifer system in the northern Midwest, United States. USGS Professional Paper 1405-C. pp.1-97.

Perry, G., Grundl, T. and Gilkeson, R. 1982. H,O, and S isotopic study of the Cambro-Ordovician aquifer system of northern Illinois. *in* Perry and Montgomery, eds. Isotope Studies of Hydrologic Processes., NIU Press pp. 35-43.

Ryling, R.W. 1961. A preliminary study of the distribution of saline water in the bedrock aquifers of eastern Wisconsin. Wisconsin Geological and Natural History Survey Information Circular #5. 23 pp.

Siegel, D.I.. 1992. Geochemistry of the Cambro-Ordovician aquifer system in the northern Midwest, United States. USGS Professional Paper 1405-D. pp.1-76.

Siegel, D. 1990. Sulfur isotopic evidence for regional recharge of saline water during continental glaciation, north-central United States. Geology 18:1054-1056.

Simo, J.A., Freiberg, P.G., and Freiberg, K.S. 1996. Geologic constraints on arsenic in groundwater with applications to groundwater modeling. Groundwater Research Report WRC GRR 96-01. pp. 1-48.

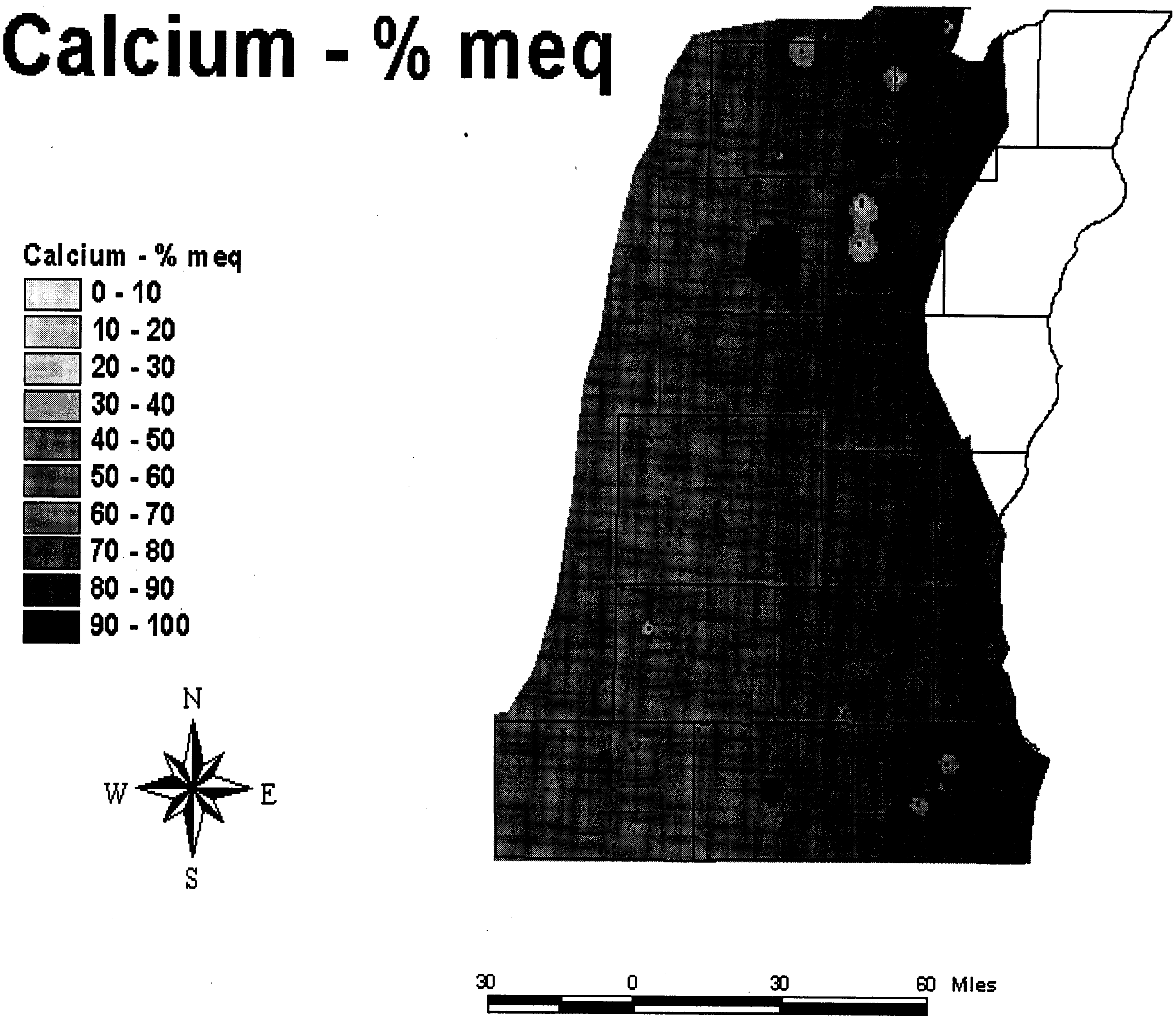
Taylor, R.W. and Jansen, J. 2000. Time domain electromagnetic induction survey of eastern Waukesha County and selected locations. Final Project Report to Water Resources Institute.

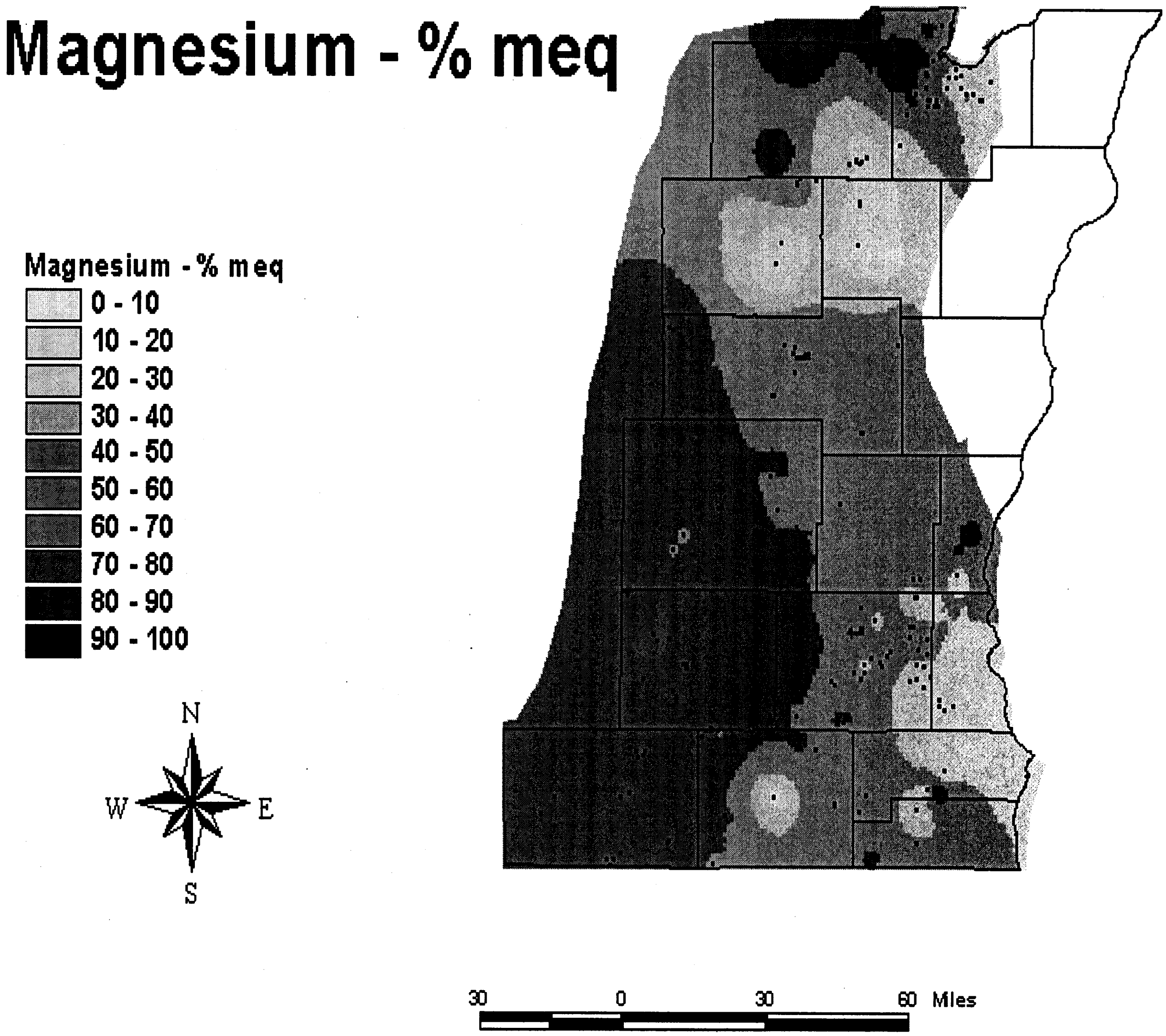
Weaver, T. and Bahr, J. 1991a. Geochemical evolution of the Cambro-Ordovician aquifer, eastern Wisconsin: 1. Major ion and radionuclide distribution. Ground Water 29:350-356.

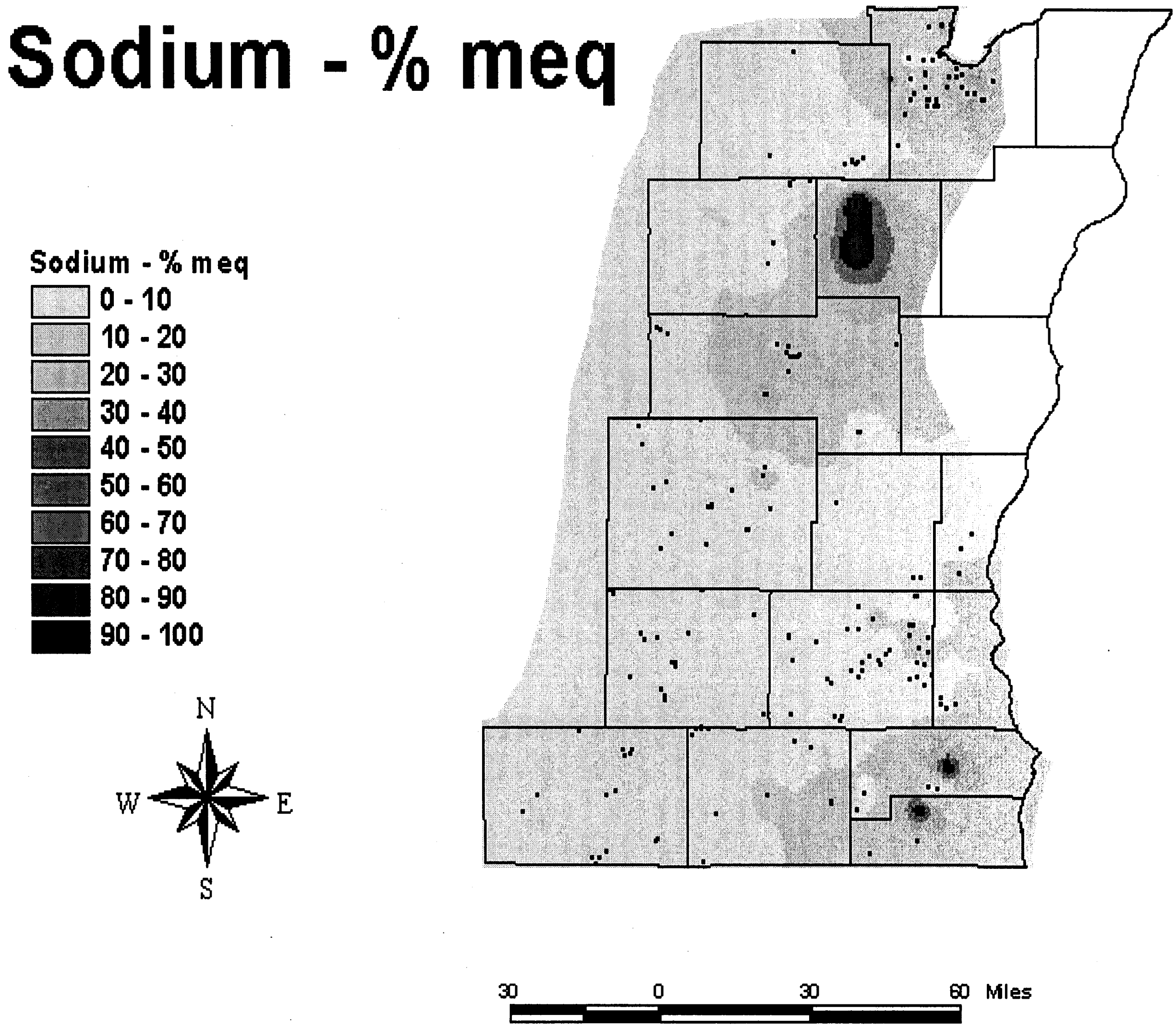
Weaver, T. and Bahr, J. 1991b. Geochemical evolution of the Cambro-Ordovician aquifer, eastern Wisconsin: 2. Correlation between flow paths and ground water chemistry. Ground Water 29:510-515.

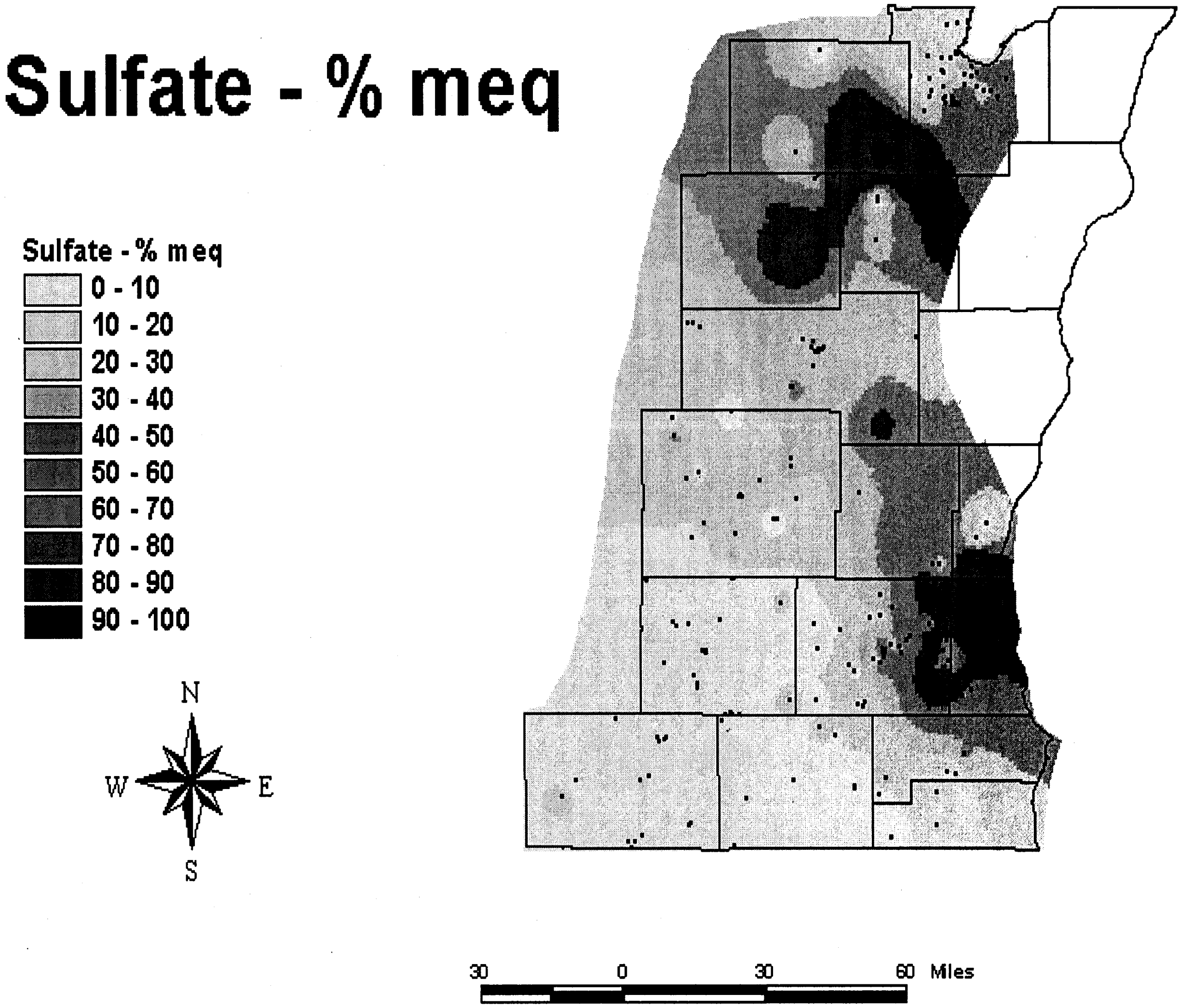
APPENDIX A: Percent milliequivalent maps of the Cambro-Ordovician aquifer of eastern Wisconsin for all 18 counties within the study area. Maps are given for each major ion. Sulfate, calcium and bicarbonate maps are also seen as figures within the text. Black spots indicate individual wells.

Calcium - % meq

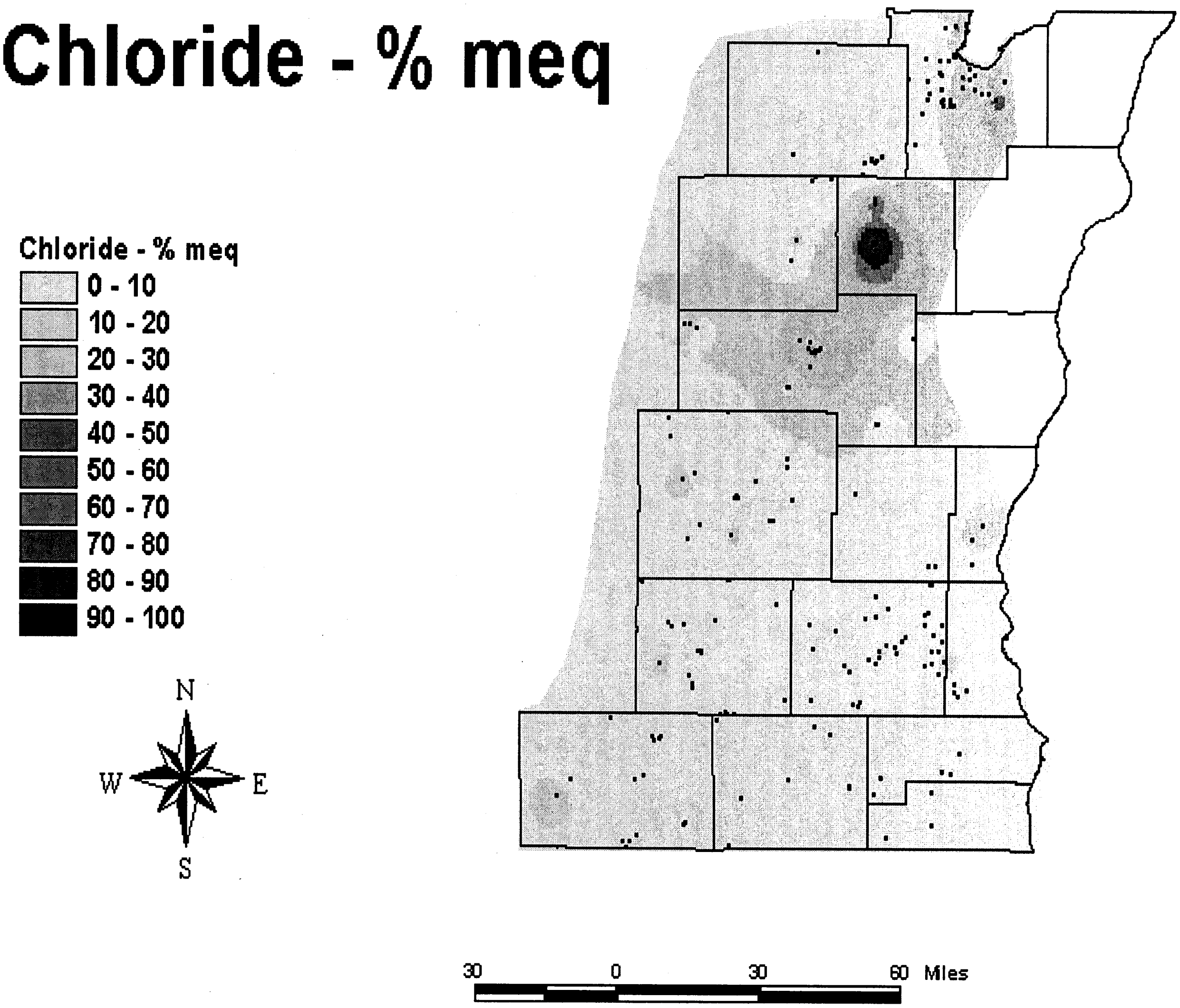

Calcium - % meq
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 90
90 - 100
N
W
E
S
30
0
30
60 Miles

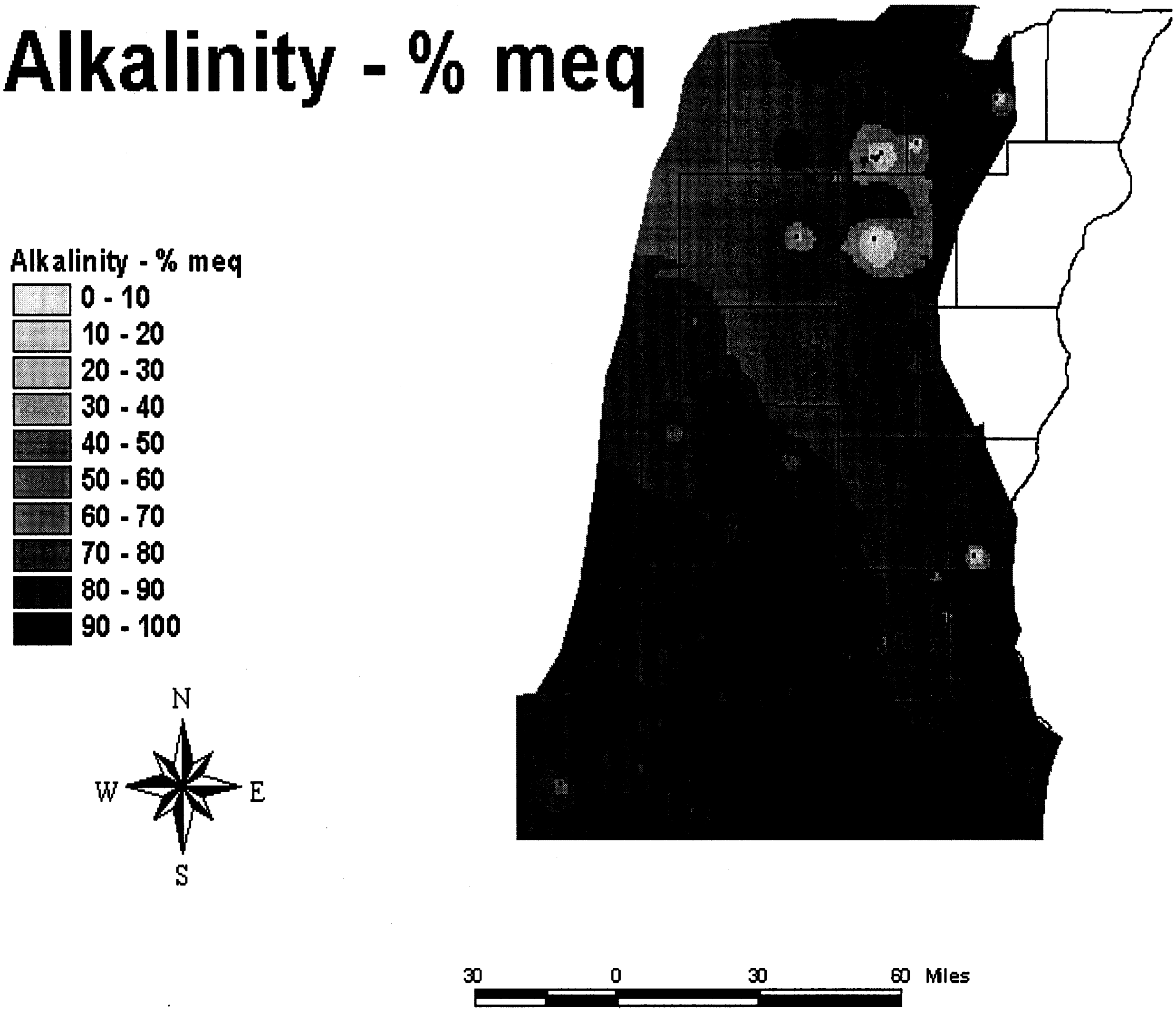

Magnesium - % meq
Magnesium - % meq
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 90
90 - 100
N
W
E
S
30
0
30
60 Miles


Sodium - % meq
Sodium - % meq
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 90
90 - 100
N
W
E
S
30
0
30
60 Miles

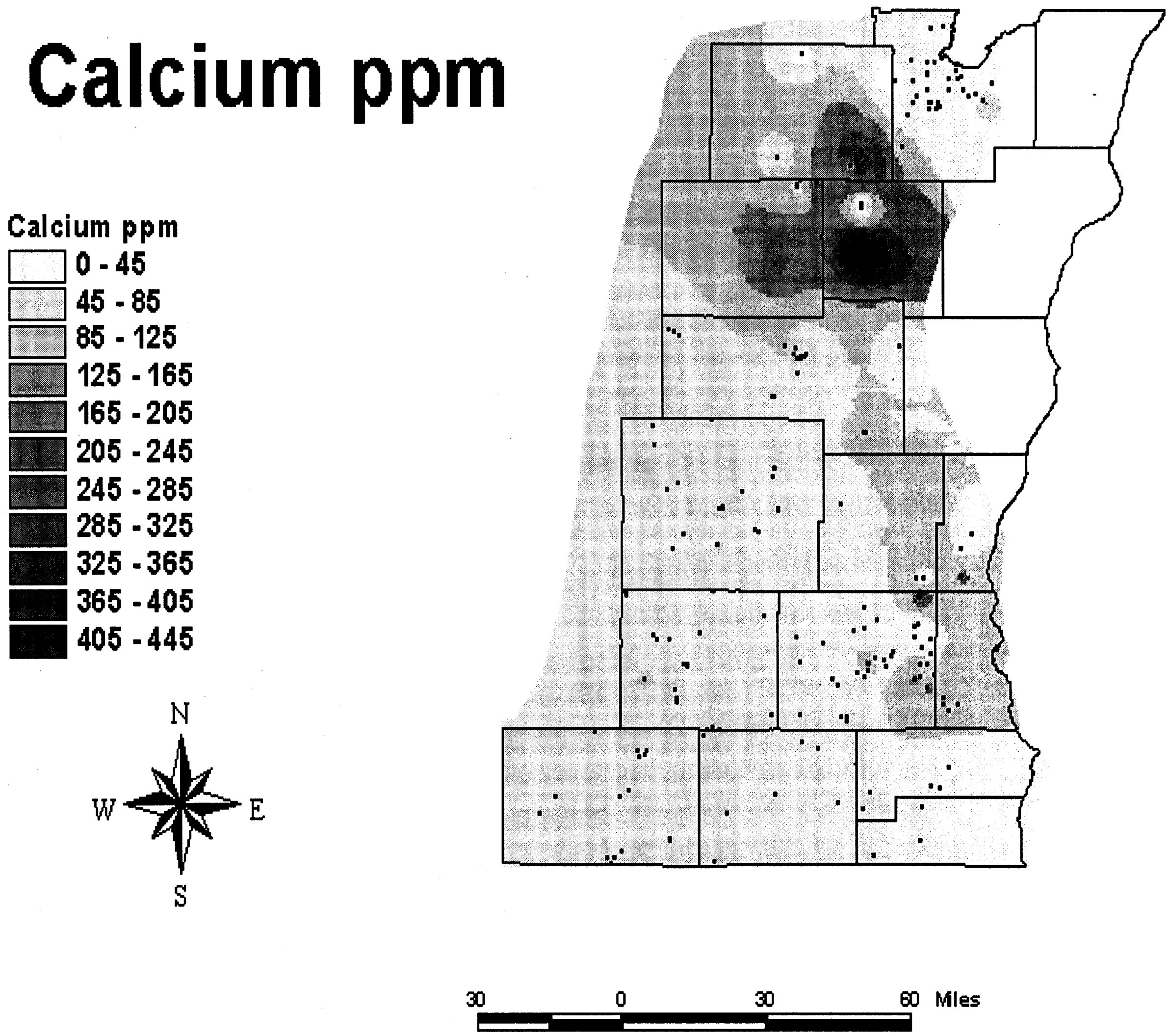

Sulfate - % meq
Sulfate - % meq
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 90
90 - 100
N
W
E
S
30
0
30
60 Miles

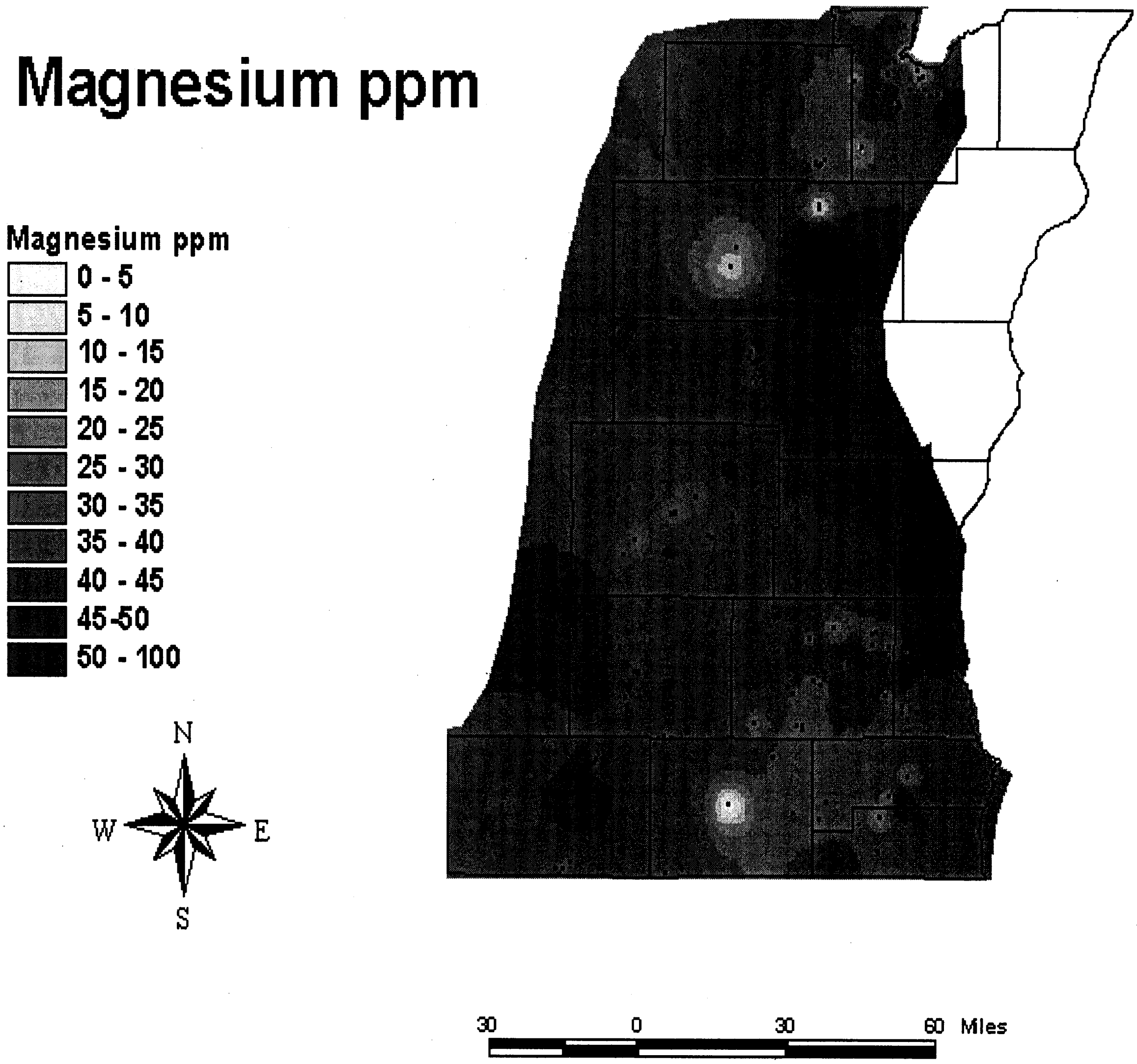
Chloride - % meq

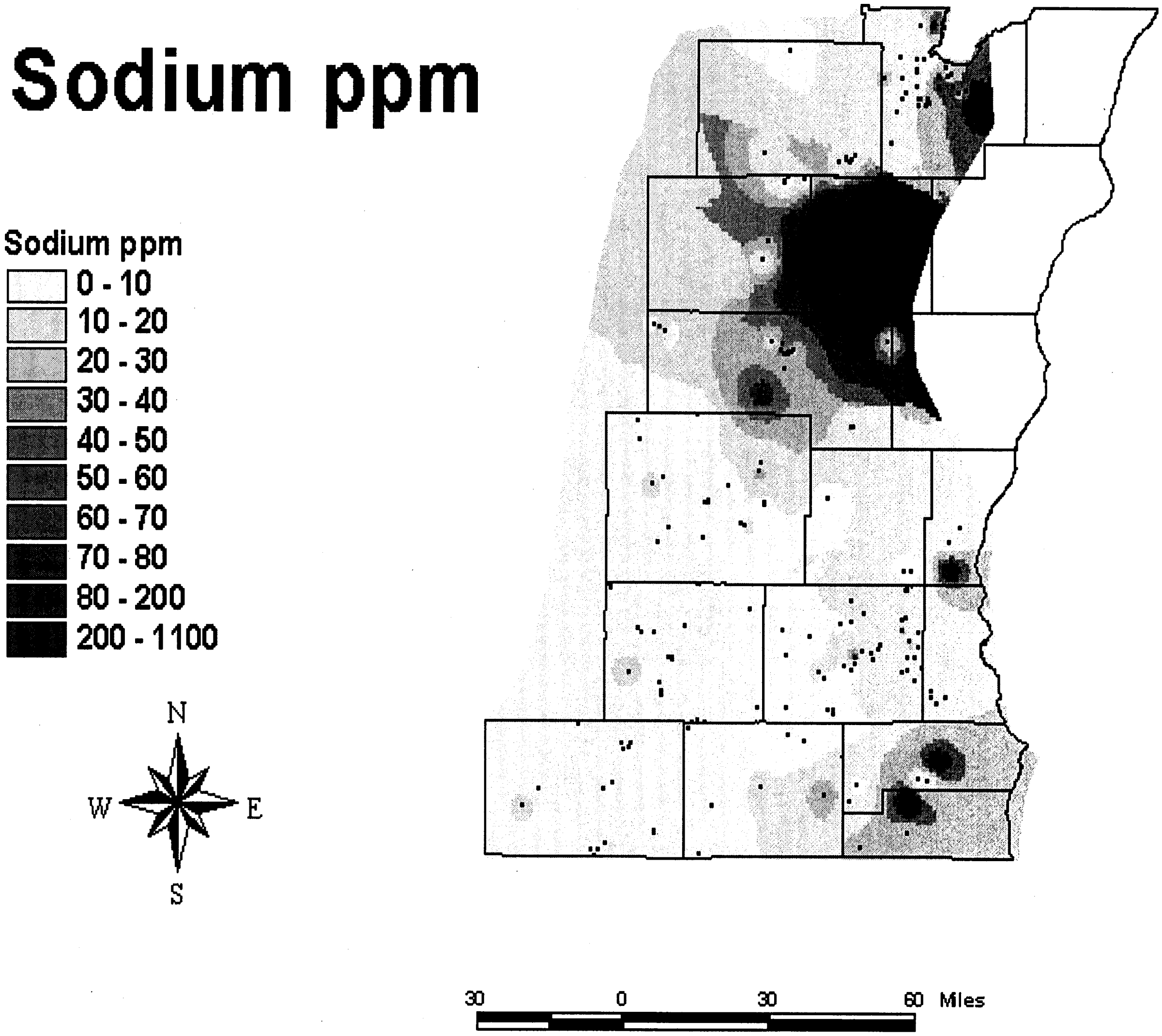



Alkalinity - % meq
Alkalinity - % meq
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 90
90 - 100
N
W
E
S
30
0
30
60 Miles

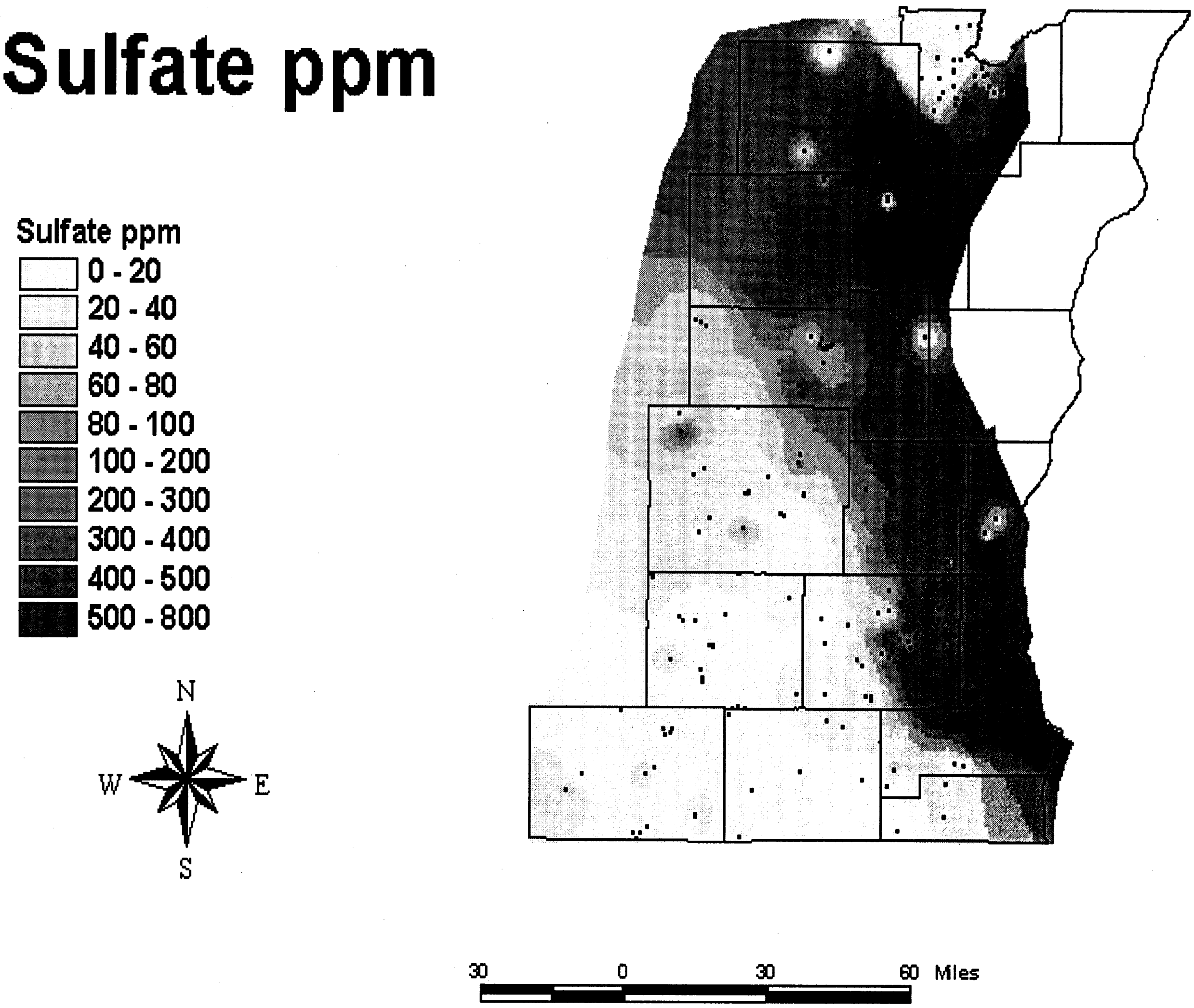
APPENDIX B: Absolute concentration maps of the Cambro-Ordovician aquifer of eastern Wisconsin for all 18 counties within the study area. Maps are given for each major ion. Concentrations are given in parts per million. Black spots indicate individual wells. Cations are contoured in shades of pink, anions in shades of orange.


Calcium ppm
Calcium ppm
0 - 45
45 - 85
85 - 125
125 - 165
165 - 205
205 - 245
245 - 285
285 - 325
325 - 365
365 - 405
405 - 445
N
W
E
S
30
0
30
60 Miles

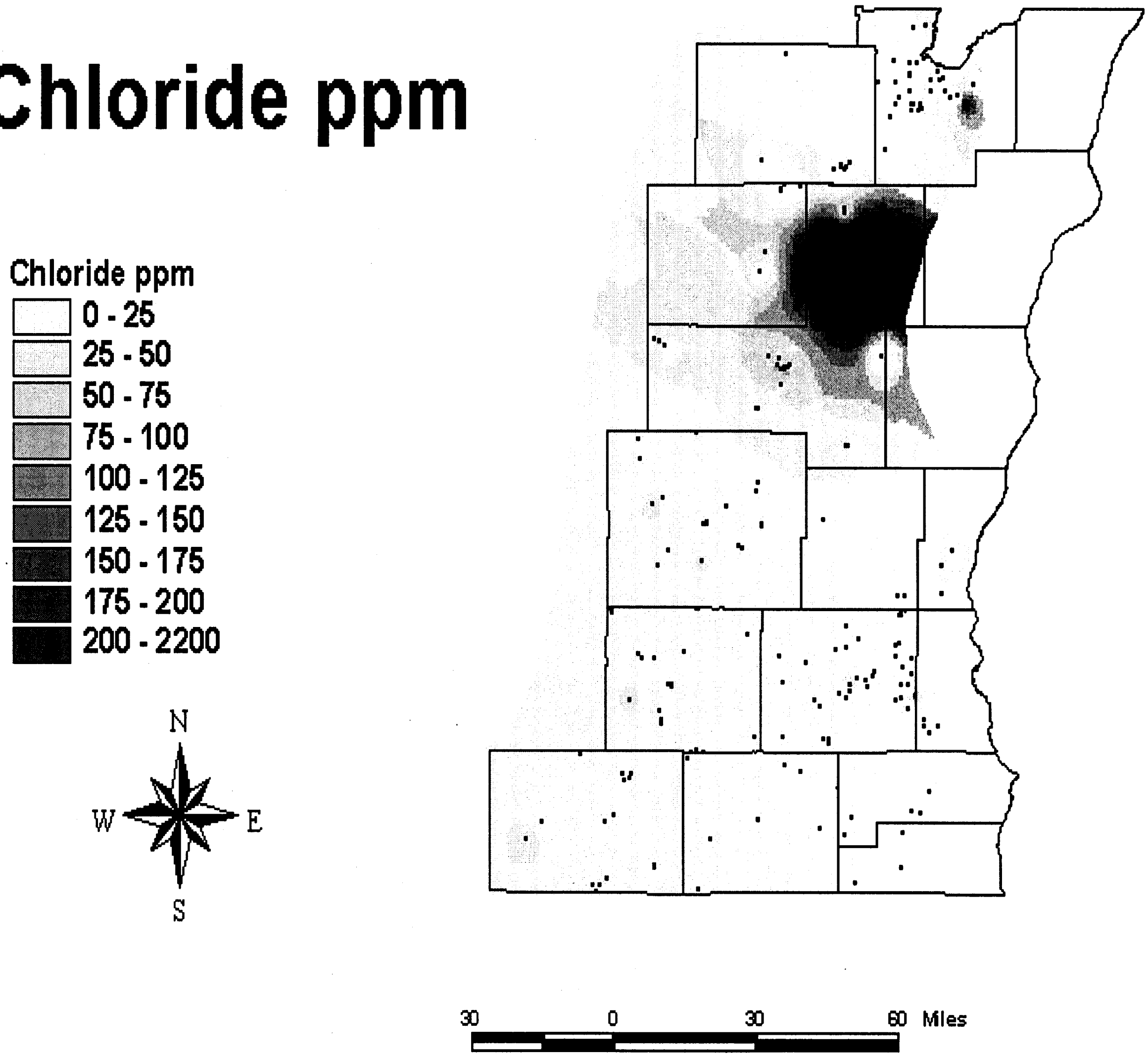

Magnesium ppm
Magnesium ppm
0 - 5
5 - 10
10 - 15
15 - 20
20 - 25
25 - 30
30 - 35
35 - 40
40 - 45
45-50
50 - 100
N
W
E
S
30
0
30
60 Miles

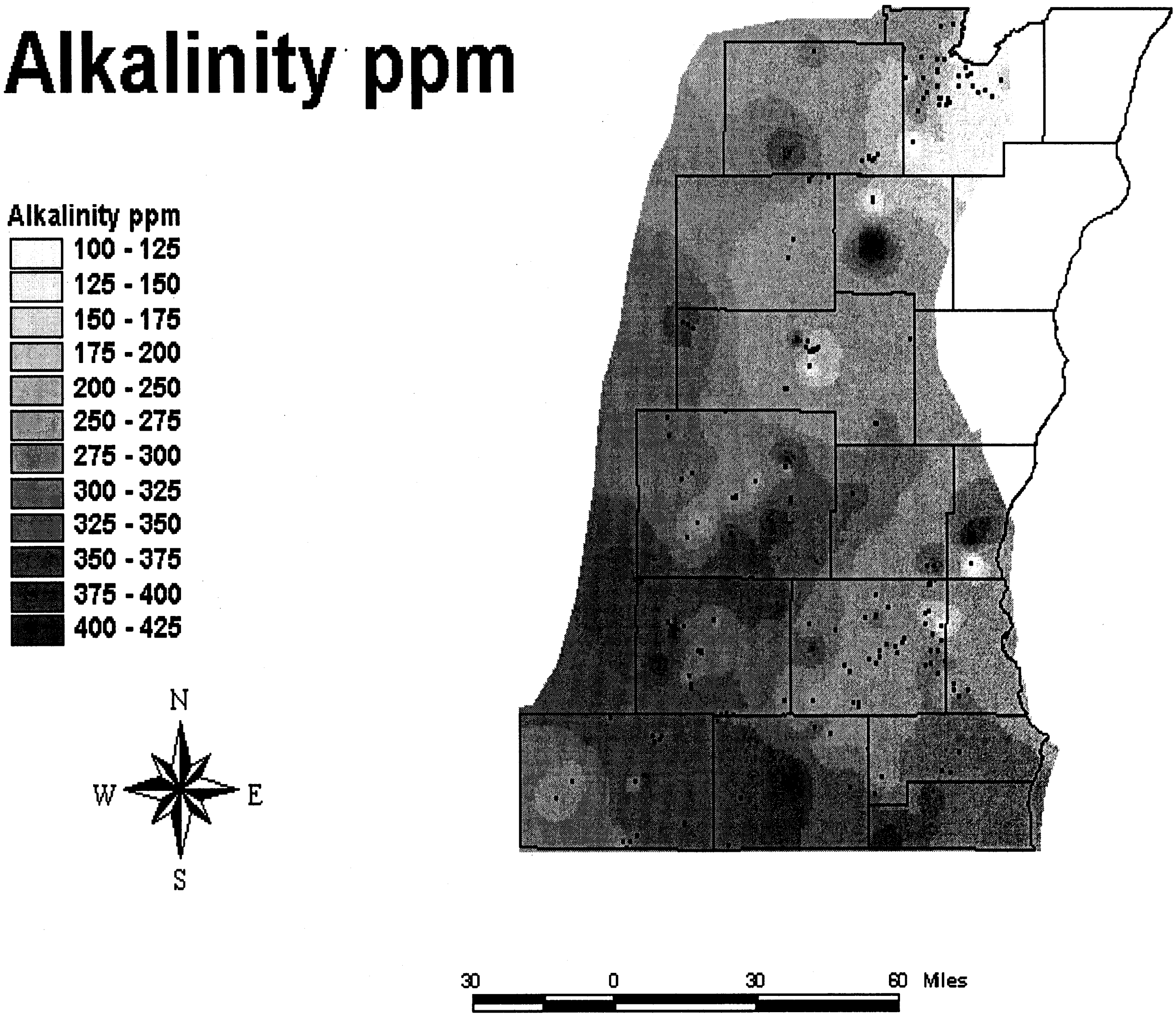

Sodium ppm
Sodium ppm
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 200
200 - 1100
N
W
E
S
30
0
30
60 Miles

Sulfate ppm


Sulfate ppm
0 - 20
20 - 40
40 - 60
60 - 80
80 - 100
100 - 200
200 - 300
300 - 400
400 - 500
500 - 800
N
W
E
S
30
0
30
60 Miles

Chloride ppm

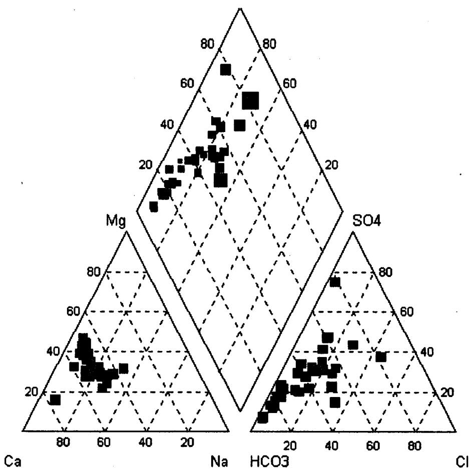



Alkalinity ppm
Alkalinity ppm
100 - 125
125 - 150
150 - 175
175 - 200
200 - 250
250 - 275
275 - 300
300 - 325
325 - 350
350 - 375
375 - 400
400 - 425
N
W
E
S
30
0
30
60 Miles

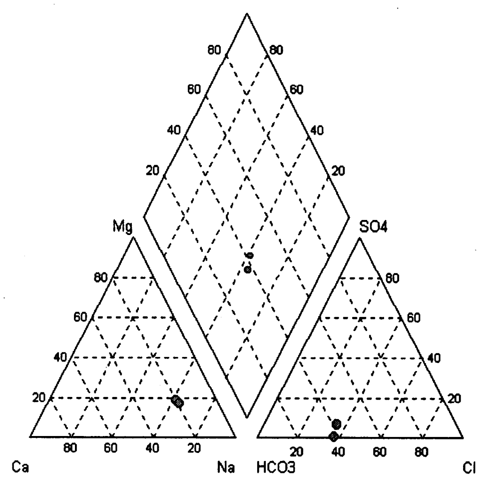
APPENDIX C: Piper diagrams showing the chemical character of the water produced from the Cambro-Ordovician aquifer of eastern Wisconsin for each of the 15 counties within the study area that contained chemical data. Note that the scaling of data points varies from county to county.

Counties: Scaled to TDS

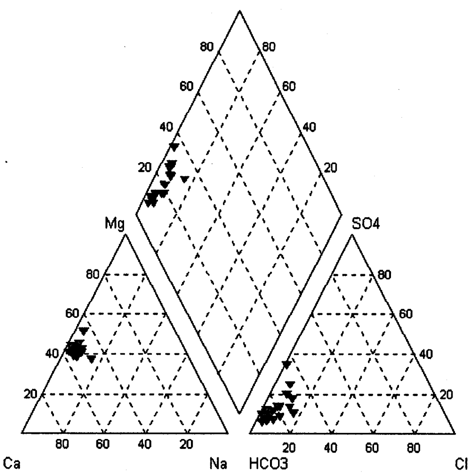
County	Min TDS (ppm)	Max TDS (ppm)
Brown	203.58	922.54
Calumet (w/o EQ020)	312.40	312.84
Dodge	304.14	598.26
Fond du Lac	289.08	779.55
Jefferson	370.30	625.82
Kenosha	450.05	495.50
Milwaukee	473.10	545.20
Outagamie	223.00	1245.60
Ozaukee	526.49	806.13
Racine	355.30	503.21
Rock	350.30	532.24
Walworth	367.08	468.57
Washington	454.40	495.62
Waukesha	299.73	870.49
Winnebago	383.61	835.70



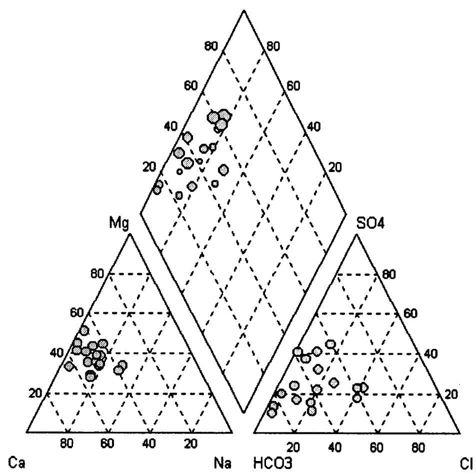
Brown County



Calumet County

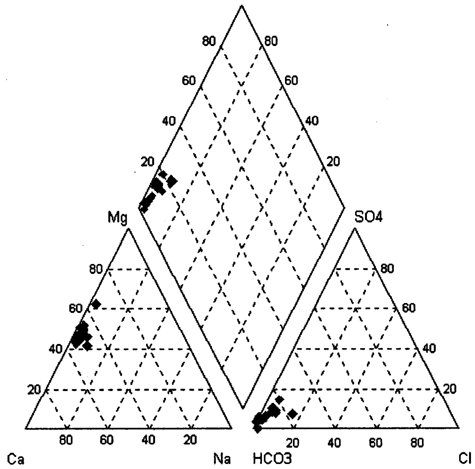


Dodge County

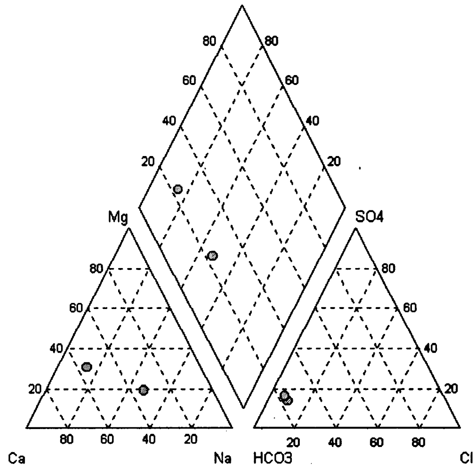


Fond du Lac County

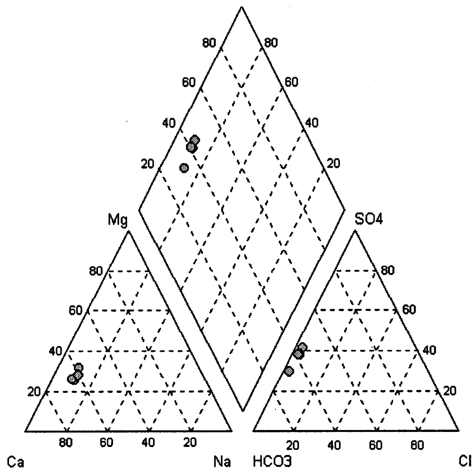
Counties: scaled to TDS (continued…)



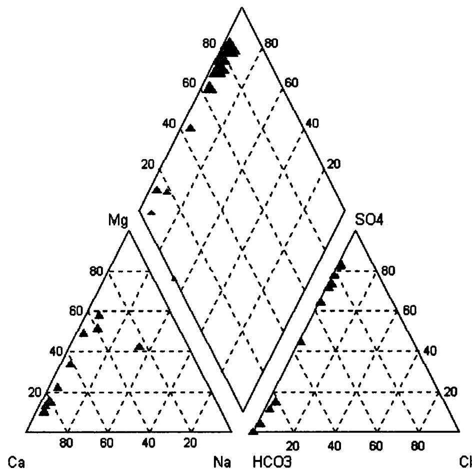
Jefferson County



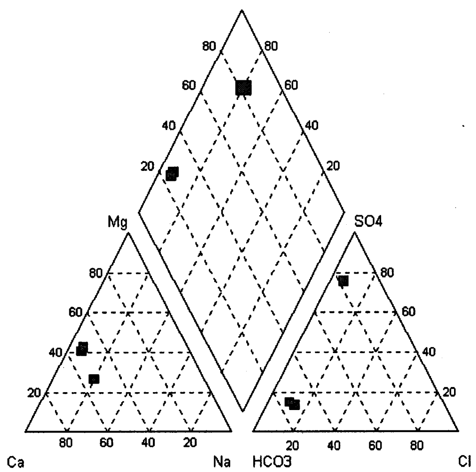
Kenosha County



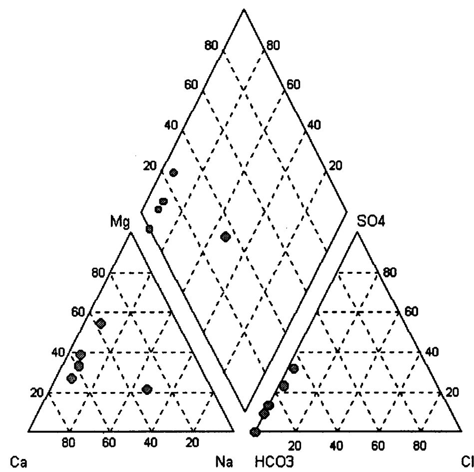
Milwaukee County



Outagamie County

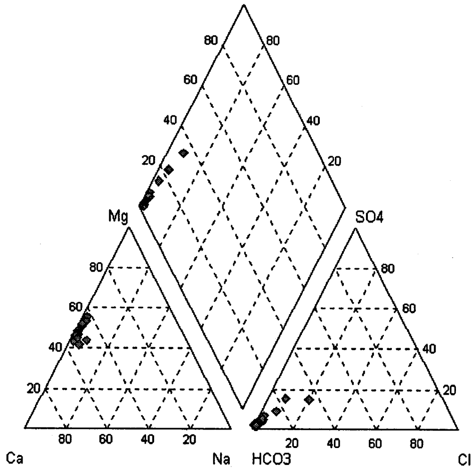


Ozaukee County

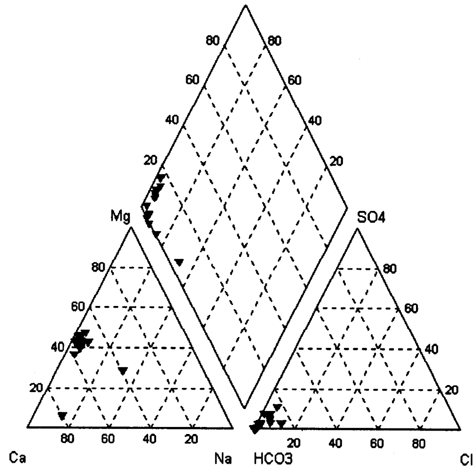


Racine County

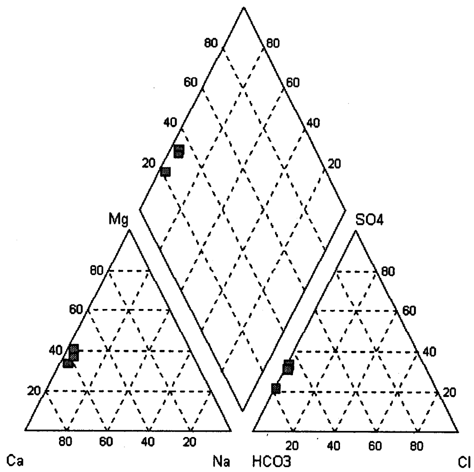
Counties: Scaled to TDS (continued...)



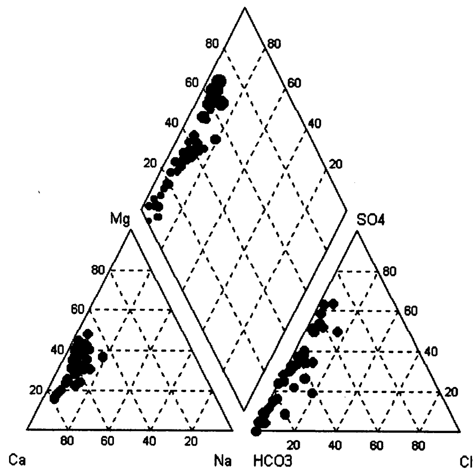
Rock County



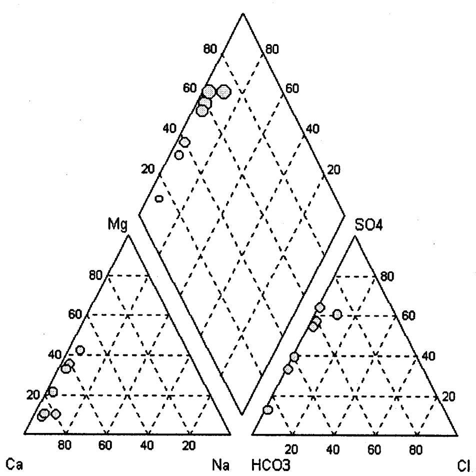
Walworth County



Washington County



Waukesha County



Winnebago County

APPENDIX D: Basic data tables.