# Time domain electromagnetic induction survey of eastern Waukesha County and selected locations. October 2000

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# Time Domain Electromagnetic Induction Survey Of Eastern Waukesha County And Selected Locations

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## Waukesha County, Wisconsin

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## I. PROJECT SUMMARY

Project Title: Time Domain Electromagnetic Induction Survey of Eastern Waukesha County and Selected Locations
Project Number UW-WRI # 00-HDG-8
Principal Investigators:
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A. Background/Need

The sandstone aquifer is the major source of municipal and industrial water in Waukesha County. The aquifer has been heavily exploited over the last century, creating a regional cone of depression that is over 500 feet deep and currently centered on eastern Waukesha County. Over the last ten to fifteen years, total dissolved solids (TDS) levels have risen significantly in several of the higher capacity municipal wells in Waukesha County. TDS levels in at least two municipal wells have risen to over 1,000 ppm. A new municipal sandstone well, in the City of Brookfield, unexpectedly encountered high TDS water (2,200 ppm), causing substantial additional expense to the water utility. While high TDS water is certainly present within portions of the sandstone aquifer, the spatial distribution of this water is poorly defined. The location and depth of high TDS water in the sandstone aquifer must be understood before the cause of the problem and potential solutions can be identified.

B. Objectives

The goal of this study was to map the distribution of high TDS water in the sandstone aquifer in Waukesha and Milwaukee Counties. Direct water sampling through packer tests in existing wells or dedicated monitoring wells was prohibitively expensive. Geophysical methods offered the only practical method of mapping zones of high TDS water in the aquifer. A secondary goal of the study was to map the base of the aquifer.

C. Methods

A geophysical survey consisting of 69 Time Domain Electromagnetic Induction (TEM) soundings was conducted in Waukesha and Milwaukee Counties using a Geonics EM57 system. The layout of the soundings was optimized to measure the electrical resistivity of the sandstone aquifer at depths of about 500 to 2,000 feet. The data were interpreted using the TEMIX two-dimensional modeling software by Interpex. Ltd.

D. Results and Discussion

The TEM data yielded two distinct patterns, depending on the location of the sounding relative to the Waukesha fault. Most soundings on the up-thrown (northwest) side of the fault show a trend toward rising resistivity with depth, indicating high resistivity basement rock. Most soundings on the down-thrown (southeast) side of the fault indicate a highly conductive electrical half space at depth, suggesting high salinity ground water in the lower portion of the sandstone aquifer.

Modeling data from the up-thrown side of the fault produced reasonable agreement between the interpreted depth of the high resistivity half space and the known elevations of Precambrian basement rock. Down hole water sampling, conducted in a Village of Sussex municipal well for a different study, indicated no significant change in water salinity for the sandstone aquifer. A few soundings in west-central Waukesha County indicated shallower basement rock than expected with some apparent pockets of elevated TDS ground water adjacent to the apparent Precambrian highs.

Modeling data from the down-thrown side of the fault produced estimates of the depth to elevated TDS water that were generally shallower than expected. Geophysical well logs, obtained by the USGS in Waukesha Well No. 5, indicated TDS rising from about 300 ppm at 1,200 feet to over 2,000 ppm at 1,600 feet. The TEM interpreted depth to the top of the high conductivity zone in the Waukesha area is between about 700 and 1,000 feet, and the interpreted resistivity value indicates substantially higher TDS levels. This disparity in the interpreted data is probably true for the other soundings on the down-thrown side of the fault. The cause of the disparity is unknown but could be caused by supression of the fresh water layer between two conductors.

E. Conclusions

The results of the TEM survey strongly suggest the presence of the high TDS water in the lower portion of the Mount Simon unit of the sandstone aquifer. High TDS water appears to be migrating upward in response to heavy pumpage in eastern Waukesha County. The top of the saline water interface appears to be high near heavily pumped wells and near deeper wells, which are likely to penetrate thin shale units in the upper few hundred feet of the Mount Simon sandstone that act as a weak confining unit. This observation is supported by strong correlations between elevated TDS, total depth, and annual pumpage observed in the Waukesha Water Utility well field. The TEM data also suggests that isolated mounds may be present on the Precambrian surface in western Waukesha County with potential zones of elevated TDS ground water adjacent to the mounds.

F. Implications

The data suggest that poor water quality could be minimized by drilling shallower sandstone wells and pumping less, with the development of other wells to offset the loss in capacity. The deeper portions of the sandstone aquifer appear to by generally separated form the upper fresh water zone. For the purposes of modeling the hydraulic response of the sandstone aquifer, the top of the saline water zone at depth may be the practical base of the aquifer.

The Precambrian surface and Waukesha fault may be more complex then initially anticipated.

G. Related Publications

Jansen, J., Taylor, R.W., and Powell, T., 2000, A regional TEM Survey to Map Saline Water in the Cambrian-Ordovician Sandstone Aquifer of Southeastern Wisconsin, accepted for publication, Proceedings of the Environmental and Engineering Geophysical Society.

**Key Words:** Sandstone aquifer, TDS levels, Water quality, TEM surveys

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## II. INTRODUCTION

The sandstone aquifer is the major source of ground water for municipal supplies in southeastern Wisconsin. Approximately fifty communities and 200 industries in southeastern Wisconsin rely on the sandstone aquifer for at least part of their water supply. The sandstone aquifer supplies about 95% of municipal supply in Waukesha County and a significant portion of the municipal supply in several surrounding communities. From 1975 to 1995 municipal demand from the sandstone aquifer increased by 27% in Walworth County, 29% in Waukesha County, and 54% in Washington County. In 1995, at least 92 municipal wells produced about 28 million gallons per day (mgd) of water from the sandstone aquifer in the area including Milwaukee, Waukesha, Ozaukee, Washington, Racine, Kenosha, and Walworth Counties (Bonestroo, Rosene, Anderlik and Associates, 1998).

While the sandstone aquifer may be the major source of ground water for the region, it is not well understood. Most wells are terminated at a depth where adequate water quantity is obtained. As a result, few wells penetrate the full thickness of the aquifer, particularly on the down-thrown side of the Waukesha fault. Due to the lack of data, the thickness of the aquifer is poorly known in much of southeastern Wisconsin. In many cases it is possible to reasonably estimate the elevation of the base of the aquifer by triangulation from surrounding wells. However, ridges of quartzite and mounds of granite are present on the Precambrian surface. These features are poorly known or unmapped in may places and can cause the sandstone to be thinner than expected and the yield of a well to be less than projected. Unmapped mounds on the Precambrian surface have resulted in sandstone wells terminating shallower than expected in at least two cases in Waukesha County. In 1996 the Village of Pewaukee drilled a sandstone well to the top of granite. The depth to the granite was estimated at 1200 feet based on surrounding well logs. Unfortunately, the well encountered an unmapped quartzite ridge at 790 feet. Due to the reduced thickness of the Mount Simon sandstone, the well produces about 600 gpm instead of the projected capacity of 1100 gpm. In 1995, the Village of Delafield drilled Well 1, which encountered Quartzite at 1225 feet instead of 1500 feet as predicted from regional data.

Saline water is known to be present in the sandstone aquifer near the Lake Michigan shore (Ryling, 1961). The areas of elevated total dissolved solids (TDS) in the aquifer appears to be associated with the location of quartzite ridges (Ryling, 1961, Weaver and Bahr, 1991). However, the exact position of the interface between fresh water and salt water is not well known in southeastern Wisconsin. In addition to the saline water along the Lake Michigan shore, problems with elevated TDS ground water have been encountered in several municipal wells in Waukesha County. The City of Brookfield drilled Well 29 to a depth of 2160 feet, which is about 400 feet deeper into the Mount Simon than typical for wells in the area. The well had a capacity of about 2000 gpm, which is much higher than normal, but produced water with TDS levels of 2400 ppm. The well was plugged back to 1680 feet and the TDS levels were reduced to about 600 ppm. The deepest well in the area, Waukesha Well 9 is 2226 feet deep and produced water with 360 ppm TDS in 1985. TDS levels have risen steadily in the well and currently exceed 1000 ppm. At least two other municipal wells in the Waukesha well field are experiencing rising levels of TDS. The City of New Berlin, immediately east of Waukesha, has six sandstone wells. Well 8 is one of their deeper wells at 1984 feet. While this well produced water with a TDS level of 772 ppm when it was drilled in 1986, the levels have risen steadily and currently exceed 1000 ppm. TDS levels are rising in at least two other sandstone wells in the City.

Several communities are considering drilling new sandstone wells deeper into the Mount Simon sandstone to increase well yield and compensate for the regional decline in head. Waukesha Well 11 was planned to reach the base of the sandstone aquifer or a minimum depth of 2500 feet. Due to the recent observations of declining water quality, the Waukesha Water Utility has suspended its plans for this well and is considering a major study to identify its future water supply options. Several other communities are facing similar uncertainty at a time when additional capacity is needed quickly.

The cause of the rising TDS in these wells is unknown but has significant consequences on future water supply planning. Hypotheses for the increasing TDS levels include; lateral migration of saline water from the western edge of the Michigan Basin, downward migration of saline water from the Maquoketa shale , and upward migration from an unmapped layer of saline water in the deeper portion of the Mount Simon sandstone. Each of these hypotheses is possible, but each would suggest significantly different courses of action to resolve the problem. Knowing the distribution of saline water in the aquifer is a critical step in determining the cause of the changes in water quality and formulating plans to deal with the problem.

The cost of installing dedicated monitoring wells or conducting meaningful packer tests in existing wells exceeds $50,000 per well. Obviously, the costs to map the distribution of saline water by these methods would severely limit the number of data points that could be generated. Geophysical methods offer a reasonable alternative to direct water sampling and can provide a reasonable indication of the distribution of saline water in the aquifer as well as map the shape of the aquifer. The cost of these methods is a fraction of the cost of direct measurements.

## III. PROCEDURES AND METHODS

A geophysical survey consisting of 69 Time Domain Electromagnetic Induction (TEM) soundings was conducted during August and September of 1999 in Waukesha and Milwaukee Counties using a Geonics EM57 system. Twelve of the soundings were funded by the Waukesha Water Utility as part of a separate study, but with other data, were graciously offered to this study at no cost. Survey sites were chosen on the basis of site availability, adequate open area free of cultural interference, and position on or near three planned east west transects. In general, field sites were limited to parks, school sites, golf courses, and undeveloped private land without crops. Given the highly developed nature of eastern Waukesha County and all of Milwaukee County, the availability of field sites was a limiting factor for the survey.

The TEM method uses a heavy gauge wire laid out as a square or rectangle to form a transmitter loop. A current of several amps is passed through the transmitter loop. The current is cut off with a steep ramp function creating a broad band EM pulse as the electric field of the transmitter loop collapses. The EM pulse propagate vertically into the subsurface and induces eddy currents in horizontal conductors. The intensity of the magnetic field created by the eddy currents is measured as a function of time by a receiver coil positioned in the center of the transmitter loop. The field data is then modeled to produce a horizontally layered resistivity model of the subsurface. Current modeling technology does not account for three dimensional structures so significant errors can occur near abrupt lateral resistivity contrasts such as the Waukesha fault.

The depth of maximum sensitivity of TEM surveys is limited and must be selected based on the desired target. The layout of the soundings was optimized by forward modeling to measure the electrical resistivity of the sandstone aquifer at depths of about 500 to 2000 feet. The sensitivity of the survey to shallower interfaces was unavoidably sacrificed by the choice of instrument and layout of the transmitter loop. The forward modeling suggested that adequate penetration could be achieved with a 50 meter by 50 meter transmitter loop. The nominal transmitter loop used for the survey was increased to a target value of 100 meters by 100 meters to increase the signal to noise ratio of the data. For most sites, we were able to use the target loop size, however, the amount of open area at several sites required 50 meter by 150 meter or smaller transmitter coils. The data was interpreted using the TEMIX two dimensional modeling software by Interpex. Ltd.

## IV. RESULTS AND DISCUSSION

Figure 1 shows the location of the 69 soundings conducted as part of this study. While the majority of the soundings produced useable data, several soundings were not used for cross-sections because they were located too far off the line of transect to be of value. In most soundings, the data from about the last five time windows was unusable due to a low signal to noise ratio. In several other soundings, only about ten time windows (out of 20) produced usable data. Several soundings could not be used due to excessive noise or three-dimensional effects. The field data and models for all soundings are included in Appendix A.

The interpreted position of the Waukesha fault is also shown on Figure 1. Based on the TEM soundings and well control, we interpret the fault to trend northeast-southwest across the county, passing near the northeast and southwest corners of Waukesha County. The fault appears to bend near the City of Waukesha. In the area of the bend, the fault is interpreted to consist of at least two parallel normal faults. The interpretation of the bend in the fault and the potential for a parallel fault splay is supported by the regional gravity data (Bruckardt, 1983 Sverdrup, et al, 1992 ) and magnetic data (Mudrey, 2000), which both show an offset in the steep gradient caused by the fault. The TEM data will indicate the Waukesha fault to be a major factor controlling the distribution of saline water in the sandstone aquifer.

Figures 2, 3, and 4 are geoelectrical cross sections that transect the survey area from west to east. The stratigraphy shown on the cross-sections was interpreted solely from well control down to the base of the Galena-Platteville dolomite. The depth to Precambrian basement shown on the up-thrown side of the Waukesha fault is a combination of the TEM data and well control. The Precambrian surface was not encountered by any wells nor detected by the TEM data on the down-thrown side of the fault. The contact between the fresh water and saline water portion of the sandstone aquifer is interpreted from the TEM data on both sides of the fault. As illustrated by the cross-sections, the TEM data displays two distinct patterns depending on the position of the sounding relative to the Waukesha fault. Most soundings on the up-thrown side of the fault show a trend toward rising resistivity with depth, indicating high resistivity basement rock. Most soundings on the down-thrown side of the fault indicate a highly conductive electrical half-space at depth, suggesting high salinity ground water in the lower portion of the sandstone aquifer.

Modeling data from the up-thrown side of the fault produced reasonable agreement between the interpreted depth of the high resistivity half space and the Precambrian basement rock elevation. However, the data on the up-thrown side of the fault also defined several places where the high resistivity half-space is closer to the surface than expected from surrounding well control. These areas are generally located in extreme northwestern Waukesha County north and east of Oconomowoc and in an area of west-central Waukesha County south of Delafield. These areas are interpreted as potential mounds on the Precambrian surface, similar to Precambrian mounds known to be present in Washington, Jefferson, and Dodge Counties (Young and Batten, 1980, Borman and Trotta, 1975, Devaul, et al, 1983). This interpretation is consistent with areas of unexpectedly high Precambrian rock encountered in municipal wells (Village of Pewaukee Well 5 and Village of Delafield Well 1) in recent years. The position of the potential Precambrian highs interpreted from the TEM data are also in the general area of positive anomalies in the regional gravity and magnetic data (Bruckardt, 1983, Sverdrup et al., 1992, Mudrey, 2000), but have not been confirmed by well data.

The TEM data indicated that the quality of the water in the sandstone aquifer on the up-thrown side of the fault is generally fresh from the base of the Galena-Platteville dolomite to the top of the Precambrian. This interpretation is consistent with known salinity problems, which are all on the down-thrown side of the fault. This interpretation is further supported by the results of a down-hole water sampling study conducted in Well 4 in the Village of Sussex (Aquifer Science and Technology, 2000). Water samples were collected at several depths in the well while purging the aquifer. The TDS levels of the samples were all within 10% of

440 ppm from the base of the Maquoketa shale to the top of the Precambrian. A few soundings indicated that isolated zones of elevated TDS ground water may be present on the up-thrown side of the fault, apparently in general proximity to the suspected Precambrian highs. While these apparent pockets of elevated TDS water have not been confirmed, the correlation between zones of saline water and Precambrian highs in eastern Wisconsin is well established (Ryling, 1961, Layne Northwest and Aquifer Science & Technology, 1999).

Modeling the data from soundings on the down-thrown side of the fault clearly indicated the presence of elevated TDS levels at depth. However, the estimates of depth to the elevated TDS water were generally shallower than expected. The modeled depths the high conductivity interface were well above the bottom of most of the high capacity wells. In some areas the interface was modeled to be above the base of the Galena-Platteville dolomite. The modeled depth of the brackish to saline water is clearly problematic. Most wells on the down-thrown side of the fault produce water with TDS levels well below 1000 ppm. Clearly a substantial fresh water lens is present in the upper portion of the aquifer. Obtaining accurate estimates of formation water quality is difficult in most sandstone aquifer wells due to extensive mixing that occurs between different head zones in a non-pumping well. Extensive purging is required to obtain representative water samples. A suite of geophysical well logs conducted in Waukesha Water Utility Well 5 after extensive purging indicated that TDS levels rise from about 300 ppm at 1200 feet to over 2000 ppm at 1400 feet (Paillet, 1999). The water quality measured at the pump discharge at the time of the logging was 710 ppm. Based on the heavy pumpage from the sandstone aquifer by the Waukesha Water Utility, the elevation of the brackish to saline water zone could be expected highest near at Well 5. However, other wells in the Waukesha Water Utility well field are pumped harder and have higher TDS levels. It is possible that the top of the layer of elevated TDS ground water is higher near other wells, but probably does not rise to the base of the Galena Platteville dolomite.

The TEM interpreted depth to the top of the high conductivity half space in the Waukesha area is between about 700 and 1000 feet. In general, it appears that the modeled depth to the top of the zone of high TDS water is too high by several hundred feet. In addition, the resistivity values needed to match the TEM data suggest very high TDS values, probably in the range of several thousand to over ten thousand ppm in several soundings. These TDS values are well above any water quality samples taken from any well in Waukesha County to date, although the water quality from the portion of the aquifer backfilled in the City of Brookfield Well 29 may have been in the range of TDS values suggested by the TEM data.

The disparity between the interpreted depths and TDS values of the zone of poor quality water and the values expected from the water quality data cannot be explained at this time. The available data seems to clearly indicate that a zone of elevated TDS water is present in the lower portion of the aquifer and that water quality in the lower portion of several boreholes is probably brackish to saline. However, the elevation of the top of this layer is probably several hundred feet deeper than our interpretation of the TEM data suggests. The cause of the disparity is unknown but could be caused by the difficulty in modeling a relatively thin layer of moderate resistivity between the moderately conductive layer of the Maquoketa shale and the apparently high conductivity electrical half-space. The fact that the contact between the fresh water and the zone of saline water is probably gradational also contributes to the problem.

## V. CONCLUSION AND RECOMMENDATIONS

The results of the TEM survey strongly suggest that the lower portion of the Mount Simon sandstone contains brackish to saline water. The observed increase in TDS in several high capacity wells appears to be caused by high TDS water migrating upward in response to heavy pumpage in eastern Waukesha County. The top of the fresh water/brackish water interface appears to be high near heavily pumped wells and near deeper wells. The deeper wells are likely to penetrate more thin shale units in the upper portions of the Mount Simon and these shales act as a weak confining unit. This observation is supported by strong correlations between elevated TDS and total depth and annual pumpage observed in the Waukesha Water Utility well field (Aquifer Science and Technology, 1999). Plots of these correlations are included in Appendix B. The data also suggests that isolated mounds may be present on the Precambrian surface in western Waukesha County with potential zones of elevated TDS ground water adjacent to the mounds.

Assuming that our hypothesis for the source of the rising TDS values is correct, the deterioration in water quality might be minimized or reversed by back filling the lower portion of deeper wells and pumping less water. This hypothesis is supported by an observed reduction in TDS levels of 23% in Waukesha Water Utility Well 7 in 1991 after filling the lower 200 feet of the well. (Detro, 1999). This hypothesis will be tested further in 2001 as part of a well rehabilitation study of Waukesha Water Utility Well 9 being conducted by one of the authors of this report. In addition, new wells could potentially be protected from rising TDS levels by drilling shallower sandstone wells, preferably on the up-thrown side of the Waukesha fault, and pumping the wells at lower rates.

The change in water quality with depth suggests that the deeper portions of the sandstone aquifer are separated from the upper fresh water zone. For the purposes of modeling the hydraulic response of the sandstone aquifer, the top of the saline water zone at depth may be the practical base of the aquifer.

The survey also suggested that the shape of the Precambrian surface and Waukesha fault may be more complex that initially anticipated. Unmapped mounds may be present on the up-thrown side of the fault with associated zones of elevated TDS water. The presence of these features has not been confirmed, but additional investigation is warranted in these areas before developing new high capacity wells in the sandstone aquifer.

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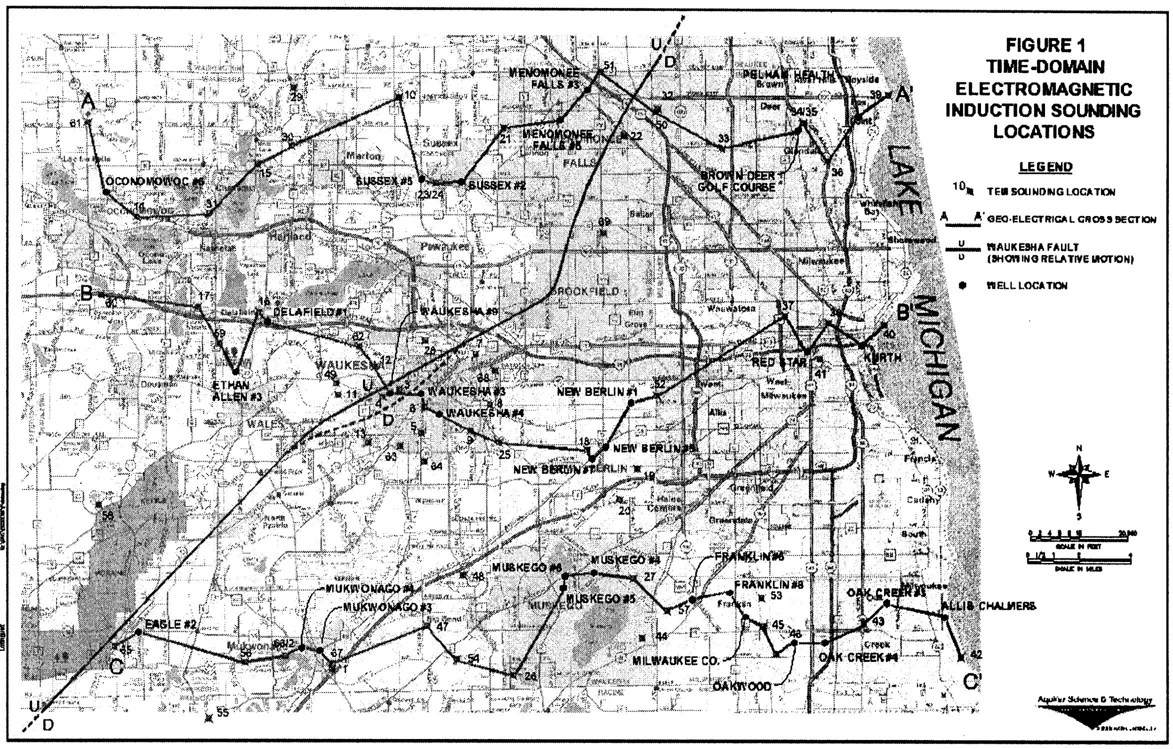
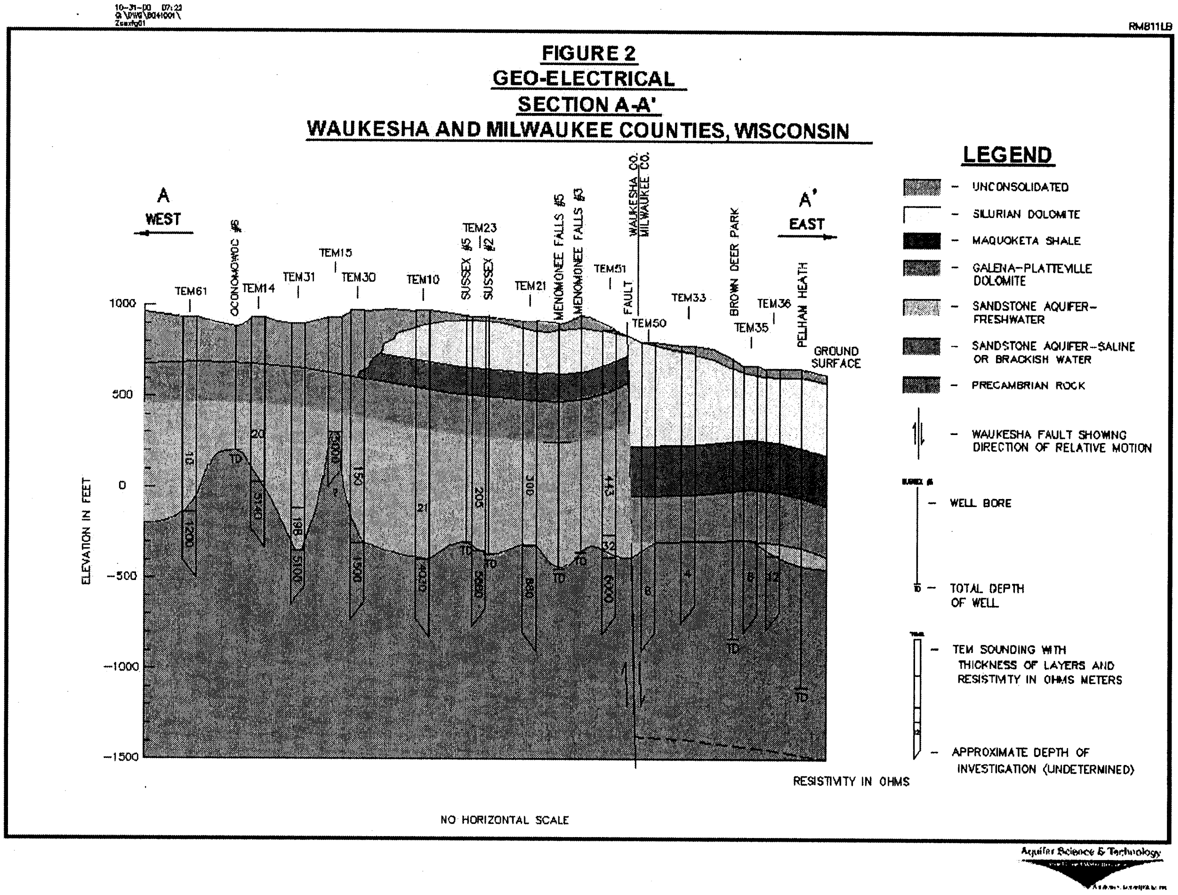
# FIGURE 1 - TIME DOMAIN ELECTROMAGNETIC INDUCTION SOUNDING LOCATIONS

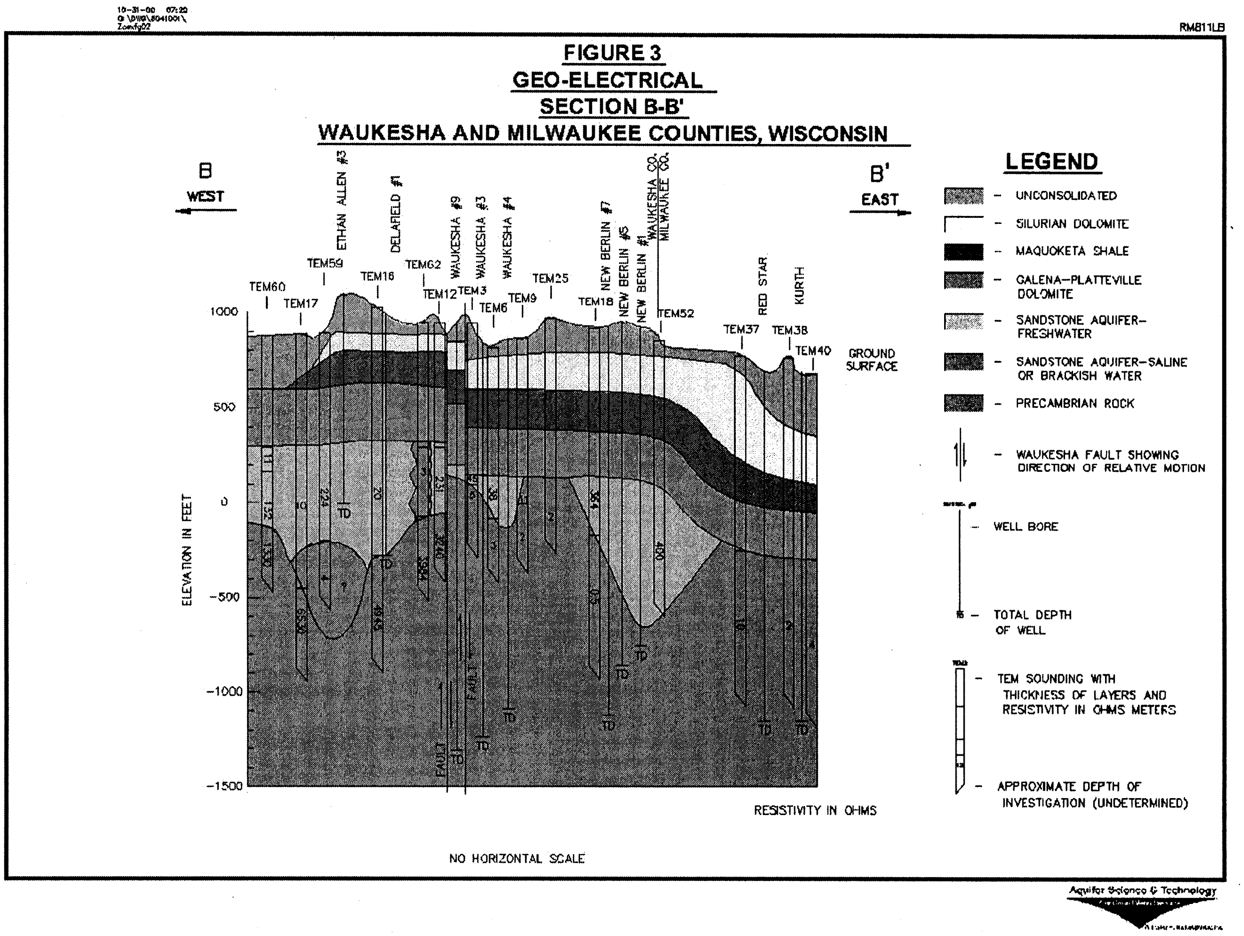



SOURCE: SEEGER MAPS

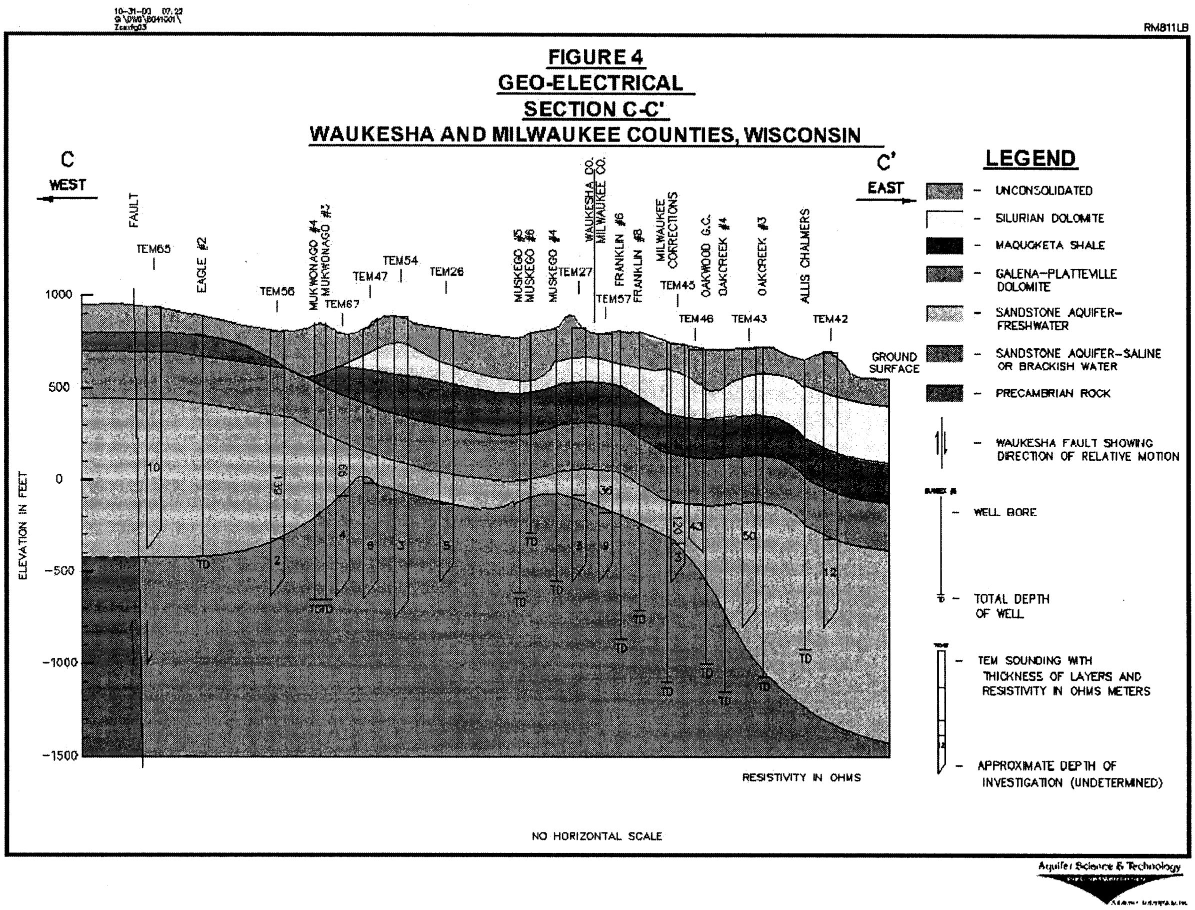
# FIGURE 2 - GEO-ELECTRICAL SECTION A-A'



# FIGURE 3 - GEO-ELECTRICAL SECTION B-B'



# FIGURE 4 - GEO-ELECTRICAL SECTION C-C'



## VIII. APPENDICES

Appendix A, TEM Models

Appendix B, Correlation Plot of TDS, Well Depth, and Annual Pumpage for the Waukesha Water Utility Well Field