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UW Extension WISCONSIN GEOLOGICAL AND NATURAL HISTORY SURVEY

3817 Mineral Point Road
Madison, WI 53705-5100
Tel 608/262.1705
Fax 608/262.8086
www.uwex.edu/wgnhs/

James M. Robertson
Director and State Geologist

November 10, 1998

Jeff Helmuth
DG-2
Wisconsin Department of Natural resources
P.O. Box 7921
Madison, WI 53707

Dear Jeff,

Under separate cover you should have received, or soon will receive, the final report on the project **Preliminary model design and literature review for the sandstone aquifer system in southeastern Wisconsin.** This report presents a review of most of what is know about the hydrogeology of southeastern Wisconsin. We are grateful to you and the DNR for providing funding and oversight of this project.

Sincerely,

Kenneth R. Bradbury, Timothy T. Eaton
Hydrogeologists

Preliminary Model Design and Literature Review for the Sandstone Aquifer System in Southeastern Wisconsin

Letter Report

Submitted to Jeff Helmuth, Wisconsin Department of Natural Resources

Submitted by United States Geological Survey, Water Resources Division and Wisconsin Geological and Natural History Survey

November 1998

Preliminary Model Design and Literature Review for the Sandstone Aquifer System in Southeastern Wisconsin

The principal objective of this report is to determine what is well known and what is less well known about the regional groundwater system in southeast Wisconsin in preparation for a comprehensive model aimed at addressing important water-supply issues. This overall objective is addressed in two ways: first, by the development of a fully three-dimensional screening model for southeast Wisconsin based on previous studies, and, second, by a thorough review of the available data needed to quantify hydrogeologic parameters. Both tasks have as a major aim the identification of gaps in our understanding of the groundwater system.

The development of a screening model involves the translation of the regional hydrostratigraphy into the input arrays that constitute a fully three-dimensional numerical model. This step incorporates preliminary evaluation of key model elements: the geometry of the grid, the regional boundary conditions, the thickness of hydrogeologic units, and the distribution of hydraulic conductivity in each unit. It is intended to not only provide preliminary model design, but also to identify uncertainties in our understanding of the hydrostratigraphic framework that require additional interpretation or fresh data sources.

The second task is a review of existing hydrologic and geologic databases that bear on various inputs to the model, including aquifer properties and sources of water. This step is an initial effort to establish a complete hydrogeologic database for Southeast Wisconsin that will support the full groundwater model.

This report is divided into two parts. Part 1 addresses preliminary model design and is, in turn, divided into two sections. The first draws heavily on previous modeling work performed at the Wisconsin District of the U.S. Geological Survey to prepare a *modeling framework* for Southeast Wisconsin. The second identifies gaps or anomalies in that framework and provides *recommendations for future work.*

Part 2 of the report is a review of existing geologic and hydrologic data for Southeast Wisconsin. The database preparation is an outgrowth of research conducted by Doug Carlson at the University of Wisconsin-Milwaukee in connection with his doctoral dissertation. It contains sections on hydraulic conductivity, porosity, recharge, and mineral content as a guide to permeability. Particular attention is paid to the distribution of data across hydrogeologic units in order to determine where future work should be focused.

Part 1.

Preliminary Model Design

Figures

Appendix Figures

Section A: Hydrostratigraphic Framework Based on Existing Work

Previous Modeling

A groundwater MODFLOW model for the Chicago-Milwaukee area was developed by the Wisconsin District of the USGS in the 1980s.[/*] It is a submodel constructed as part of a larger modeling effort under the Regional Aquifer-System Analysis (RASA) project undertaken for the Northern Midwest by the USGS (Mandle, R.J, and Kontis, A.L., 1992). The submodel contained five layers corresponding to the following hydrostratigraphic units in ascending order:

- the Mt. Simon aquifer (base of model overlying Precambrian bedrock)
- the Ironton-Galesville aquifer
- the St. Peter-Prarie du Chien-Jordan aquifer
- the Silurian aquifer
- Unlithified (or "drift") aquifer

Each aquifer is represented by spatially varying values of transmissivity (equal to the hydraulic conductivity of the unit multiplied by its thickness). For example, the transmissivity value of the Mt. Simon aquifer might vary between 100 and 10,000 ft^2/day in different parts of the model domain.

The RASA submodel did not explicitly include the confining units between aquifers. Instead, it incorporated them as spatially varying "leakance" terms (equal to the vertical hydraulic conductivity of the confining unit divided by its thickness). The leakance value assigned at any given location of the model imposes the vertical resistance to flow between the overlying and underlying aquifer at that location. The four confining units represented by leakance terms are in ascending order:

- the Eau Claire between the Mt. Simon and Ironton-Galesville aquifers
- the St. Lawrence-Franconia between the Ironton-Galesville and St. Peter-Prairie du Chien-Jordan aquifers

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1. /* *a description of the model is presented in:* Young, H.L., MacKenzie, A.J., and Mandle, R.J., 1988, "Simulation of Ground-Water Flow in the Cambrian-Ordovician Aquifer System in the Chicago-Milwaukee Area of the Northern Midwest", collected in Regional Aquifer Systems of the United States, Aquifers of the Midwestern Region, American Water Resources Association.

- the Maquoketa-Sinnipee between the St. Peter-Prairie du Chien-Jordan and the Silurian aquifers
- the Mesozoic (Pennsylvanian and Mississippian rocks) between the Silurian and Unlithified aquifers in Illinois and Michigan

The RASA framework corresponds in general terms to the accepted hydrostratigraphy for Southeast Wisconsin (see, for example, Kammerer, P.A. Trotter, L.C., Krabbenhoft, D.P., and Lidwin, R.A., 1998). One possible refinement to this scheme is to include the Sinnipee as an aquifer in areas where it subcrops (that is, in areas west of Waukesha where overlying units including the Maquoketa Shale are absent).

The Chicago-Milwaukee submodel was never published as part of the overall collection of RASA studies. However, the computer files containing node-by-node transmissivity values for the aquifers and node-by-node leakance values for the confining units were stored on U.S.G.S computers. In addition, structural contour maps prepared as part of the project that contain top and bottom elevations for the aquifers and confining units were preserved. Pumping and water-level information for different years was also archived.

Boundary Conditions

Figure 1 shows the extent of the RASA submodel and the arrangement of its model nodes. The boundaries were set very distant from the areas of interest where the density of nodes is greatest to minimize their effects on the finite-difference solution in the vicinity of Milwaukee and Chicago. This same boundary configuration is maintained in the preliminary model framework proposed in this report. Note that the western boundary extends almost to Madison, the northern boundary extends beyond Sheboygan, the southern boundary into Indiana, and the eastern boundary into the state of Michigan. This configuration has several advantages beyond moving the boundary conditions far from the area of interest. The western edge of the model extends sufficiently far that findings from the recently completed Dane County model can be exploited. It also allows the model to explicitly solve for the (shifting) groundwater divide that separates flow into the Lake Michigan Basin from the Mississippi Basin. The southern extent of the model grid allows all the major pumping centers to be explicitly included in the model so that the (shifting) divide between the Milwaukee and Chicago cones of depression can be resolved. Little is known about hydrostratigrahic conditions below Lake Michigan – extending the model east to Michigan allows the model to be anchored to available data from that state. It also helps to constrain the location of the divide under Lake Michigan by allowing the model to honor flow directions on either shore.

It is anticipated that all the side boundaries of the new model will be represented by constant head values. The variation of head with depth across model layers will incorporate significant uncertainty, but it is expected that the boundaries are sufficiently distant from the areas of interest that any error introduced will be unimportant.

The bottom boundary condition for the RASA submodel represents the contact between the Precambrian and the Ordovician Mt. Simon aquifer. It is considered to be a no-flow boundary. This boundary is maintained in the new model.

The top boundary of the RASA submodel was a constant head surface in the uppermost model layer taken to represent the unconfined surface of the groundwater system. The use of constant heads effectively removed the unlithified layer from participation in the model solution and eliminated the possibility of treating the unlithified material as an active aquifer. This limitation will be eliminated from the new model. Heads in the unlithified material will be solved directly. Recharge will be applied to the top layer and major surface water bodies will be incorporated to allow for local discharge. However, these changes represent future work that is not included in this preliminary treatment of the regional hydrostratigraphy.

The RASA submodel consisted of the 71 rows and the 46 columns represented by node points in Figure 1 as well as the 5 layers corresponding to aquifer systems. The model extended over 237 miles from east to west and 301 miles from north to south. While we propose that the overall dimensions of the grid be maintained in the new model, we anticipate that the number of rows, columns, and layers will each be increased to enhance model resolution in southeast Wisconsin. In this preliminary version of the new model, the number of layers has been increased from 5 to 10.

Methodology Used to Construct A Fully Three-Dimensional Model

The primary thrust of the effort described in this part of the report is to convert the quasi three-dimensional approach used in the Chicago-Milwaukee RASA submodel to a fully three-dimensional framework. This objective is a modification of the original proposal for the development of a series of two-dimensional profile models intended to test the effect of model geometry and boundary conditions on drawdown in the presence of pumping stresses. The chief reason for the change in scope is the large advantages a 3D screening model has over a 2D screening model whenever stresses are involved. Pumping induces radial flow patterns and storage effects that cannot be properly simulated with a profile model. A fully three-dimensional model allows thorough testing of critical features of a future water-supply model of southeast Wisconsin including the proper layering needed to simulate favored horizons of flow and the influence of recharge zones on system response. The conversion of the RASA submodel into a fully three-dimensional model provides the screening tool necessary for building a reliable water-supply model.

In the quasi-3D approach adopted in the RASA submodel, the confining units are represented only by their resistance to groundwater flow (inversely proportional to their leakance term). The actual movement of water through the confining bed is neglected because water is forced to move vertically from one aquifer to another through a resisting "surface". The omission of the actual thickness of the confining units implies that the model is restricted in how well it can represent groundwater or contaminant pathlines. It limits the extent to which the techniques of particle tracking and transport modeling can be used to investigate the regional system. It also underestimates the ability of groundwater to move horizontally in confining beds. Another limitation of this approach is that it cannot accommodate a unit that acts as an aquitard over much of the model domain, but should be considered an aquifer elsewhere (for example, the Sinnipee dolomite).

The RASA submodel did not specify the thickness of the 5 aquifer layers. Instead, each layer is represented strictly by a transmissivity array that has is independent of the actual geometry of the aquifers.

A fully three-dimensional model incorporates the geometry of both aquifers and aquitards. They are treated identically in that the thickness, horizontal hydraulic conductivity, and vertical hydraulic conductivity must be specified for both types of units. Consider a fully three-dimensional model that contains 10 layers (each layer corresponding to one of the aquifers and aquitards listed above, with the Maquoketa and Sinnipee considered separately). Layer 10 represents the Mt. Simon aquifer in this arrangement. Any node in layer 10 is assigned a top elevation, a bottom elevation, a horizontal hydraulic conductivity, and a vertical hydraulic conductivity. Layer 9 represents the Eau Claire aquitard. Each node in layer 9 is also assigned values representing its top, bottom, horizontal and vertical conductivity. The bottom elevation of layer 9 at any node must equal the top of layer 10. The availability of transmissivity and leakance arrays from computer files of the RASA submodel in conjunction with the structural contours from RASA work maps allows the thickness of each aquifer and aquitard unit to be calculated on a node-by-node basis. Once a thickness map is prepared for each unit, the horizontal hydraulic conductivity of aquifer nodes and the vertical hydraulic conductivity of aquitard nodes can be immediately calculated. Because values of transmissivity and leakance zones in the RASA submodel were varied to achieve calibration of its results to a series of water-level maps representing distinct pumping regimes through time (*personal communication:* R.J. Mandle, September 1998), the horizontal and vertical hydraulic conductivity values calculated from the transmissivity and leakance arrays also represent calibrated values. They serve as initial estimates of the distribution of permeabilities in the new fully 3D model that itself will be subject to a series of calibration simulations.

It is evident that this method for converting a quasi-3D model into a fully 3D model does not furnish estimates of vertical hydraulic conductivity for the aquifers or horizontal hydraulic conductivity for the confining units. These values will have to be derived independently. For the preliminary model framework an anisotropy value (horizontal:vertical) of 100:1 is assumed for all 10 units now explicitly represented in the new model.

The following text sections provide details on the steps used to generate thickness and conductivity arrays. Accompanying maps at a 1 inch = 40 mile scale show the results of each step. Major cities and the outline of Lake Michigan are provided as reference locations. The resultant hydrostratigraphy is then integrated through an interface for MODFLOW that allows cross sections to be visualized along any model row or column.

Transmissivity and Leakance Maps based on input to the RASA submodel

The input arrays to the RASA submodel represent calibrated transmissivity and leakance values on a node-by-node basis. Contoured maps of these values has been prepared for the 4 aquifer units (Mt. Simon, Ironton-Galesville, St. Peter-Prairie du Chien-Jordan, and Silurian) and the 4 confining units (Eau Claire, St. Lawrence-Franconia, Maquoketa-Sinnipee, Mesozoic) using the contouring package SURFER./* In each case the input value was paired with the X and Y coordinates of each model node location. The inverse square method allowed interpolation of values between node points along an evenly spaced grid on 10,000 ft centers. The first map, representing the Mt. Simon aquifer, is shown in Figure 2. Additional maps are contained in the Appendix to this first part of the report (Figures A-7, A-12, A-17, A-22, A-27, A-36, and A-41). In all cases the transmissivity units are ft^2/day and the leakance units are 1/day. It is worth noting that a single nodal leakance value was used in the RASA submodel for the combined thickness of the Maquoketa Shale and Sinnipee Dolomite, and that the unlithified layer was assigned a dummy transmissivity because it was everywhere assigned constant head values.

Maps of Tops and Bottoms based on digitized USGS maps

Work maps prepared as part of the larger RASA project contained contours of the tops of the 10 units that make up the hydrostratigrahic framework. Stratigraphic well logs from southeast Wisconsin and northern Illinois constituted the database for these maps. The contours themselves have been digitized for this project in an X,Y,Z format where X and Y are state plane coordinates and Z is the elevation of the contour. These XYZ points were then subjected to interpolation and extrapolation through the SURFER gridding algorithm on 10,000 ft centers. The smoothed inverse square technique was determined to be superior to other available methods (kriging, minimum curvature, and polynomial fitting), especially with respect to reasonable extrapolation to areas distant from digitized structural contours.

Figures 3 and 4 represent the top of the Precambrian and Mt. Simon respectively in feet of elevation. Note the approximate correspondence between digitized points along contours derived from the

/* The unlithified aquifer was not contoured because in the RASA submodel it is represented by a constant-head layer, eliminating the need to assign it meaningful hydraulic parameters.

original work maps (represented as stippled lines) and the contours reproduced by SURFER (represented as solid lines). The small discrepancy is owing to interpolation and smoothing.

Figures 3 and 4 show additional data points that do not lie on contours, but extend from north to south under Lake Michigan. These points were derived from cross sections of the hydrostratigraphy included in a summary of the RASA submodel prepared for the American Water Resources Association (Young, H.L., MacKenzie, A.J., and Mandle, R.J., 1988, Figures 3A and 3B). The east-west cross sections show the expected trend of the tops for each aquifer and aquitard unit east of Milwaukee and Chicago. A linear interpolation of the digitized values from these cross sections was calculated to project the tops of each unit north of Milwaukee and south of Chicago. The entire set of projected points was then added to the digitized points along the traces of the elevation contours from the work maps before the SURFER gridding was performed. The projected points were necessary to achieve reasonable structural contours under Lake Michigan and the state of Michigan.

Contour maps for the tops of additional units are contained in the Appendix (A-8, A-13, A-18, A-23, A-28, A-31, A-37, A-42, A-46.) No top map is provided for the unlithified unit because it is unconfined.

Calculation of Unit Tops at Model Node Locations and Preparation of "Corrected" Top Maps

The 10,000 ft centers produced by the SURFER gridding do not correspond to the nonuniform distribution of model node centers indicated in Figure 1. A bilinear interpolation algorithm (Wang and Anderson, 1982) was applied to interpolate the value of a top elevation at a precise node location from the nearby SURFER grid points. This algorithm was also used to shift between state plane and model coordinates.

Once a nodal array of tops for adjacent units was prepared, a check was performed to be sure that the top of the overlying unit stood above the top of the underlying unit. In certain areas of the model, the subtraction of the underlying elevation from the overlying elevation resulted in negative values. The implied negative thickness generally can be attributed to the local absence of the overlying unit (for example, the Mt. Simon northwest of Milwaukee). It can also arise because the original structural contours from the work maps were not sufficiently precise.

Whenever an implied negative thickness was calculated at a node point, a dummy thickness value of 1 ft was assigned to the unit in question. For example, when the subtraction of the top of the Precambrian from the top of the Mt. Simon produced a negative value, a thickness of 1 ft was assigned to the Mt. Simon. The use of a nominal thickness is important because it allows the numerical model to maintain its layer structure even in the absence of any real thickness, which, in turn, allows the MODFLOW solvers to remain stable.

Figure 5 shows the corrected top contours for the Mt. Simon aquifer. Comparison with Figure 4 shows that the tops have been altered in the northwest part of the grid. The dots in Figure 5 shows where the nominal 1-ft thickness nodes are present. Similar corrected top plots are included for the other hydrostratigraphic units in the Appendix (A-9, A-14, A-19, A-24, A-29, A-32, A-38, A-43, A-46). The corrected top map for the unlithified layer corresponds to the constant heads input to the RASA submodel.

Examination of these figures shows that all units are absent over at least part of the model domain. For example, the Mesozoic aquitard that constitutes model layer 2 is only present in the northeast and southwest parts of the model (see Figure A-43).

The nodal arrays that correspond to the corrected top maps are entered directly into MODFLOW as input. These arrays constitute the geometry of the model. Their representation as cross sections is discussed below.

Thickness Maps based on digitized USGS maps

Because the new model does not tolerate gaps between units, but, instead, explicitly includes the full hydrostratigrahic sequence, it is possible to calculate the thickness of a unit simply by subtracting its bottom from its top. The bottom of the unit corresponds to the top of the underlying unit. When this calculation is performed at each node, the results can be gridded on 10,000 ft centers to produce thickness maps (see Figure 6 for the Mt. Simon, Figures A-10, A-15, A-20, A-25, A-30, A-33, A-39, A-44, A-47 for remaining units). These maps generally show that units thicken to the east toward the Michigan Basin and to the south toward the Illinois Basin. There are, however, local deviations from the trend. Comparison with other data sources also reveal anomalies that are discussed in Section B of Part 1.

Hydraulic Conductivity Maps based on integration of input to the RASA submodel and generated thickness maps

With nodal transmissivity and nodal thickness arrays in hand, the implied nodal horizontal hydraulic conductivity for aquifer units (Mt. Simon, Ironton-Galesville, St. Peter-Prairie du Chien-Jordan, and Silurian) can be immediately calculated. Similarly, nodal leakance and nodal thickness arrays yield nodal vertical hydraulic conductivity arrays for aquitard units (Eau Claire, St. Lawrence-Franconia, Maquoketa-Sinnipee, Mesozoic). These arrays can be entered as input to MODFLOW and used as a basis for contour maps. Figure 7 through 14 show the implied horizontal hydraulic conductivity map for the various units. The unlithified aquifer is not included because the RASA submodel contained no transmissivity information for this layer.

The implied range of horizontal and vertical hydraulic conductivities evident from the maps accords very well with the expected range reported for each unit in the summary of the RASA submodel (Young, H.L., MacKenzie, A.J., and Mandle, R.J., 1988, pp. 45-49). Areas of the model where additional work might improve the conductivity estimates are discussed in Section B of Part 1.

Assembly of Hydrostratigraphy in 10-layer MODFLOW Framework

A powerful graphical interface for MODFLOW called GROUNDWATER VISTAS was used to assemble the geometric and conductivity data yielded by the integration of the input to the RASA submodel with the structural contours available from USGS work maps. This interface allows cross sections of model layers across any rows or column to be visualized. Three cross sections (their traces are shown on Figure 15) summarize the results. Figure 16 is an east-west section through Waukesha. Figure 17 is an east-west section through Chicago. Figure 18 is a north-south figure through Waukesha. In each case aquifers are shown in white, aquitards in gray. The Sinnipee is distinguished from the Maquoketa by a separate shade. These sections show the complex geometry that results from a fully three-dimensional regional model. Areas of thickening and thinning are evident for each unit.

Gross features of the hydrostratigraphy in the regional context are reproduced by the model representation. Figure 16 shows the general structural trend between the Wisconsin Arch and the Michigan Basin. Figure 18 shows a similar trend between the Wisconsin Arch and Illinois Basin. It also shows the Precambrian high north of Waukesha where the St. Peter directly overlies Precambrian rock. Figures 16 and 17 indicate the areas where the Sinnipee subcrops in the western part of the model domain and is expected to serve as an aquifer unit.

Figure 19 is a detail of the east-west section in the vicinity of Waukesha and Milwaukee. It is referred to below in connection with identification of some hydrostratigraphic anomalies.

Use of Updated Model as Three-Dimensional Screening Tool

The conversion of the RASA submodel into a fully three-dimensional model allows tests to be performed that determine the response of the system to the layering scheme. These tests are vital to the construction of any future water-supply model for southeastern Wisconsin.

The 10-layer geometry presented in this report corresponds to hydrogeologic units. However, it may be that some units can be lumped because their physical characteristics are not very different. More likely, it is possible that some units should be split because different horizons have different properties. Examples of distinct horizons are weathered zones or fractured zones that transmit large amounts of water through otherwise less permeable units or shaly zones that resist vertical flow in otherwise relatively transmissive units. Such horizons can represent only a small volume of a unit, but dominate its flow system. The layers in the updated fully three-dimensional model can be easily combined or split to test the effect of the layering scheme on predicted water levels and drawdown. Hydraulic properties can easily be varied in the new layers to test, for example, the influence of a weathered zone at the top of a dolomite unit.

The tests should be conducted under stressed (that is, pumping and recharge) conditions that induce three-dimensional effects by encouraging vertical flow. Such tests are not properly conducted in two-dimensional cross-section model because such a model cannot account for the radial flow and drawdown pattern produced by pumping wells. The updated RASA submodel is particularly designed to overcome this limitation. As a screening tool, it can be used to determine the best layering scheme for the future water-supply model under hypothetical conditions that will themselves be tested by comparison with field data. Despite gaps and anomalies in the present form of the updated fully-three dimensional model (discussed in Part B), it is large step forward in our power to represent the integrated groundwater system because it allows the effect of layer geometry to be realistically evaluated under stressed conditions.

Section B: Identification of Future Work Arising From Preliminary Model Design

The updated RASA submodel described in this report is a preliminary step toward a three-dimensional water-supply model for southeastern Wisconsin. In this section recommendations are given for additional steps toward a comprehensive model.

Resolution of Stratigraphic and Hydrogeologic Anomalies Evident in Three-Dimensional Data Base

The thickness and conductivity arrays generated by the methodology described in Section A are designed to reproduce the regional hydrostratigraphic trends. Because the area contained by the model is so large, the gridding resolution that underlies the arrays is coarse. Of even greater importance, the structural maps that underlie the thickness interpolation consists of contours already once removed from data points associated with well logs. Inevitably much local detail is lost.

One focus of the anticipated Southeastern Wisconsin model will be the area immediately west of Milwaukee that depends on groundwater for its drinking-water supply. The results of the preliminary model design in this area were compared to other sources of information for the thickness of hydrostratigraphic units. For example, a cross section centered on Waukesha, developed as part of a county report on groundwater resources (Gonthier, J.B., 1975), delineates the contact between the Mt. Simon aquifer and the underlying Precambrian. The well logs incorporated in this cross section indicate that the Mt. Simon at least extends to a depth of –1200 ft below sea level. Reference to Figure 19 of this report shows that the preliminary model framework places this boundary at –400 ft below sea level.

This large discrepancy, also confirmed by comparison of well logs from the Brookfield area with the Figure 19 [/*], can be attributed not only to the coarse resolution of the procedure used to generate the model framework, but also to the presence of the Waukesha fault. This important structural feature causes a dramatic thickening of the hydrostratigraphic sequence on the downthrown (east and

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[/*] see, *for example, log attached to well construction form for Brookfield Well #29, Wisconsin unique well number EM-276, Wisconsin Geologic and Natural History Survey.*

southeast) side of the fault. The structural contour maps used to define unit boundaries in the numerical model do not sufficiently reflect the discontinuities presented by the fault.

The examples of Waukesha and Brookfield clearly indicate that the model design must be improved in the focus areas of the model. These changes could be made by adding data and by recalculating unit tops and thickness at a finer resolution. Both the interpolation and the model grid should be refined in these areas. The results based on the coarse resolution should be left largely intact outside the focus areas unless new sources of data are available (see below).

It is also possible that anomalies will arise from juxtaposing the model arrays of horizontal hydraulic conductivity for the aquifer units and vertical hydraulic conductivity for the confining units with specific test locations. One example of a likely anomaly is the pattern of hydraulic conductivity for the Silurian aquifer. Recent information from the Milwaukee Deep Tunnel project suggests the existence of zones of relatively high permeability in this unit that exceed the values shown in Figure 13.

A systematic comparison of the results of field tests with preliminary parameter estimates at model nodes should be performed in the future to resolve discrepancies. Part 2 of this report represents the beginning of this process. Again, it may be necessary to use a finer resolution in both the interpolation procedure and model grid to accommodate specific field data.

The methodology presented in Section A can be accommodated to additional data and a finer resolution. New thickness arrays can be generated that, in turn, will generate new conductivity arrays that represent the calibrated output of the RASA submodel. These conductivity arrays can subsequently be amended to take account of field data. They should undergo another modification during model calibration.

Identification of Data Gaps and Data Needs

The maps of unit tops contained in this report (for example, Figures 2 and 3) show the trace of structural contours digitized from USGS work maps. It is evident that structural contours are not available from these work maps over a large part of the model domain. Some of these gaps are inevitable – notably under Lake Michigan. Others can be remedied by adding structural contours using additional data sources – notably from the state of Michigan. Future work should include adding well logs from Michigan to the database of unit geometry so that they can contribute to the next generation of thickness and conductivity maps.

It is evident that more structural data are needed in the focus areas around the Waukesha fault. Another category of data that are needed concerns variations *within* hydrostratigraphic units. For example, it is suspected that the Silurian unit is best divided into at least two layers in order to accommodate high conductivity zones. It is possible that future fieldwork will demonstrate large head differences across horizons within the Mt. Simon, implying discrete zones of flow. It is also possible that ongoing fieldwork in the Maquoketa Shale will indicate that this unit should be represented by multiple strata. Under these circumstances, it might be necessary to add layers to the model and to produce thickness and conductivity estimates proper to these layers.

Because the RASA submodel treated the unlithified material as a constant-head layer, the representation of this layer in the model is less realistic than other units. One major aim of the new model is to make the unlithified layer active so that it can respond to different pumping schemes. It is not possible to incorporate the complex heterogeneity of glacial material in a regional model. However, an effort could be undertaken to use existing maps of glacial deposits to broadly characterize the unlithified material as fine till, coarse till, outwash, or alluvium. This effort could also extend to correlating recharge values to these zones within the unlithified layer so as to reproduce the general trend of the water table and to allow a (coarse) estimate of responses to pumping.

Identification of Data Sources

The methodology outlined in Section A relied on data from working maps in the USGS archives and on input arrays from the unpublished RASA Chicago-Milwaukee model. Other sources that could be considered in generating future model arrays include:

- examination of well logs and specific capacity tests for model focus areas available from the Wisconsin Geologic and Natural History Survey

- interpretation of abundant geophysical records and some aquifer test records available from private consulting firms

- well logs and geologic maps from Michigan, Illinois, and Indiana

- recent USGS publication containing maps and cross sections that reintreprets Wisconsin hydrostratigraphy (Kammerer, P.A. Trotter, L.C., Krabbenhoft, D.P., and Lidwin, R.A., 1998)

- new maps of Pleistocene geology and the water table developed for southeast Wisconsin (Southeast Wisconsin Regional Planning Commision Technical Report #37, in preparation)

- the results of the ongoing Maquoketa study undertaken by the Wisconsin Geologic and natural History Survey (Eaton, T.T., and Bradbury, K.R., 1998)

- results of new interpretations of the subsurface stratigraphy of southeastern Wisconsin currently underway by the Wisconsin Geological and Natural History Survey

- incorporation of inputs from the recently completed Dane County groundwater model to the western side of the Southeast Wisconsin model (Krohelski, J.T., Bradbury, K.R., Hunt, R.J., and Swanson, S.K., 1996)

- incorporation of inputs from the recently completed "New Chicago Model" for northeastern Illinois (Burch, S.L., 1991)

- a reintepretation of the overall transmissivity of the Sandstone Aquifer (i.e., the units from the St. Peter to the Mt. Simon) arising from the calibration of a recently developed two-dimensional regional model for Southeast Wisconsin (Bonestroo Rosene Anderlik & Associates, 1998)

- geophysical studies conducted on the Waukesha fault (*personal communication:* Professor Keith Sverdrup, University of Wisconsin-Milwaukee, June 1998)

- recharge studies conducted on local basins in the Milwaukee area (*personal communication:* Professor Douglas Cherkauer, University of Wisconsin-Milwaukee, September, 1998)

- data collection from the USGS network of wells, including a series of deep nested piezometers at Zion, Illinois

- field work performed directly to support the model, in particular aquifer tests, head measurements and chemical samples collected from packer intervals in aquifer units

Part 2 of this report provides greater detail on some of these sources of information.

Proposed Changes to the Preliminary Model Design

Problems and questions arising from the preliminary model construction presented in Section A suggest that several major changes need to be made to improve the model design. They include:

- refinement of the model grid in focus areas
- additional stratigraphic detail in model layering(splitting of Silurian, Maquoketa-Sinnipee, Mt. Simon)
- greater emphasis on the shallow flow system by incorporating unlithified deposits, recharge, key surface-water features
- explicit treatment of the discontinuities represented by the Waukesha fault

References

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Figures

RASA MODEL GRID IN PLAN VIEW (1 inch = 40 miles)

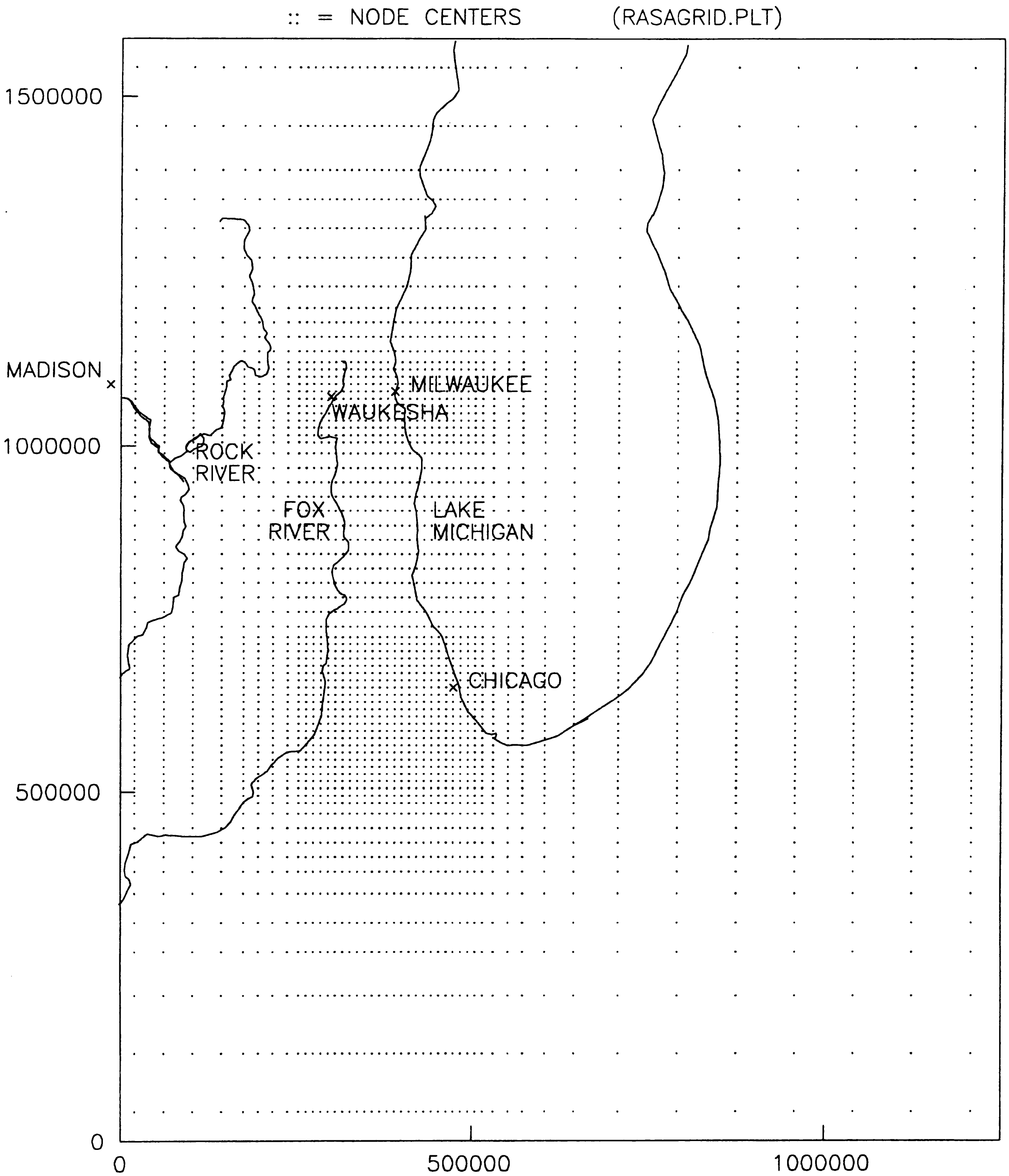


Fig. 1

Transmissivity of Mt. Simon Aquifer in RASA Model

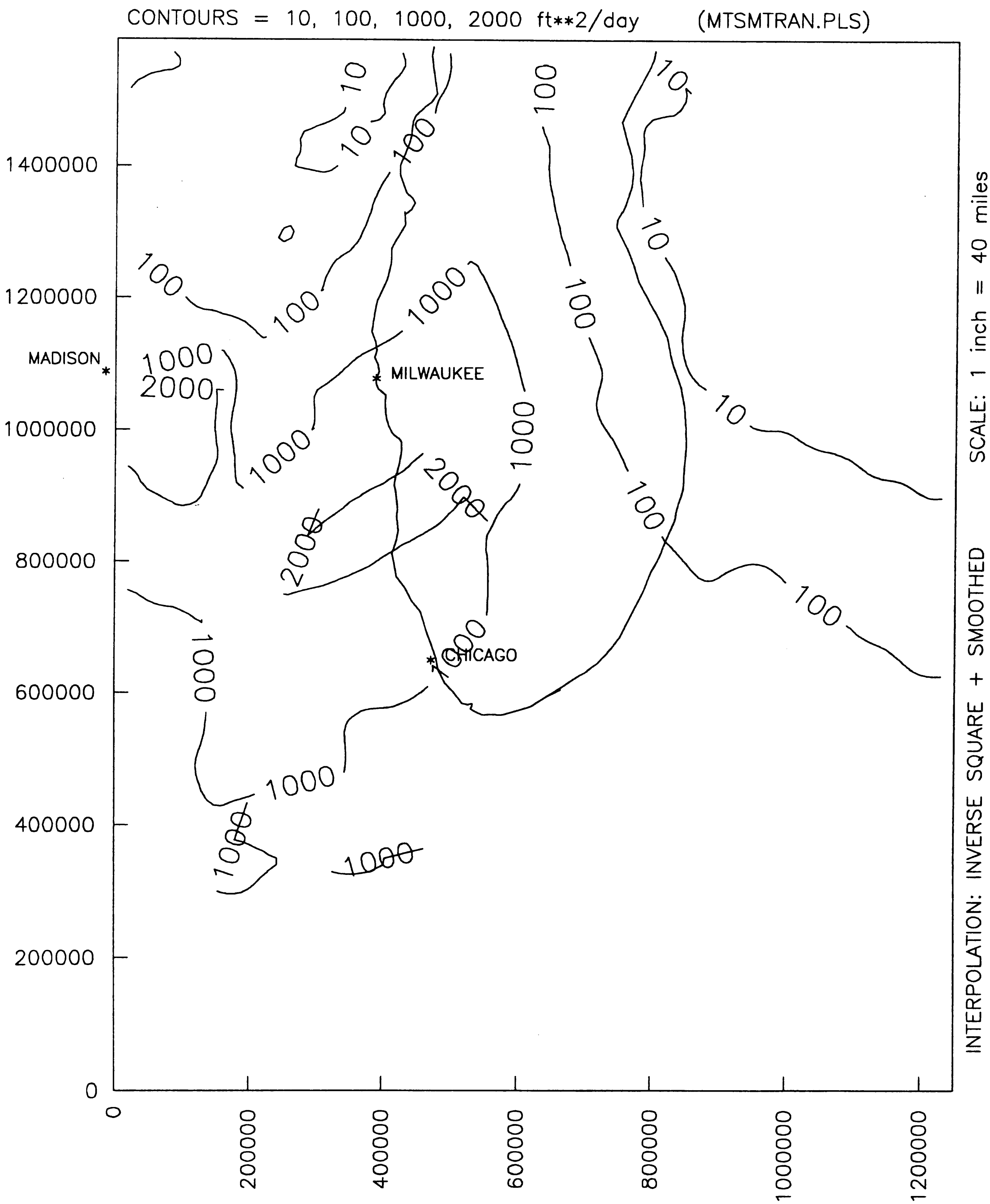


Fig. 2

TOP of PRECAMBRIAN = BOT of MT. SIMON based on digitized maps

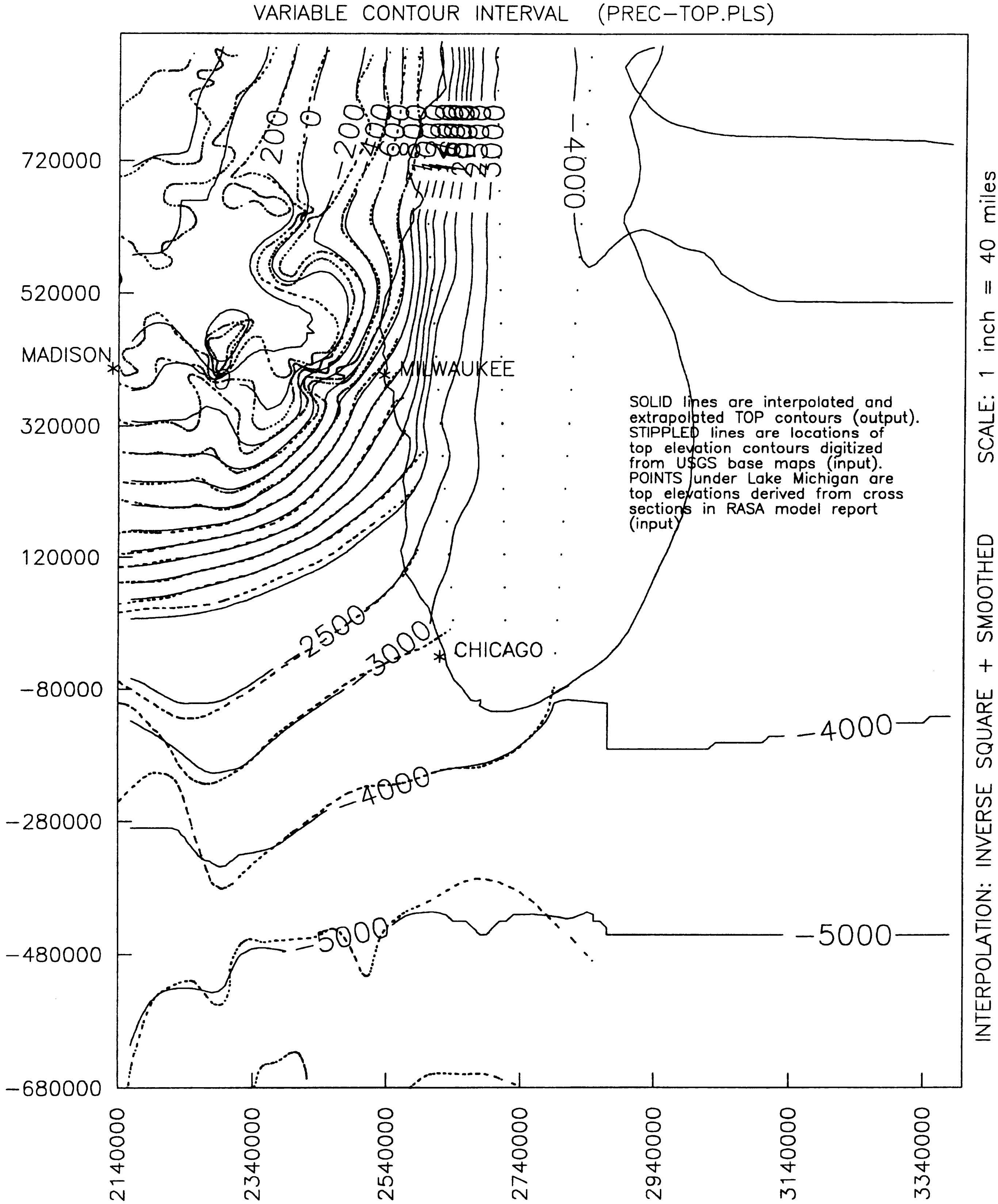


Fig. 3

TOP of MT. SIMON AQUIFER = BOT of EAU CLAIRE based on digitized maps

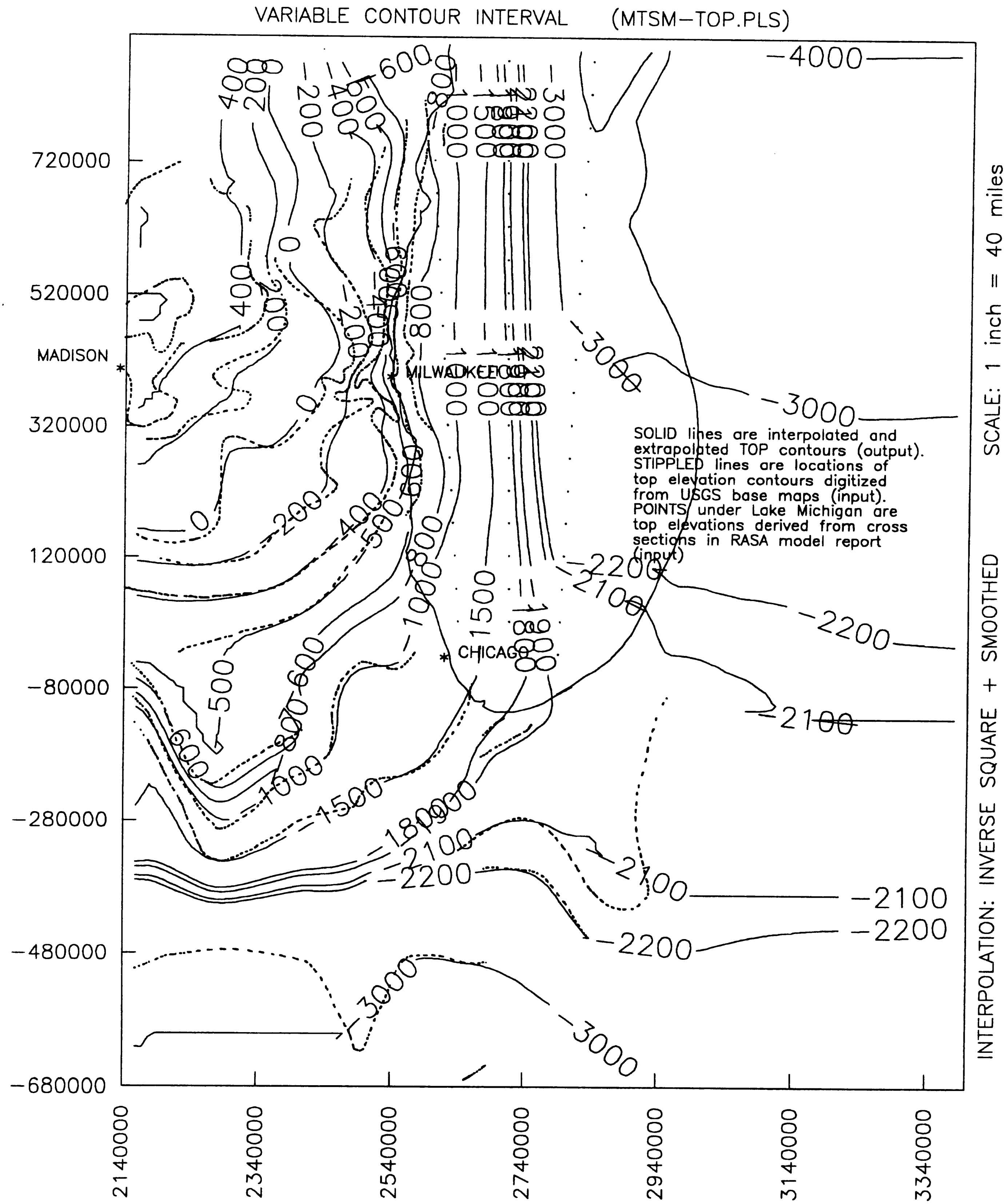


Fig. 4

"CORRECTED" TOP of MT. SIMON AQUIFER = BOT of EAU CLAIRE

CONTOUR INTERVAL = 400 ft ::: are DUMMY TOPS for 1 ft layer (MTSMTOPC.PLS)

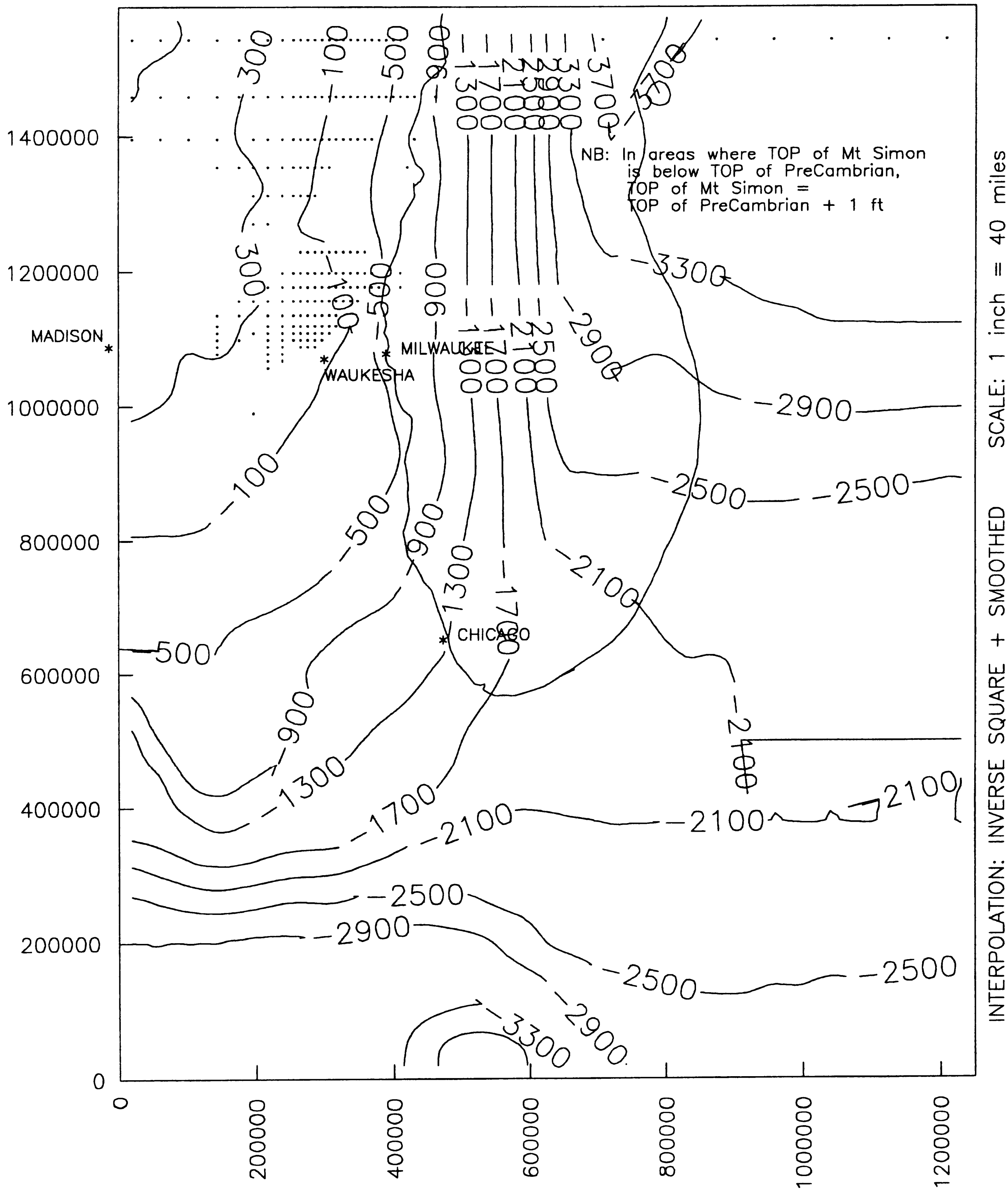


Fig. 5

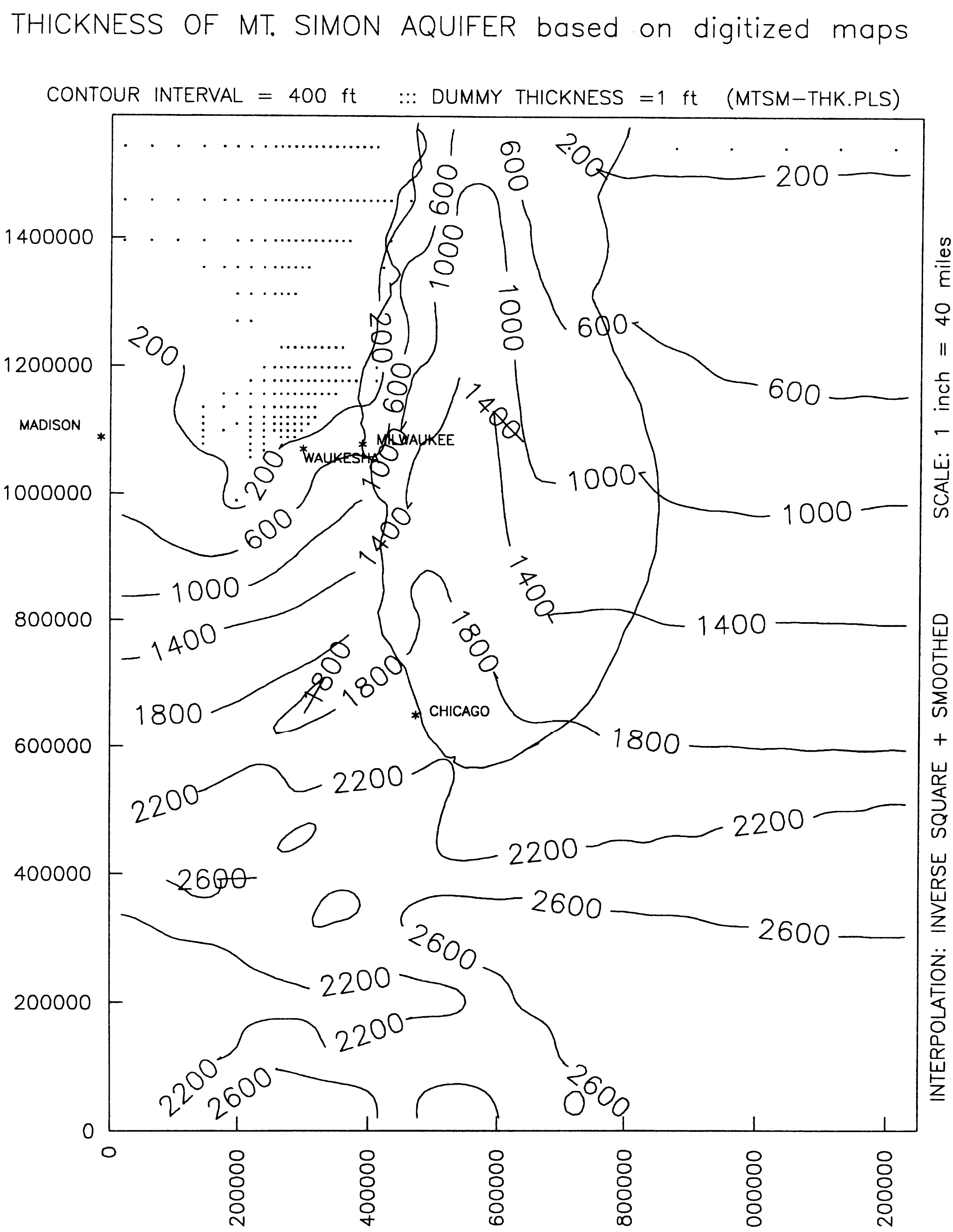

THICKNESS OF MT. SIMON AQUIFER based on digitized maps
CONTOUR INTERVAL = 400 ft ::: DUMMY THICKNESS =1 ft (MTSM-THK.PLS)
SCALE: 1 inch = 40 miles
INTERPOLATION: INVERSE SQUARE + SMOOTHED
MADISON
WAUKESHA
MILWAUKEE
CHICAGO
200
600
1000
1400
1800
2200
2600
0
200000
400000
600000
800000
1000000
1200000
1400000

Fig. 6

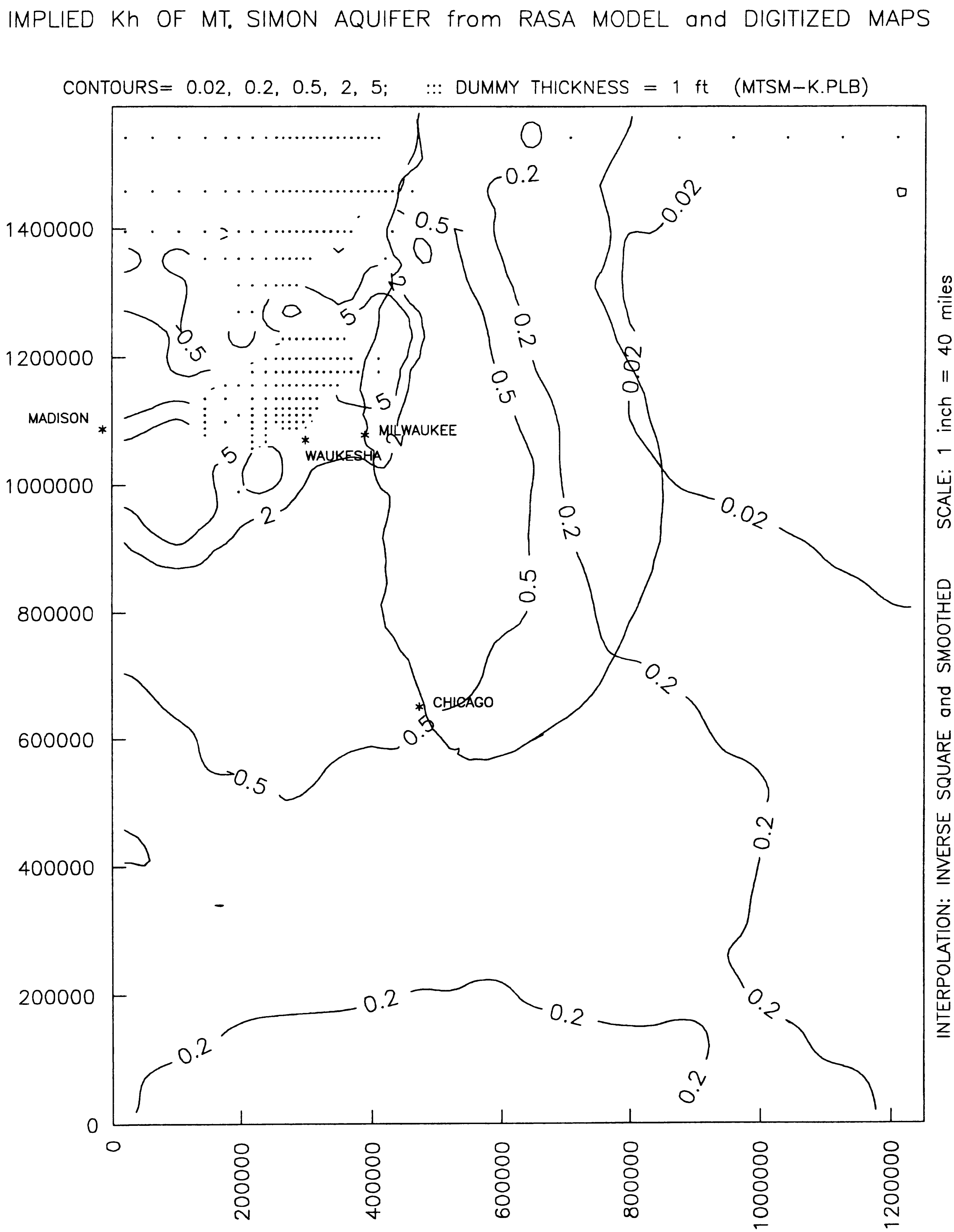

IMPLIED Kh OF MT. SIMON AQUIFER from RASA MODEL and DIGITIZED MAPS
CONTOURS= 0.02, 0.2, 0.5, 2, 5; ::: DUMMY THICKNESS = 1 ft (MTSM-K.PLB)
MADISON
MILWAUKEE
WAUKESHA
CHICAGO
INTERPOLATION: INVERSE SQUARE and SMOOTHED SCALE: 1 inch = 40 miles
1400000
1200000
1000000
800000
600000
400000
200000
0
0
200000
400000
600000
800000
1000000
1200000

Fig. 7

IMPLIED Kv OF EAU CLAIRE from RASA MODEL and DIGITIZED MAPS

LOGARITHMIC CONTOURS in ft/day ::: DUMMY THICKNESS = 1 ft (EACL-KV.PLB)

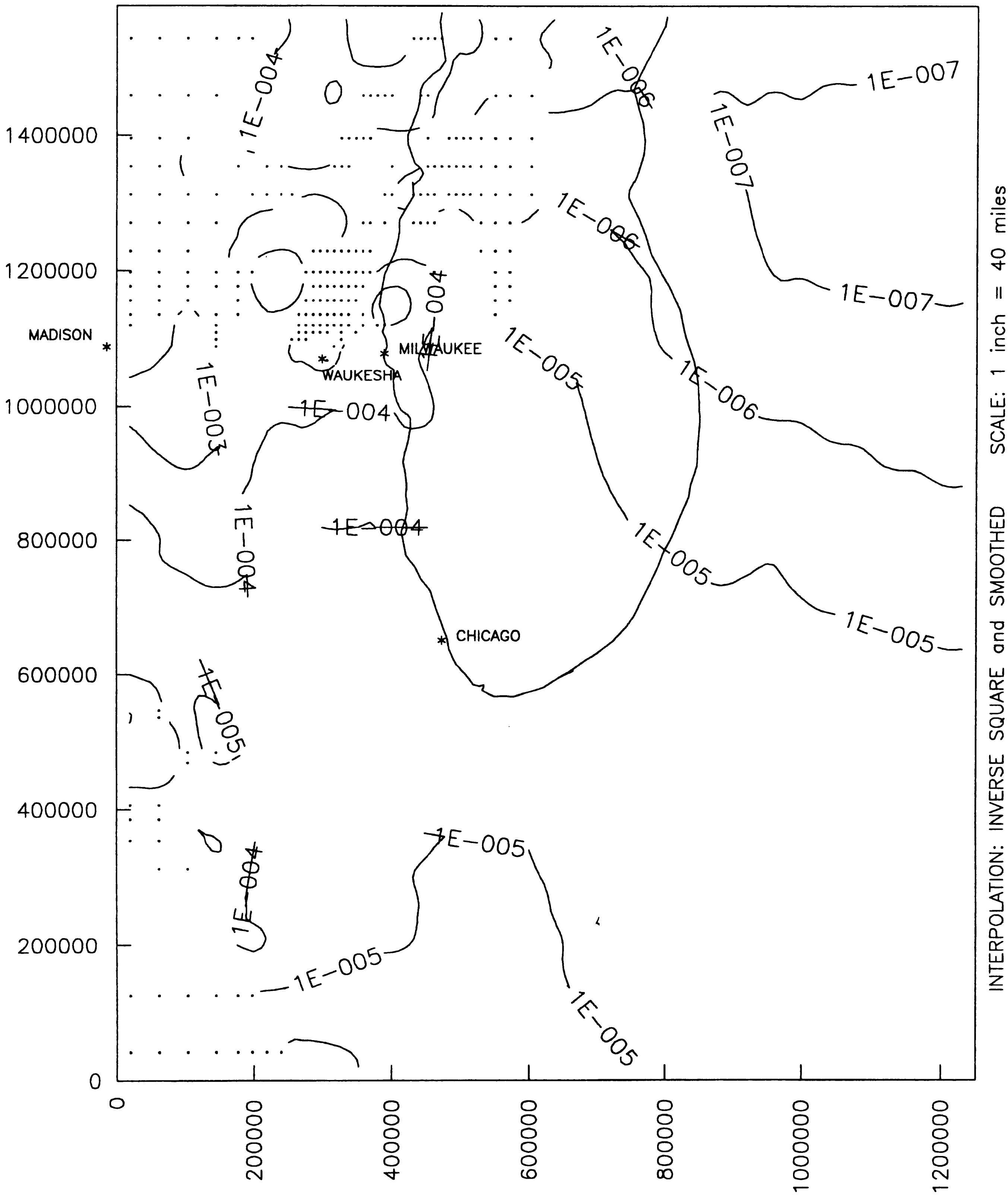


Fig. 8

IMPLIED Kh OF IRONTON–GALESVILLE from RASA MODEL and DIGITIZED MAPS

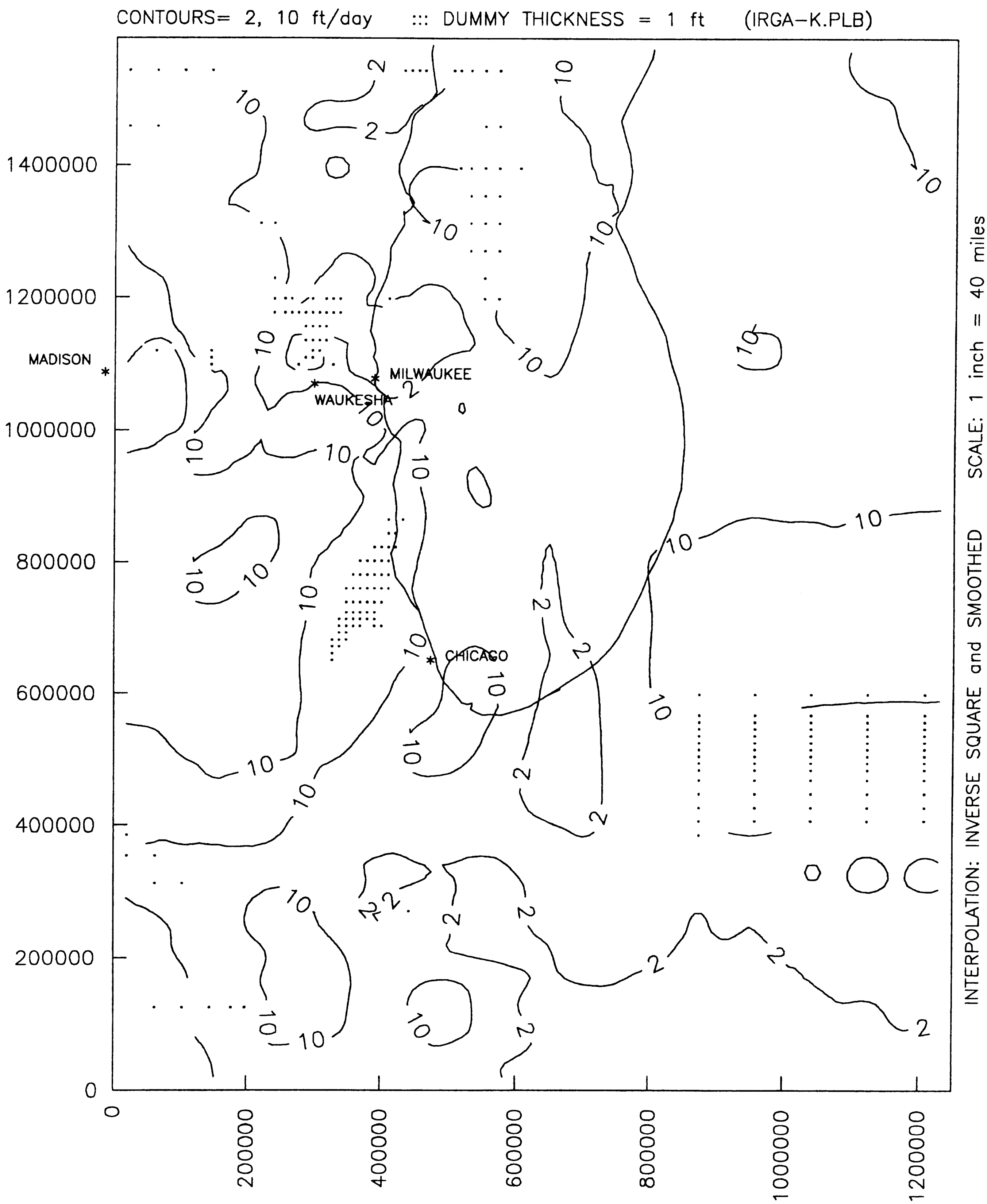


Fig. 9

IMPLIED Kv OF ST. LAWRENCE/FRANCONIA AQUITARD from RASA MODEL and DIGITIZED MAPS

LOGARITHMIC CONTOURS in ft/day ::: DUMMY THICKNESS = 1 ft (STLW-KV.PLB)

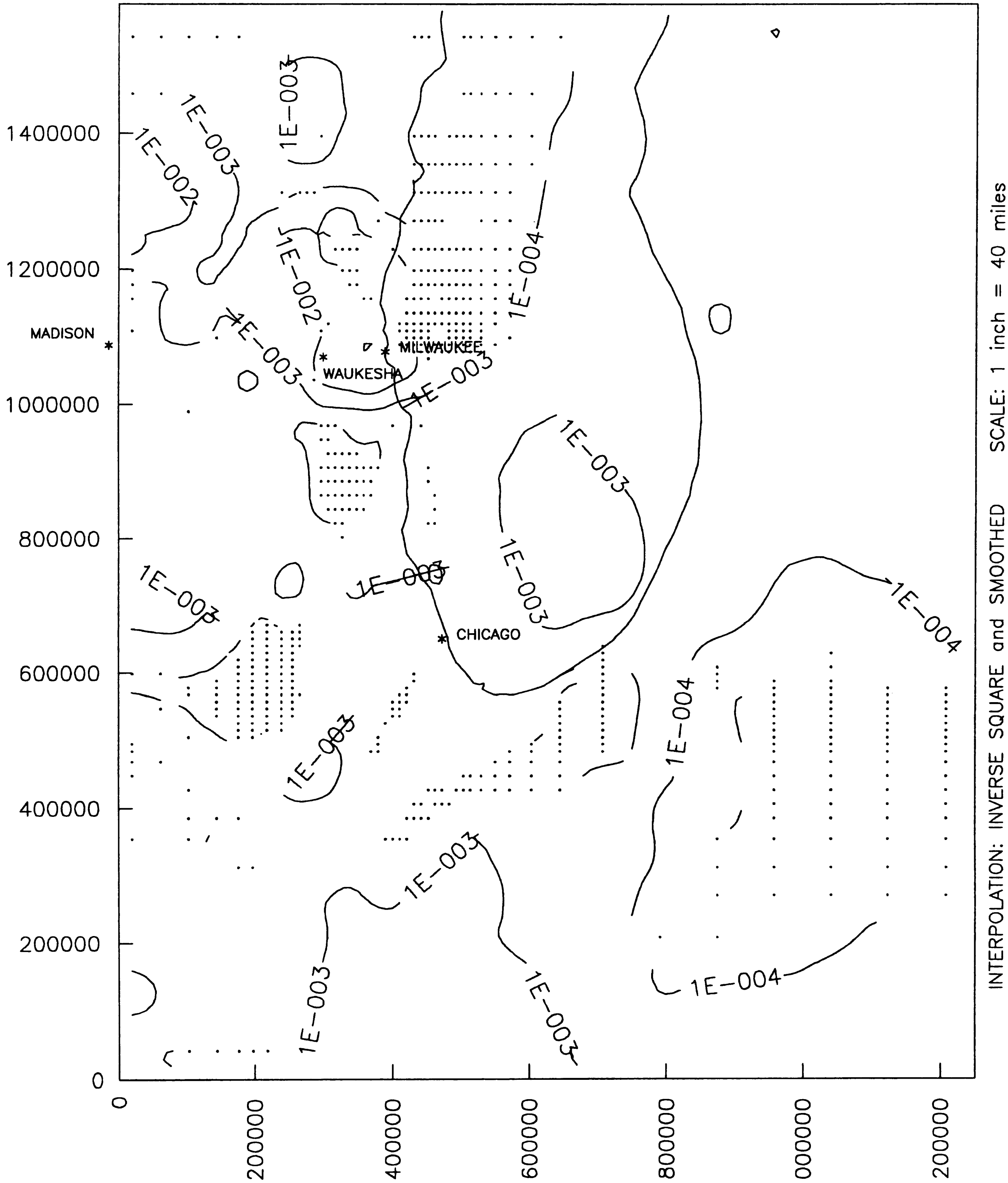


Fig. 10

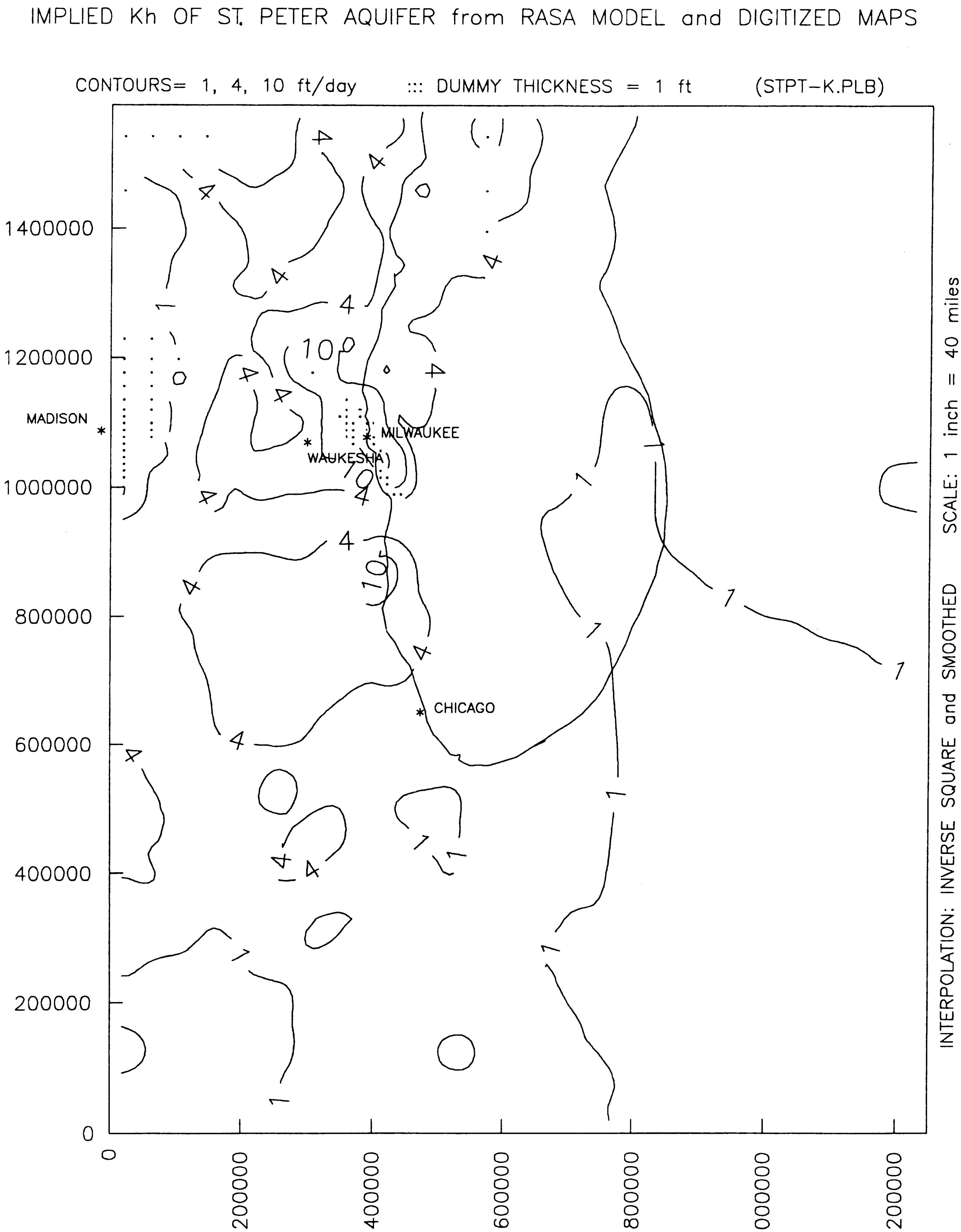

IMPLIED Kh OF ST. PETER AQUIFER from RASA MODEL and DIGITIZED MAPS
CONTOURS= 1, 4, 10 ft/day
::: DUMMY THICKNESS = 1 ft
(STPT-K.PLB)
MADISON
MILWAUKEE
WAUKESHA
CHICAGO
SCALE: 1 inch = 40 miles
INTERPOLATION: INVERSE SQUARE and SMOOTHED
0
200000
400000
600000
800000
1000000
1200000
1400000

Fig. 11

IMPLIED Kv OF MAQUOKETA/SINNIPEE Aquitard from RASA MODEL and DIGITIZED MAPS

LOGARITHMIC CONTOURS in ft/day ::: DUMMY THICKNESS = 1 ft (ORDO-KV.PLB)

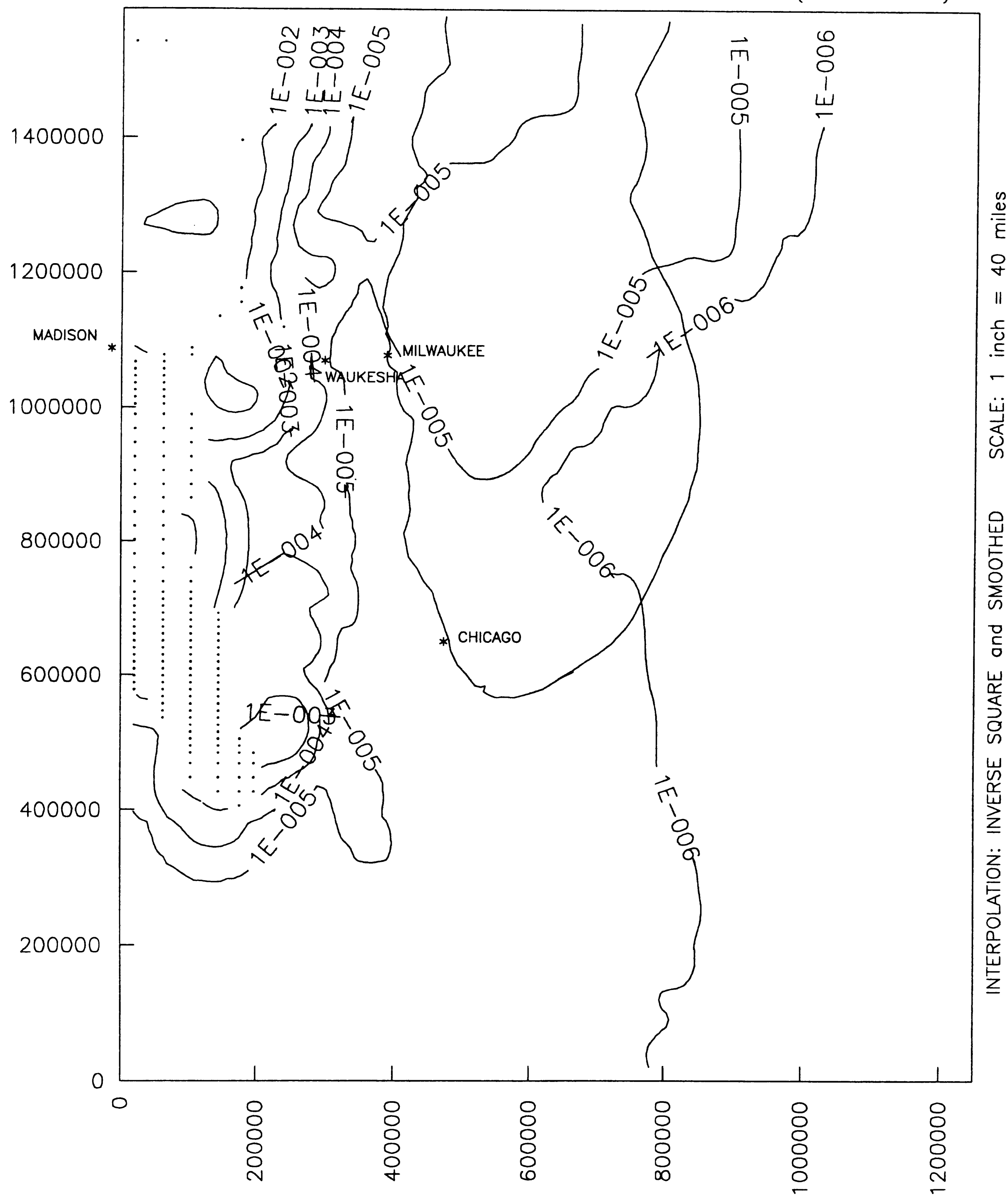


Fig. 12

IMPLIED Kh OF SILURIAN AQUIFER from RASA MODEL and DIGITIZED MAPS

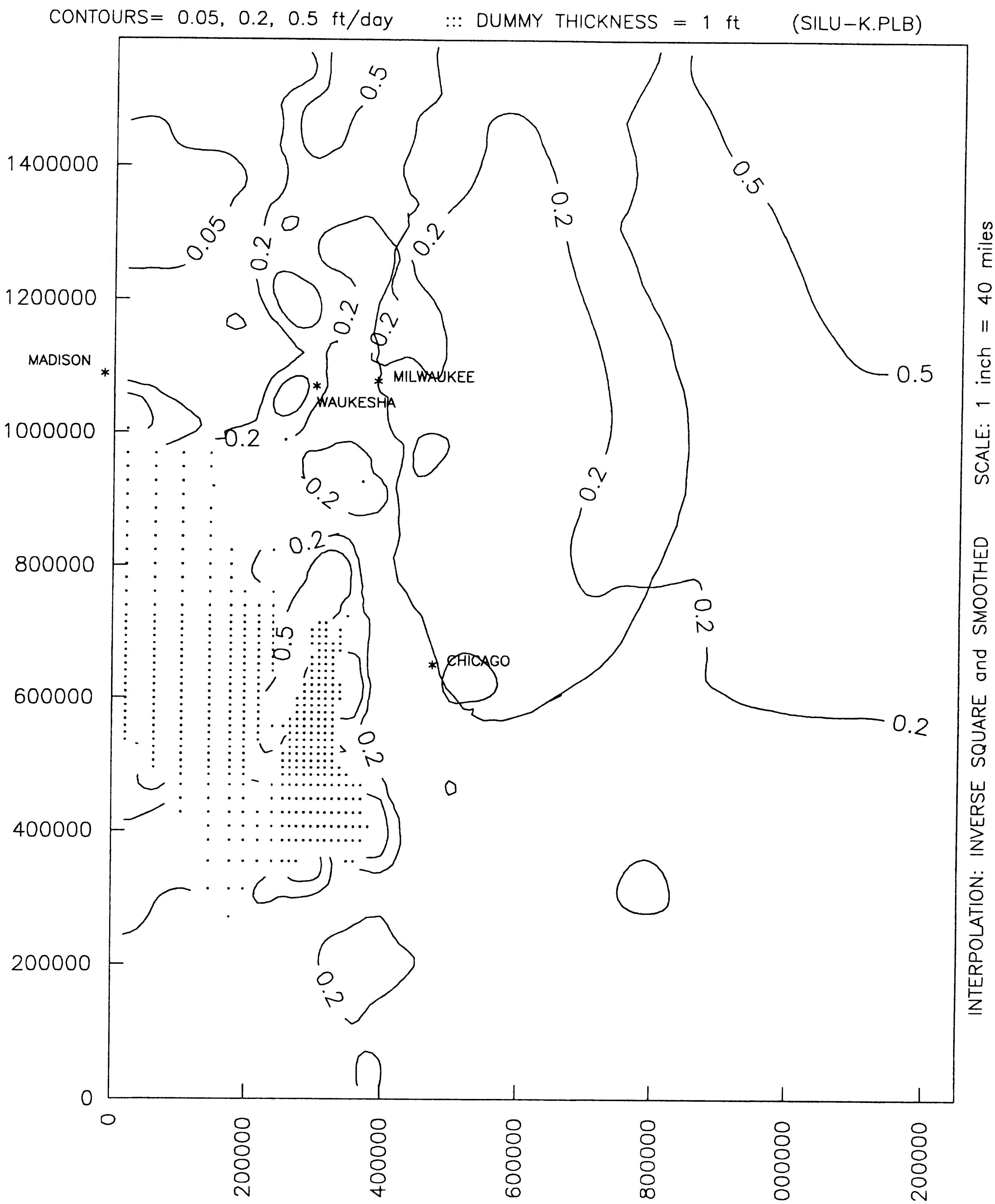


Fig. 13

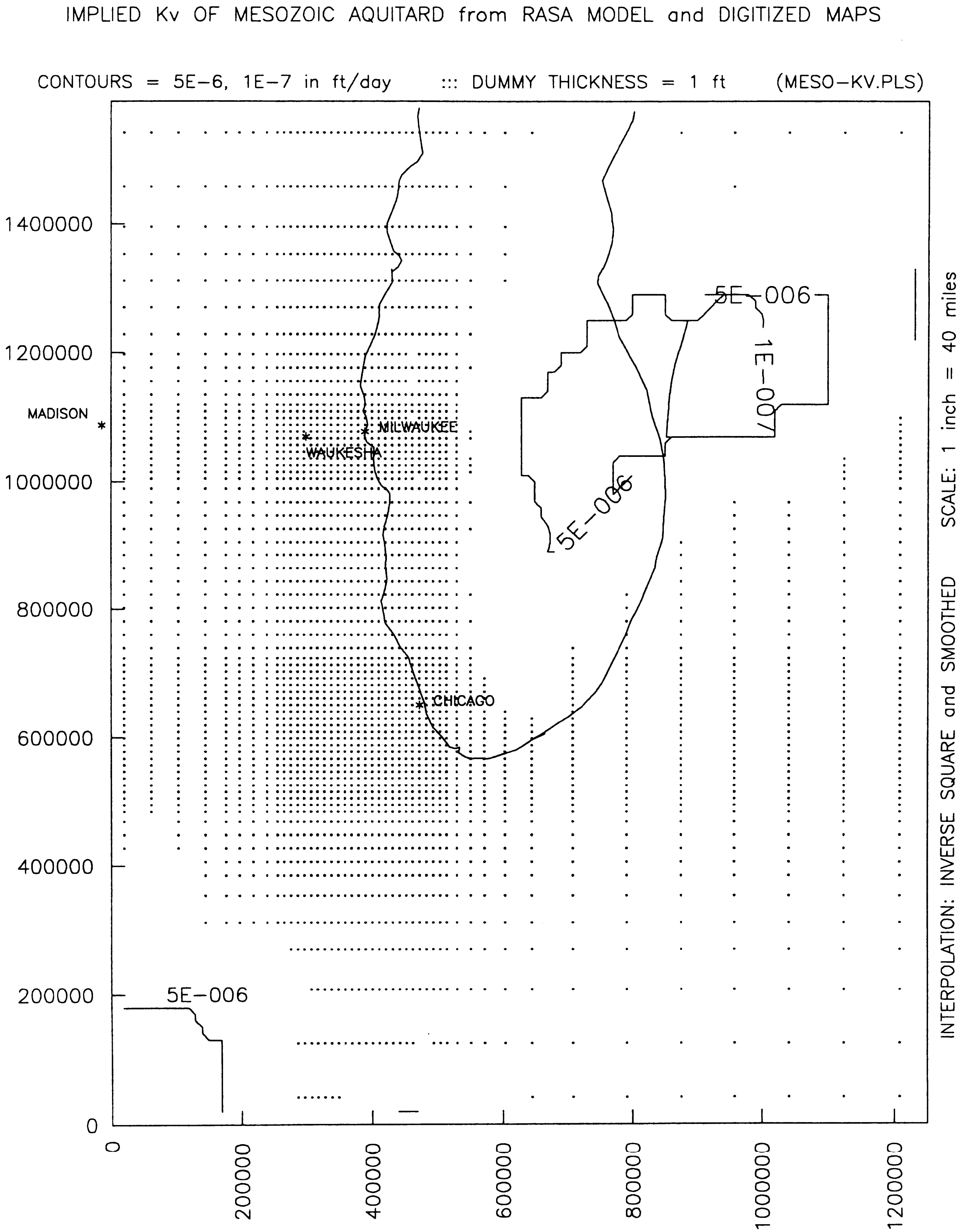
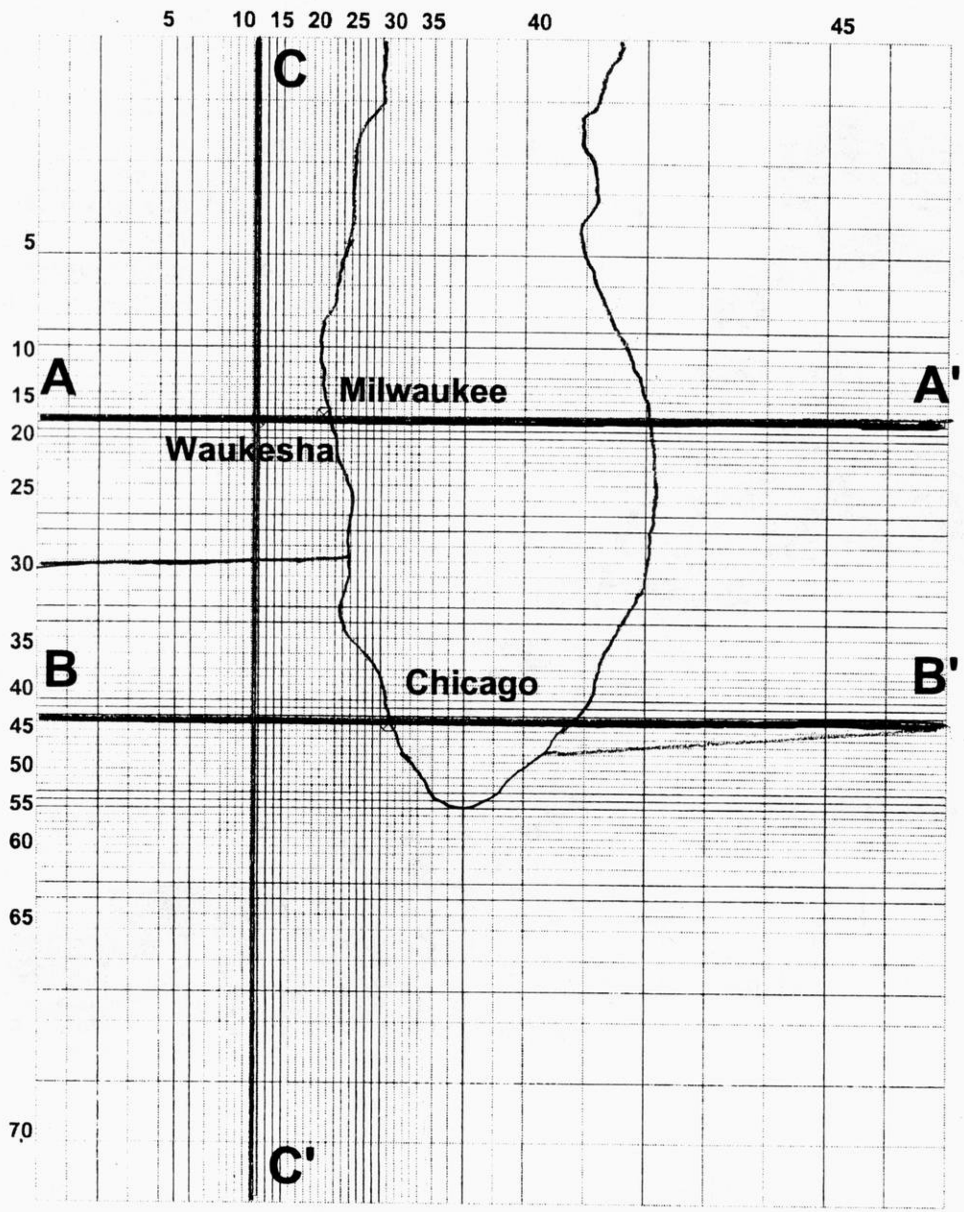

IMPLIED Kv OF MESOZOIC AQUITARD from RASA MODEL and DIGITIZED MAPS
CONTOURS = 5E-6, 1E-7 in ft/day ::: DUMMY THICKNESS = 1 ft (MESO-KV.PLS)
5E-006
1E-007
5E-006
5E-006
MADISON
MILWAUKEE
WAUKESHA
CHICAGO
1400000
1200000
1000000
800000
600000
400000
200000
0
0
200000
400000
600000
800000
1000000
1200000
INTERPOLATION: INVERSE SQUARE and SMOOTHED SCALE: 1 inch = 40 miles

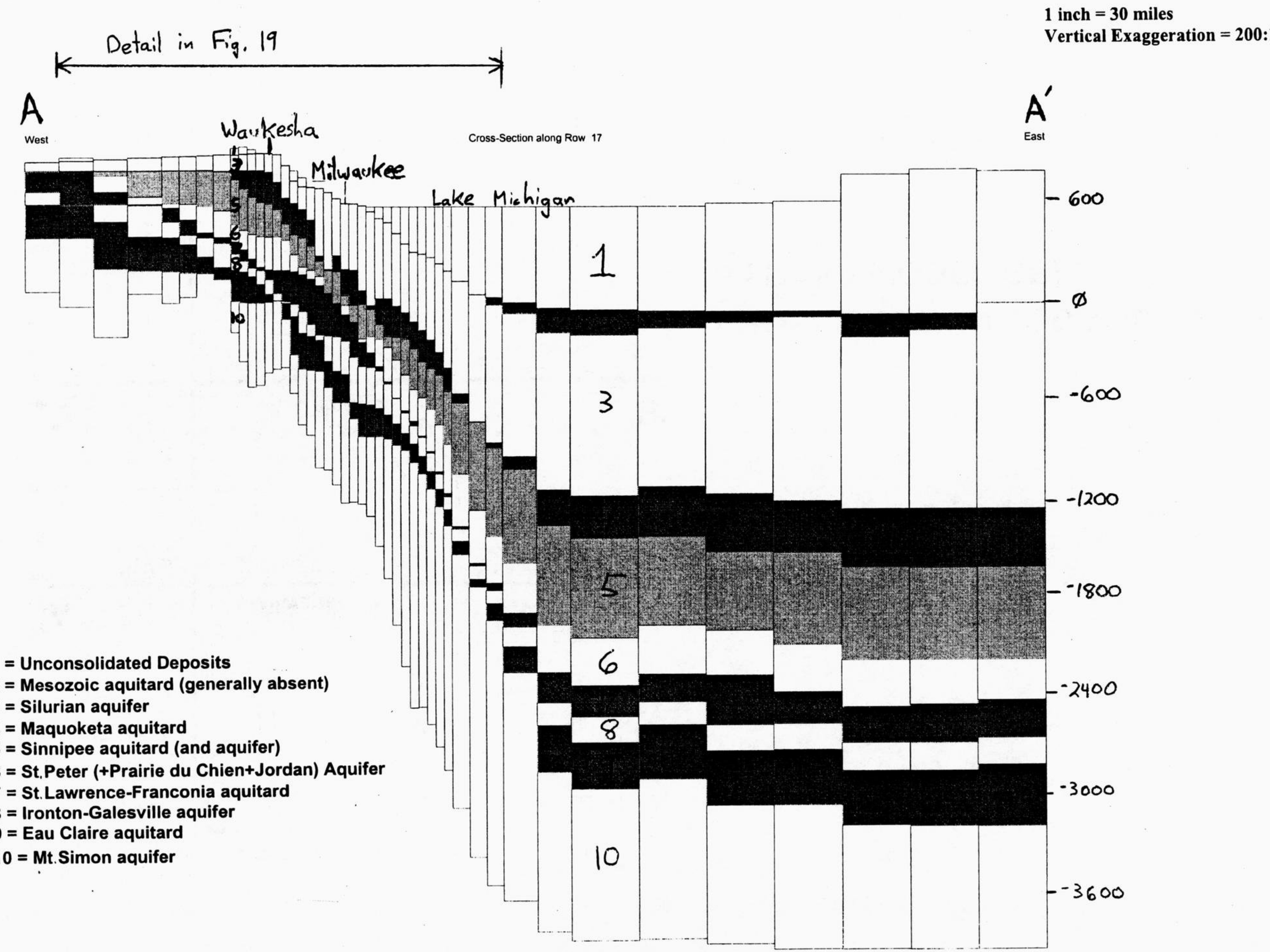
Fig. 14



CROSS SECTION LOCATIONS on RASA MODEL GRID

1 inch = 50 miles

Fig. 15

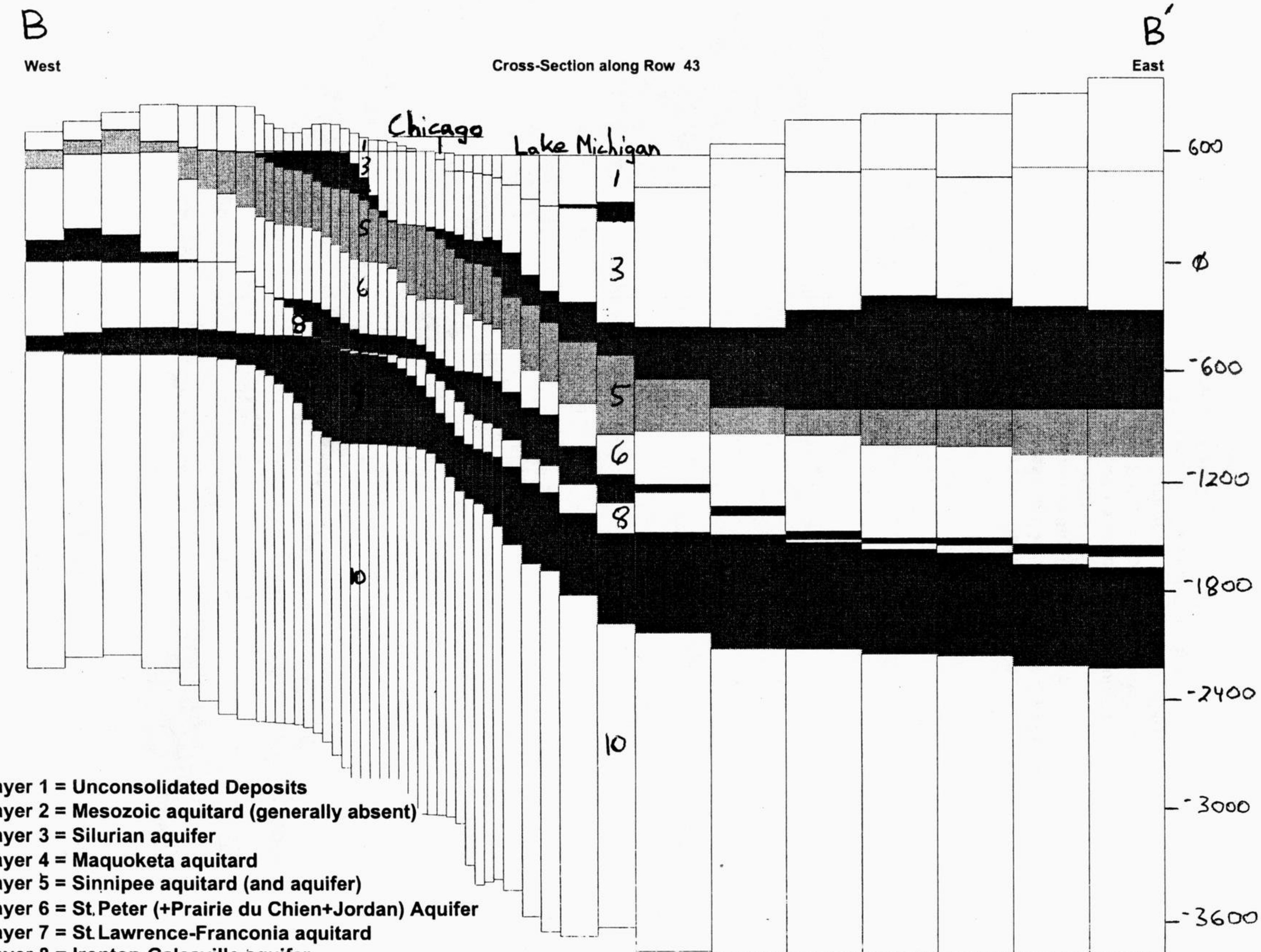


Layer 1 = Unconsolidated Deposits
Layer 2 = Mesozoic aquitard (generally absent)
Layer 3 = Silurian aquifer
Layer 4 = Maquoketa aquitard
Layer 5 = Sinnipee aquitard (and aquifer)
Layer 6 = St.Peter (+Prairie du Chien+Jordan) Aquifer
Layer 7 = St.Lawrence-Franconia aquitard
Layer 8 = Ironton-Galesville aquifer
Layer 9 = Eau Claire aquitard
Layer 10 = Mt.Simon aquifer

Fig. 16

Cross Section A-A'

1 inch = 30 miles
Vertical Exaggeration = 200:1



Layer 1 = Unconsolidated Deposits
Layer 2 = Mesozoic aquitard (generally absent)
Layer 3 = Silurian aquifer
Layer 4 = Maquoketa aquitard
Layer 5 = Sinnipee aquitard (and aquifer)
Layer 6 = St. Peter (+Prairie du Chien+Jordan) Aquifer
Layer 7 = St. Lawrence-Franconia aquitard
Layer 8 = Ironton-Galesville aquifer
Layer 9 = Eau Claire aquitard
Layer 10 = Mt. Simon aquifer

Fig. 17

Cross Section B-B'

1 inch = 50 miles
Vertical Exaggeration = 333:1

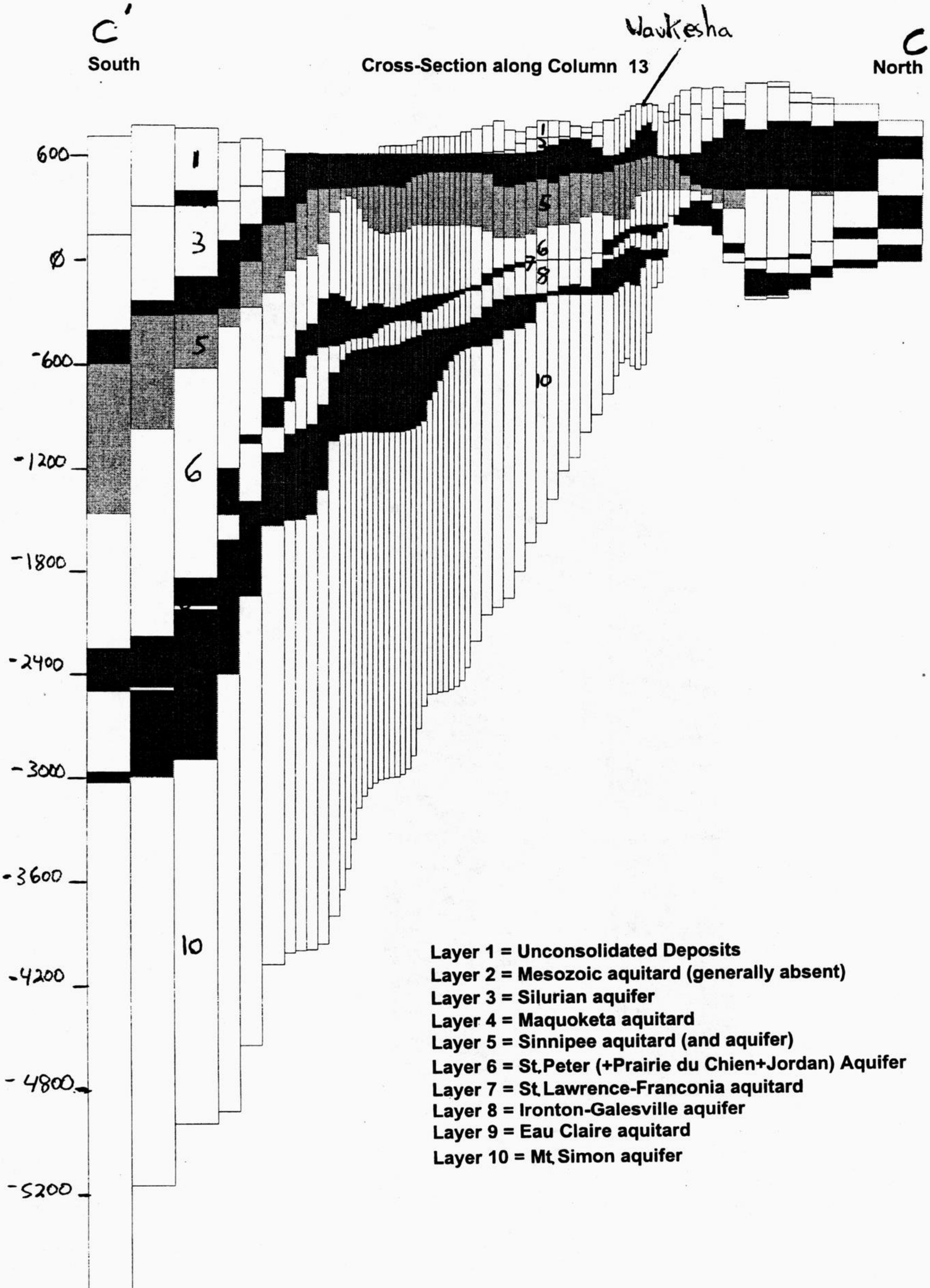
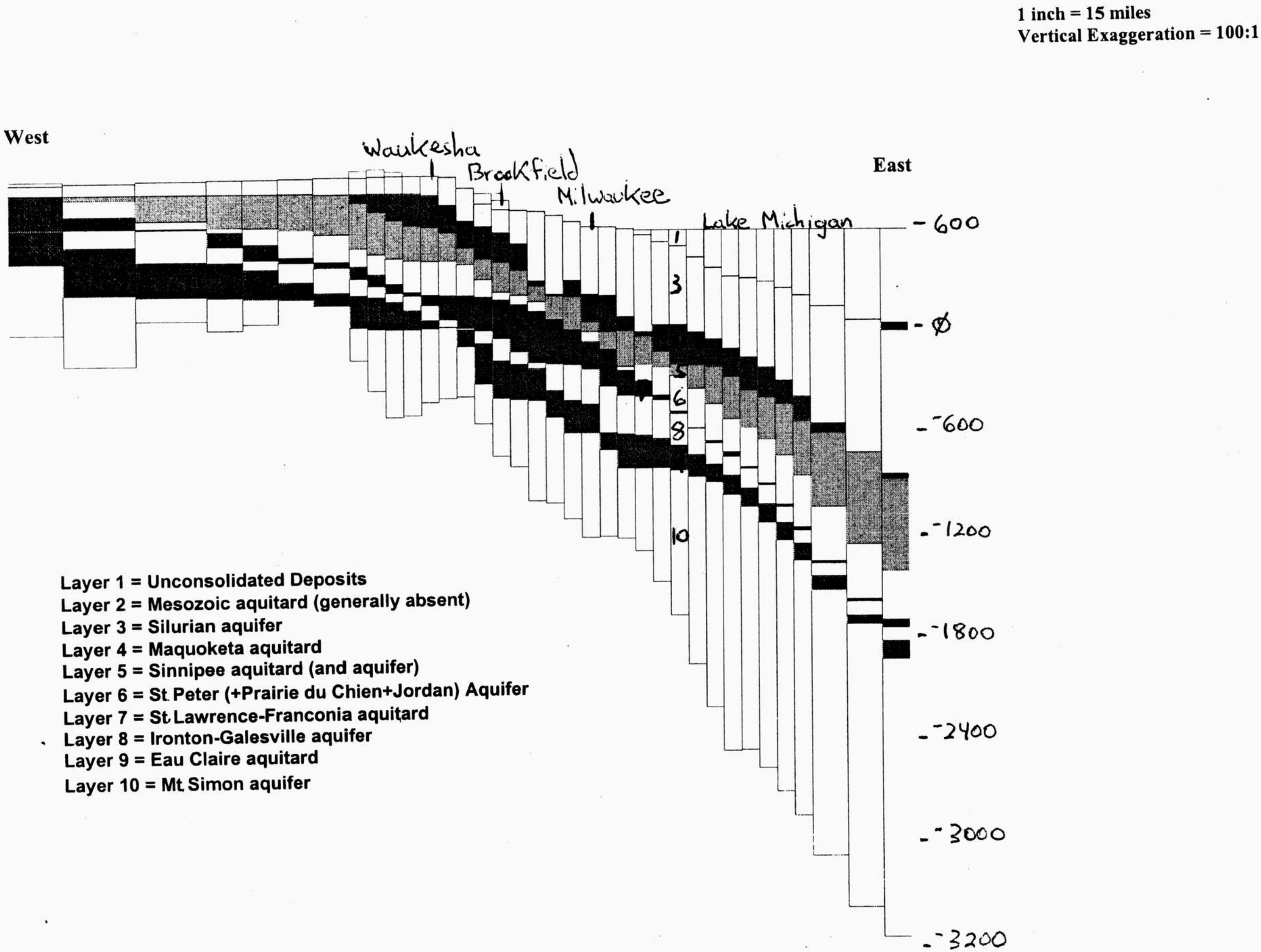


Fig. 18

Cross Section C-C'



Detail of Section A–A'

Fig. 19

Appendix

RASA MODEL GRID IN PLAN VIEW (1 inch = 40 miles)

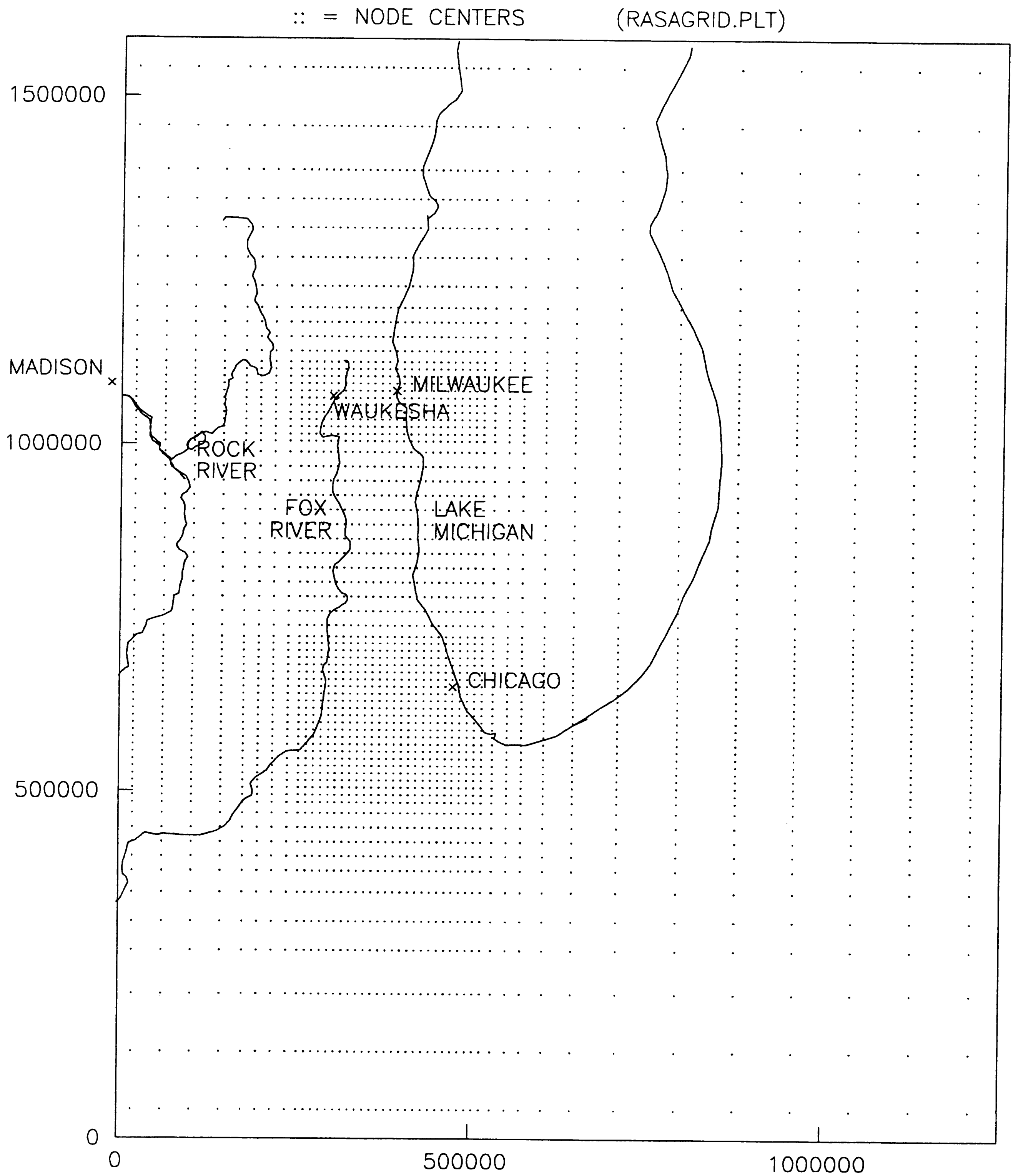


Fig. A-1

Transmissivity of Mt, Simon Aquifer in RASA Model

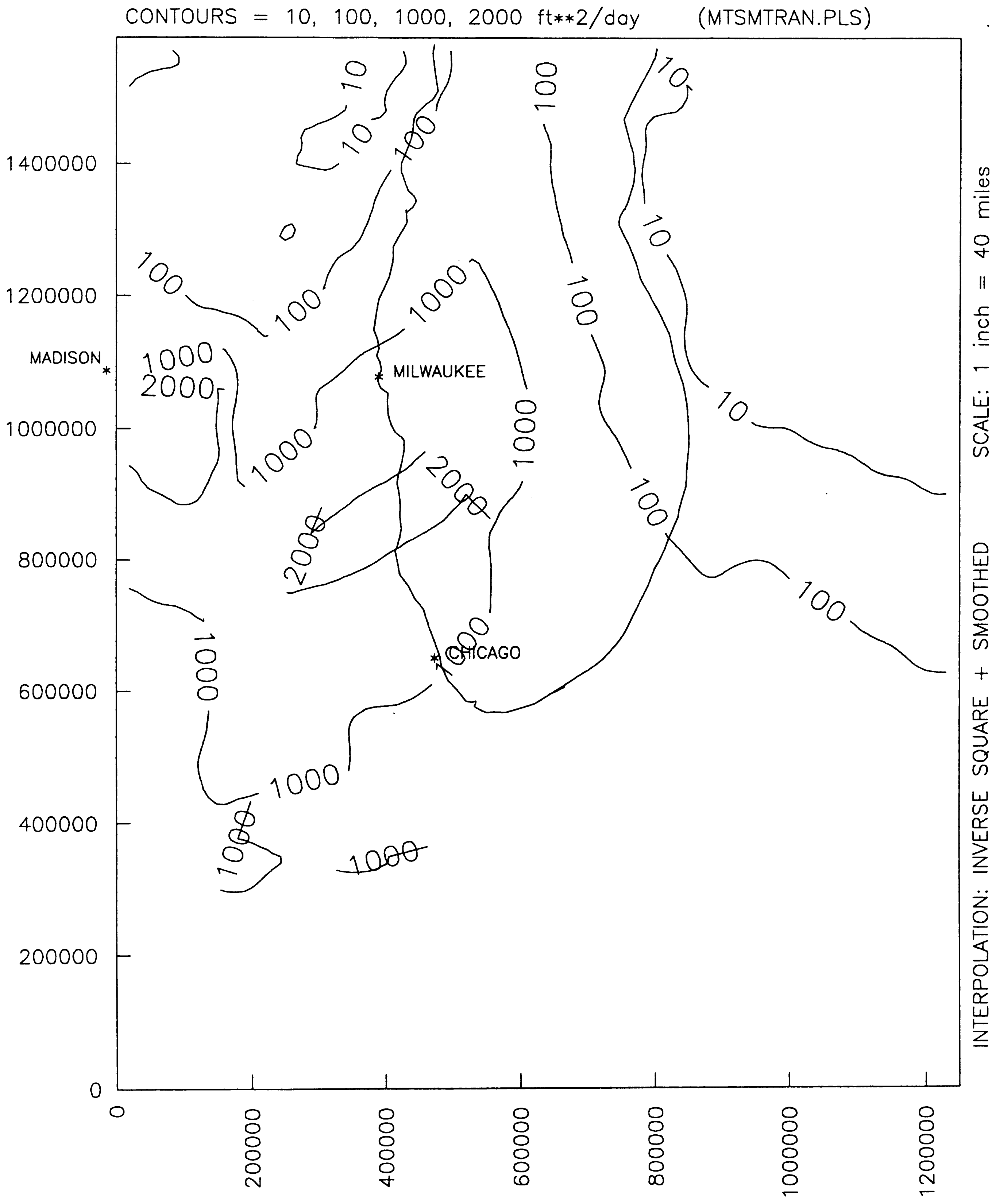


Fig. A-2

TOP of MT. SIMON AQUIFER = BOT of EAU CLAIRE based on digitized maps

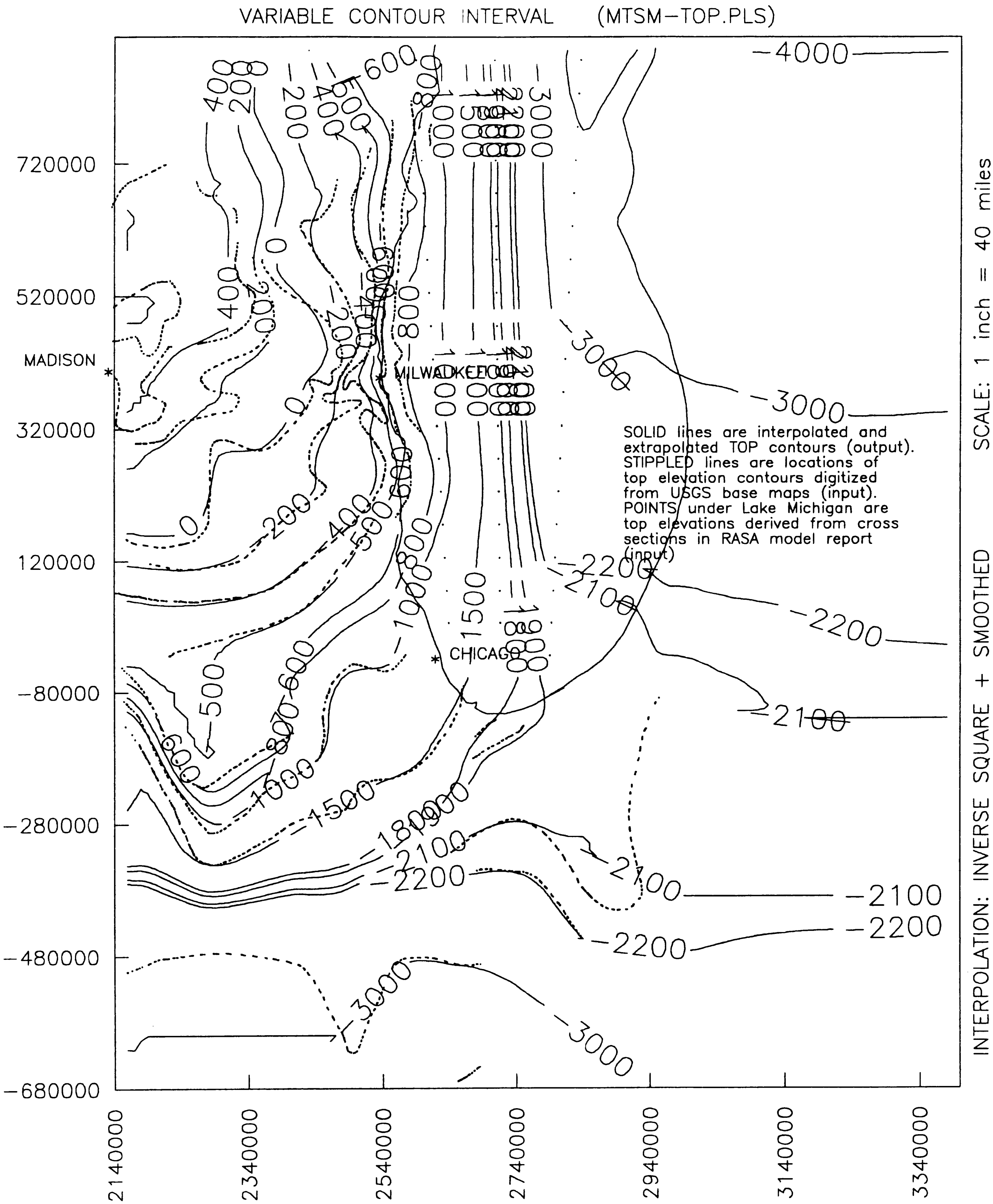


Fig. A-3

"CORRECTED" TOP of MT. SIMON AQUIFER = BOT of EAU CLAIRE

CONTOUR INTERVAL = 400 ft ::: are DUMMY TOPS for 1 ft layer (MTSMTOPC.PLS)

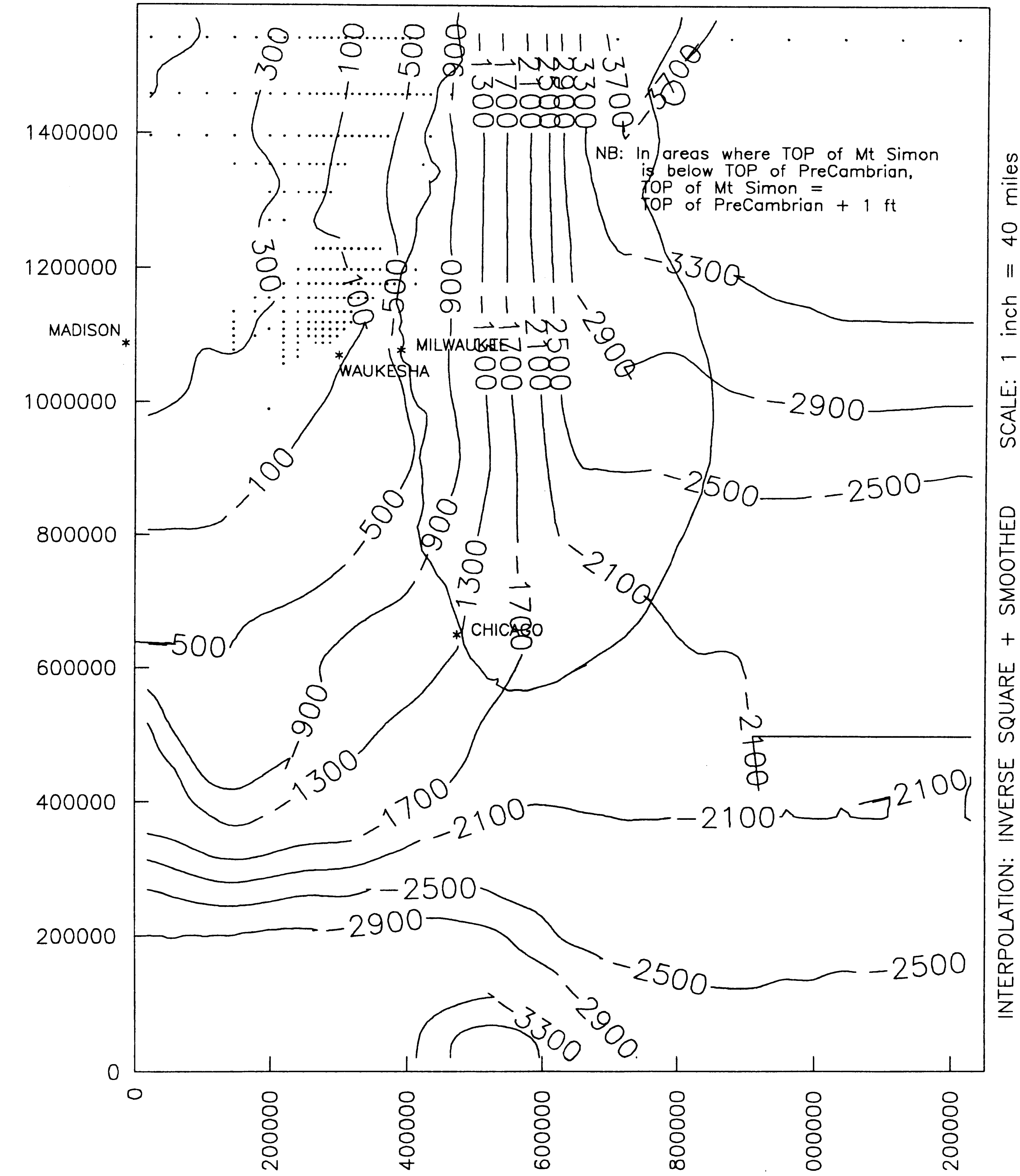


Fig. A-4

THICKNESS OF MT. SIMON AQUIFER based on digitized maps

CONTOUR INTERVAL = 400 ft ::: DUMMY THICKNESS =1 ft (MTSM-THK.PLS)

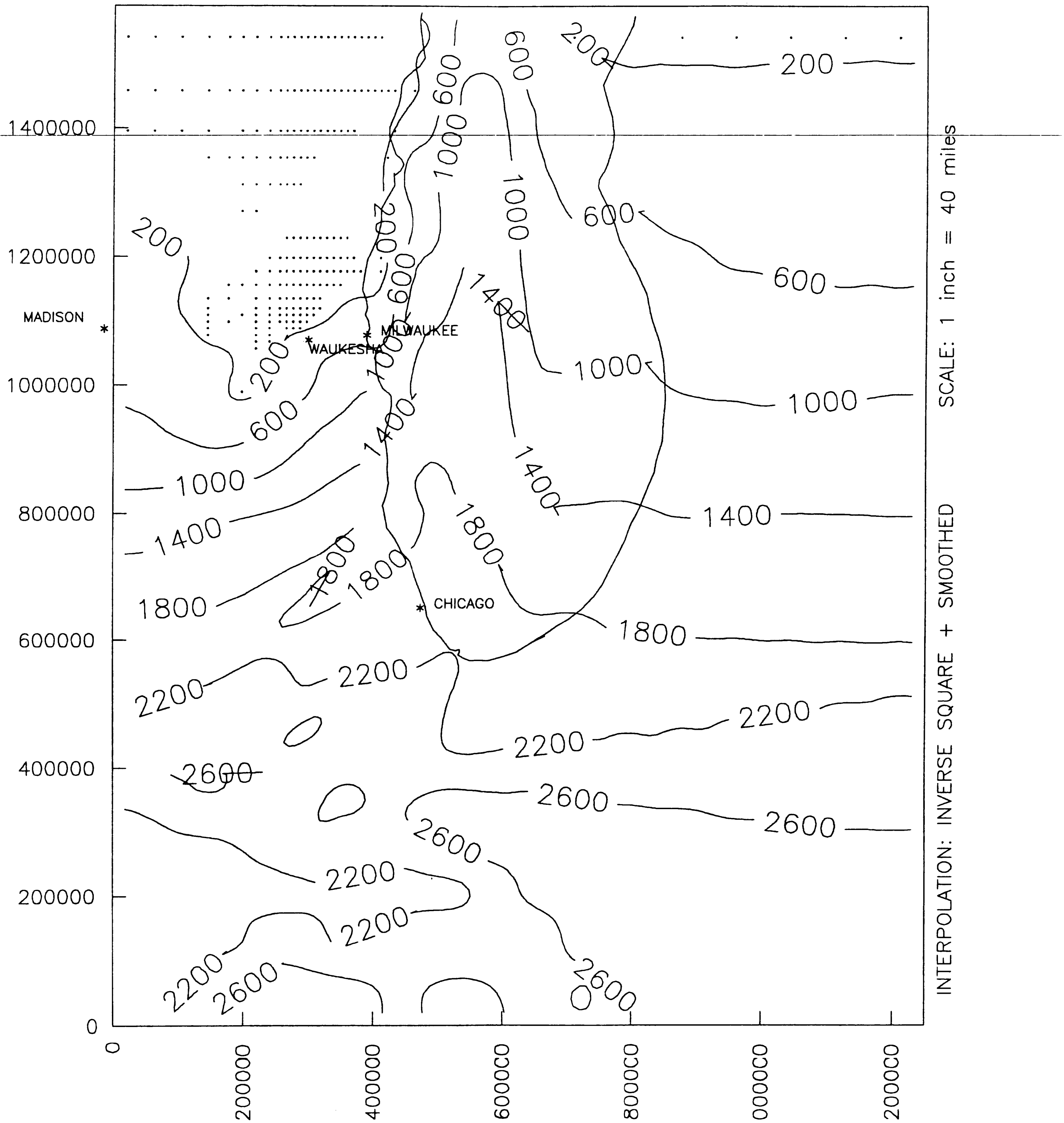


Fig. A-5

IMPLIED Kh OF MT. SIMON AQUIFER from RASA MODEL and DIGITIZED MAPS

CONTOURS= 0.02, 0.2, 0.5, 2, 5; ::: DUMMY THICKNESS = 1 ft (MTSM-K.PLB)

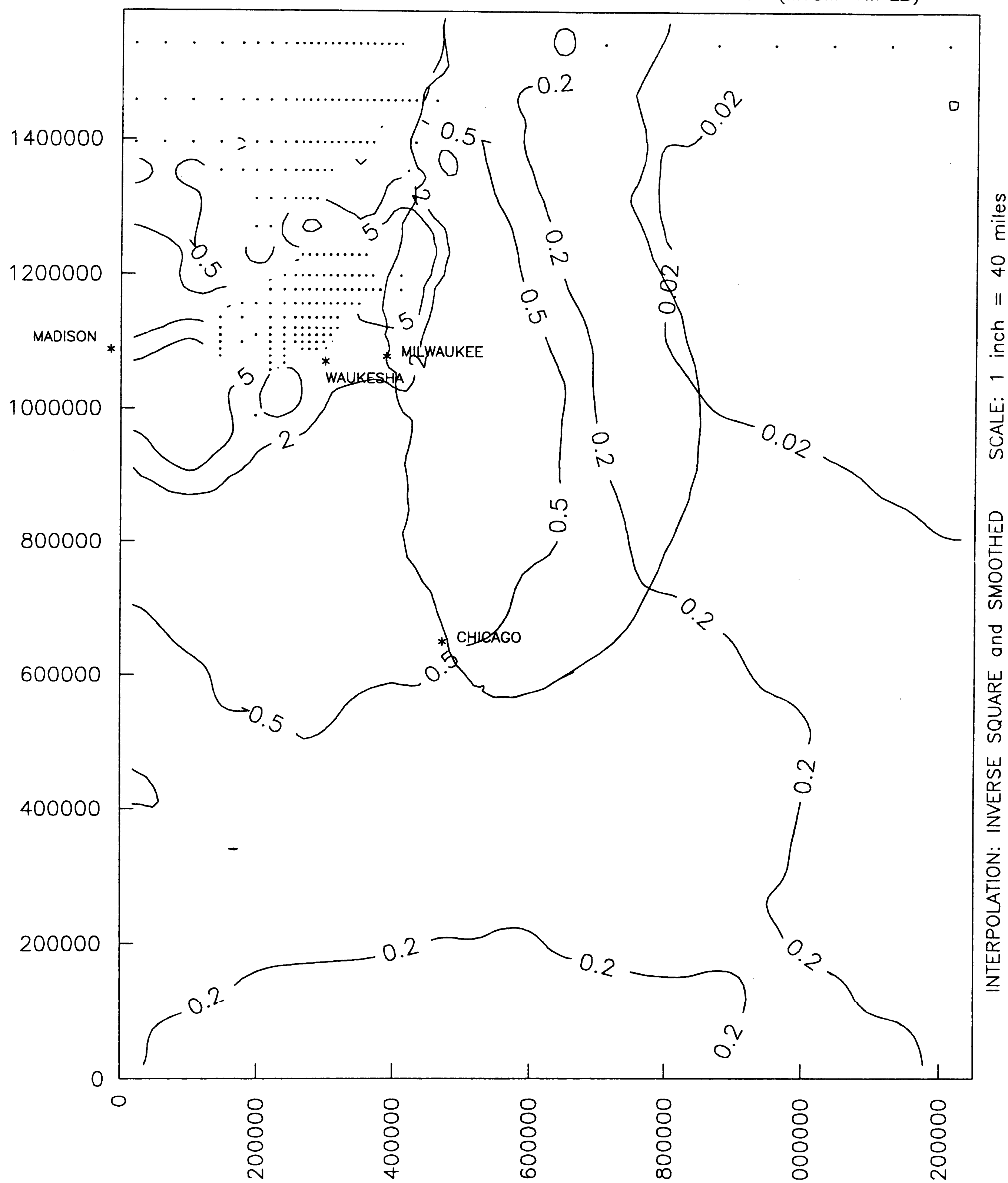


Fig. A-6

LEAKANCE (=VCONT) of EAU CLAIRE in RASA Model

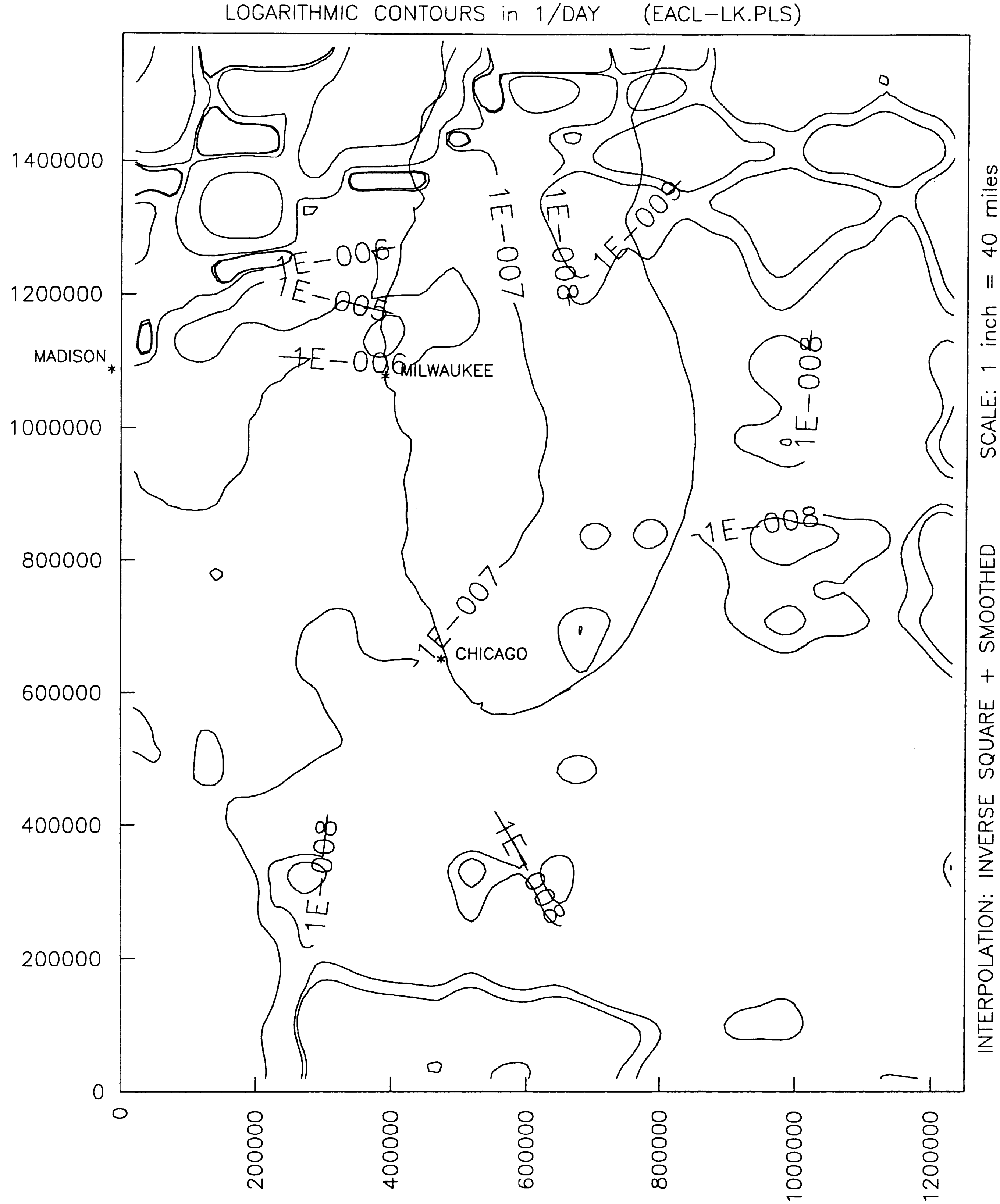


Fig. A-7

TOP of EAU CLAIRE = BOT OF IRONTON–GALESVILLE based on digitized maps

VARIABLE CONTOUR INTERVAL (EACL–TOP.PLS)

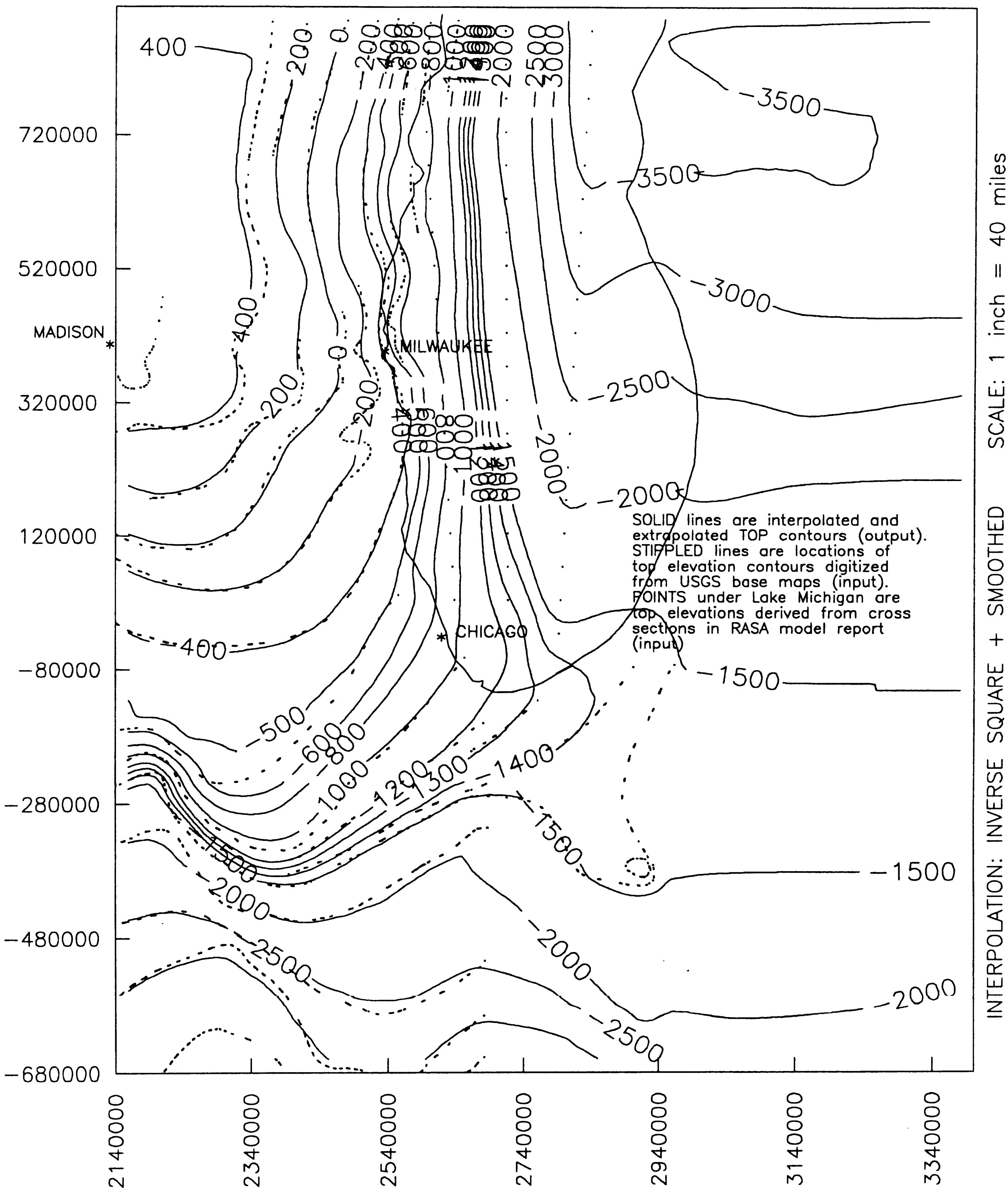


Fig. A-8

'CORRECTED" TOP of EAU CLAIRE = BOT of IRONTON-GALESVILLE

CONTOUR INTERVAL = 400 ft ::: DUMMY THIKCNESS = 1 ft (EACLTOPC.PLS)

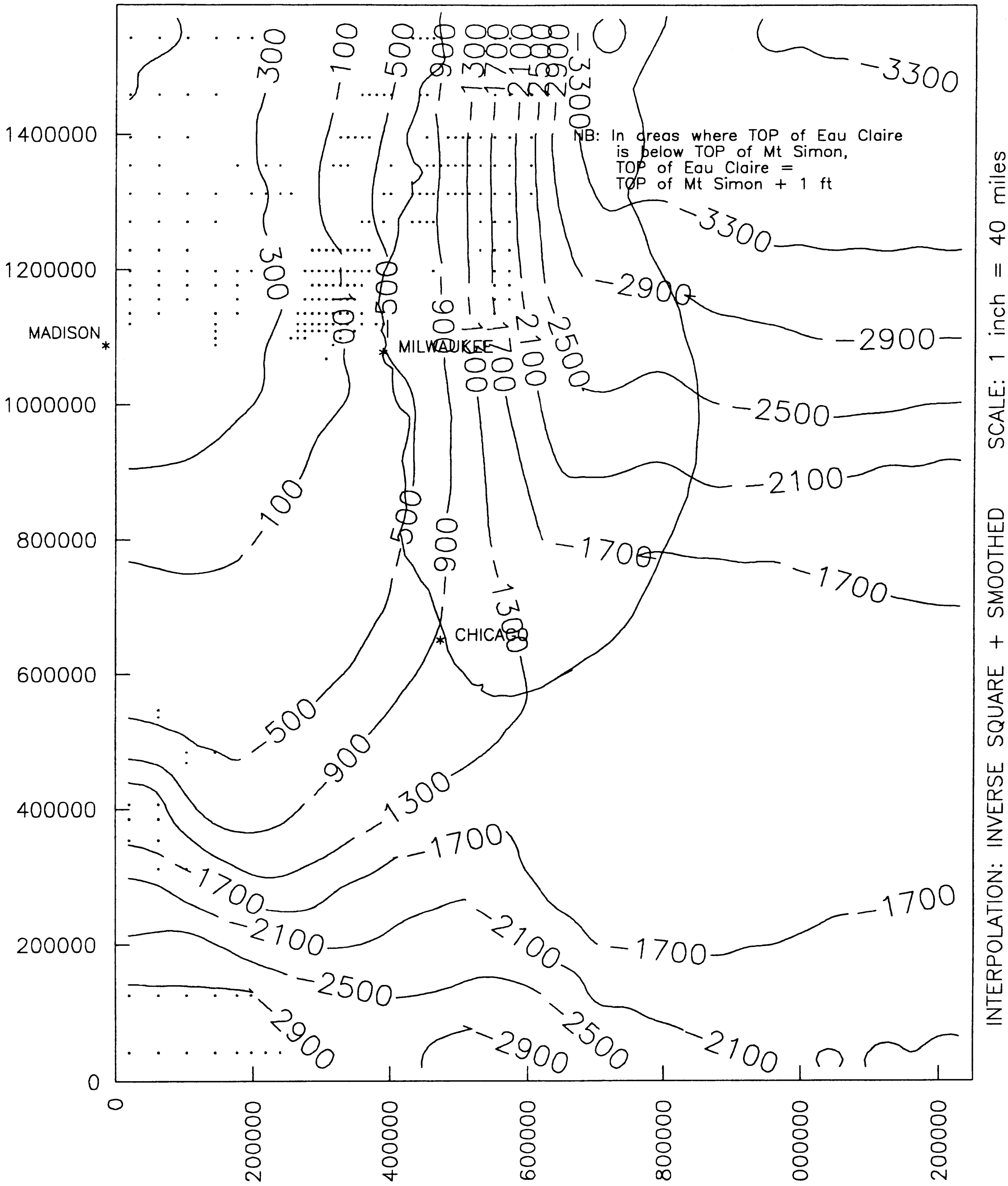


Fig. A-9

THICKNESS OF EAU CLAIRE based on digitized maps

CONTOURS = 200, 400, 600 ft ::: DUMMY THICKNESS = 1 ft (EACL-THK.PLS)

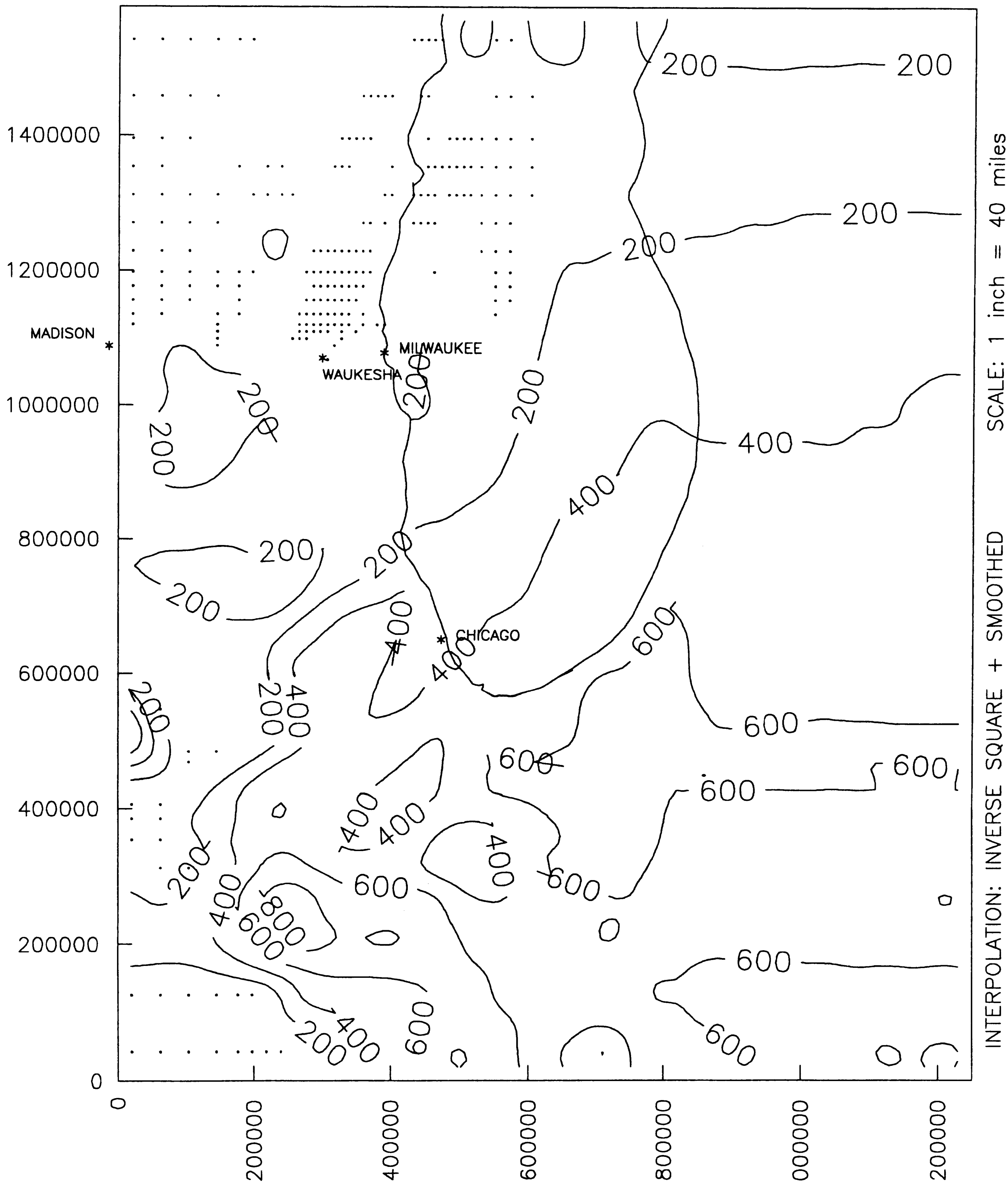


Fig. A-10

IMPLIED Kv OF EAU CLAIRE from RASA MODEL and DIGITIZED MAPS

LOGARITHMIC CONTOURS in ft/day ::: DUMMY THICKNESS = 1 ft (EACL–KV.PLB)

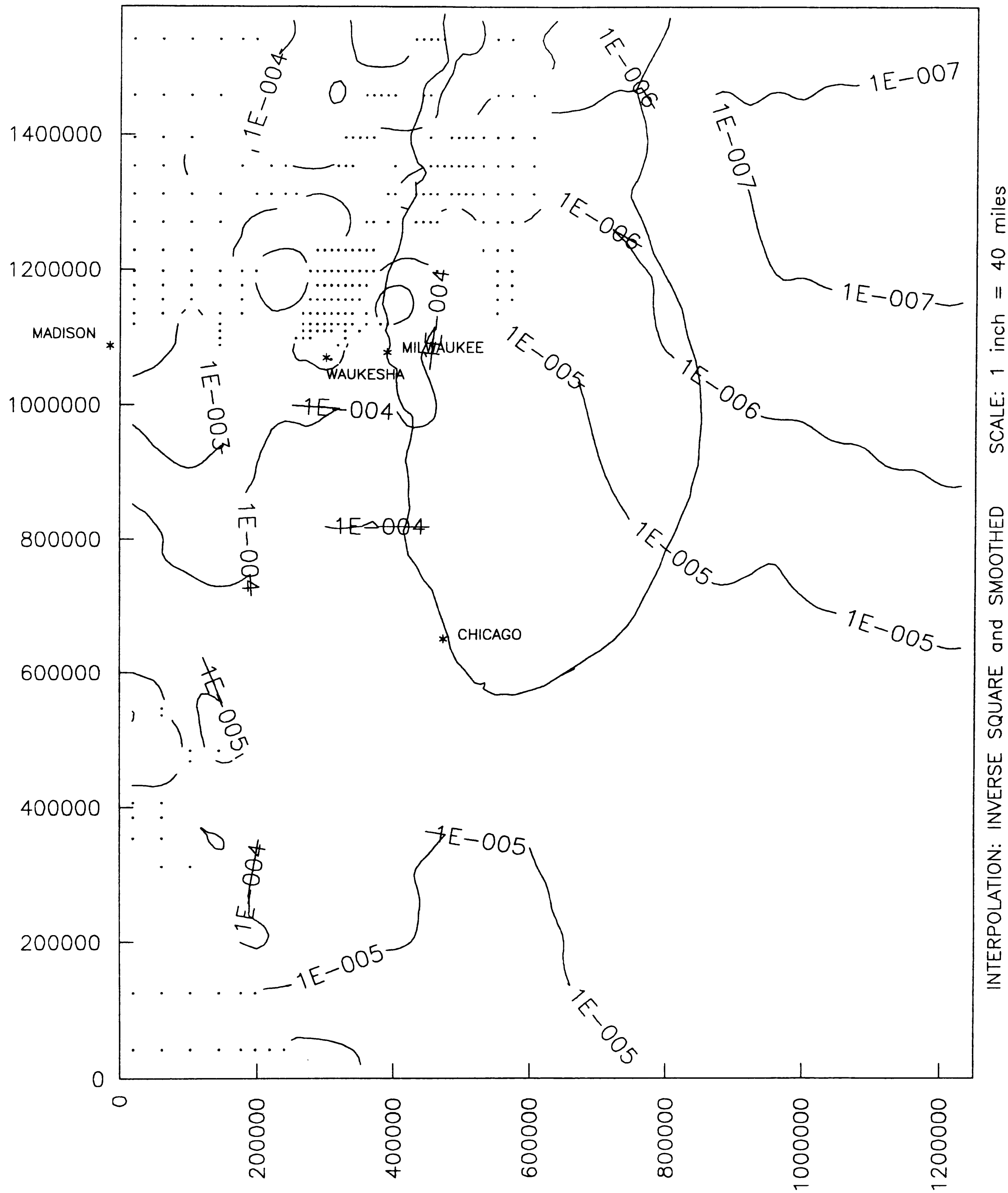


Fig. A-11

Transmissivity of Ironton–Galesville in RASA Model

CONTOURS = 10, 100, 500, 1000, 2000 ft**2/day (IRGATRAN.PLS)

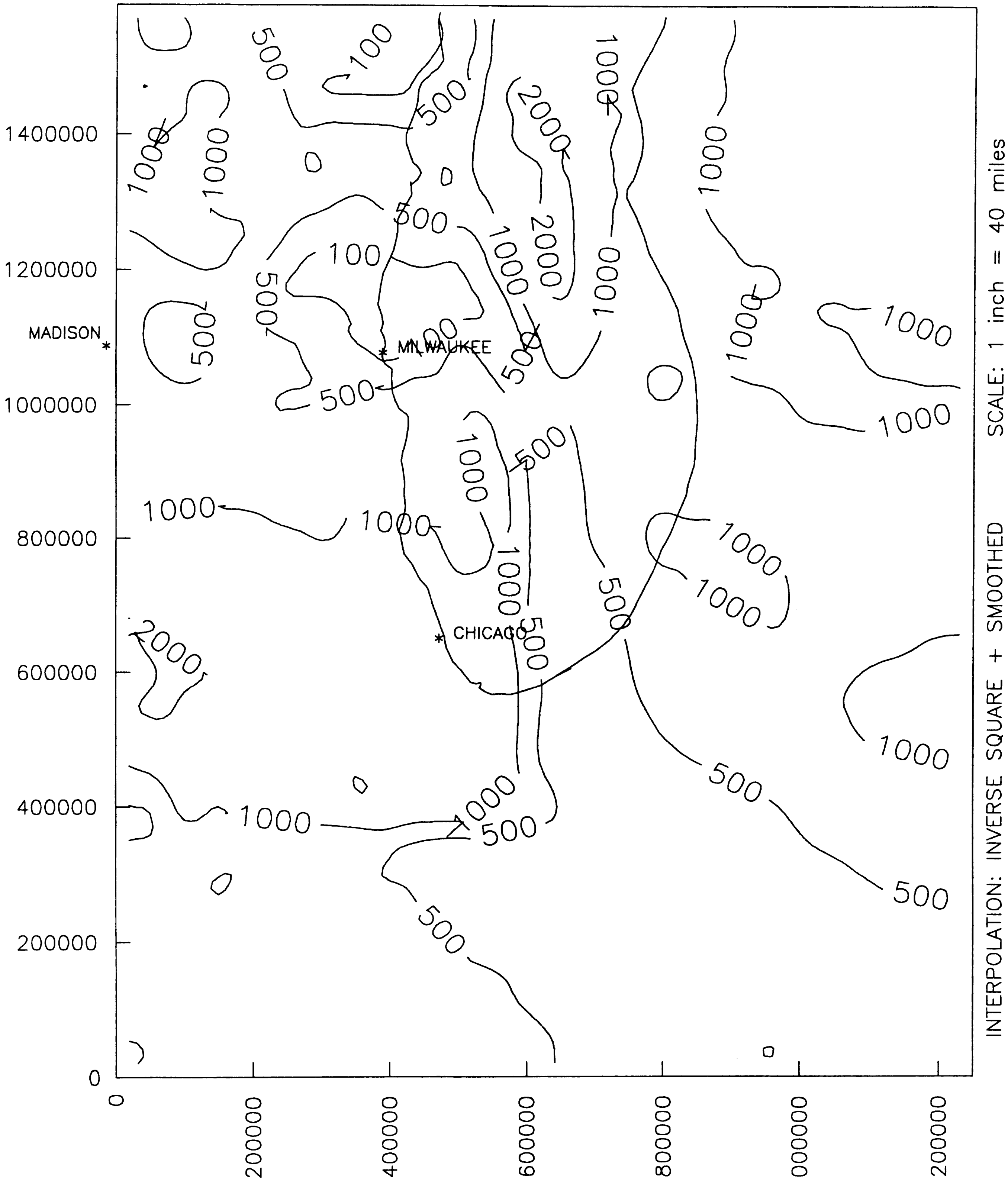


Fig. A-12

TOP of IRONTON–GALESVILLE = BOT of ST. LAWRENCE based on digitized maps

VARIABLE CONTOUR INTERVAL (IRGA–TOP.PLS)

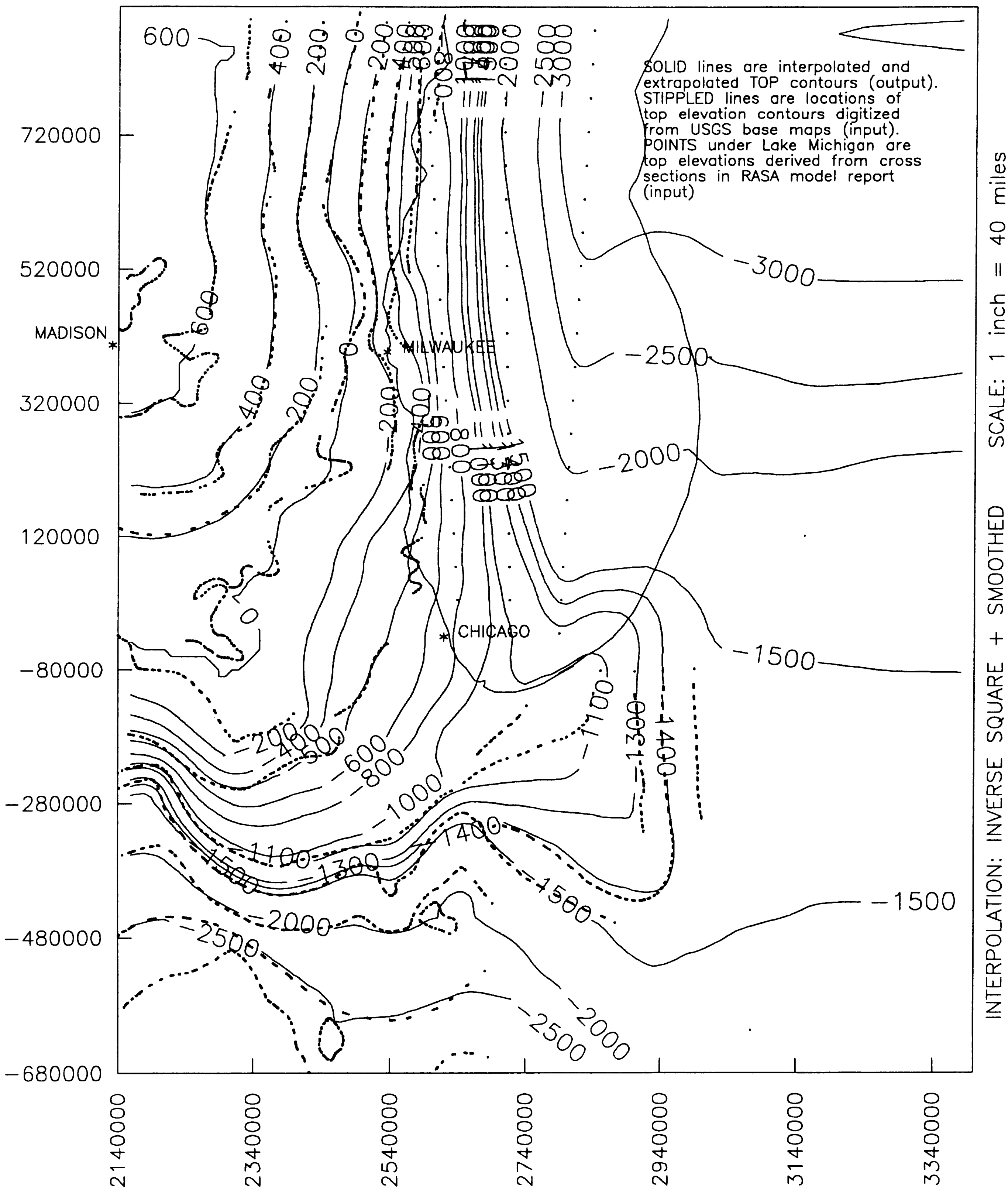


Fig. A-13

"CORRECTED" TOP of IRONTON–GALESVILLE = BOT of ST. LAWRENCE

CONTOUR INTERVAL = 400 ft ::: DUMMY THICKNESS = 1 ft (IRGATOPC.PLS)

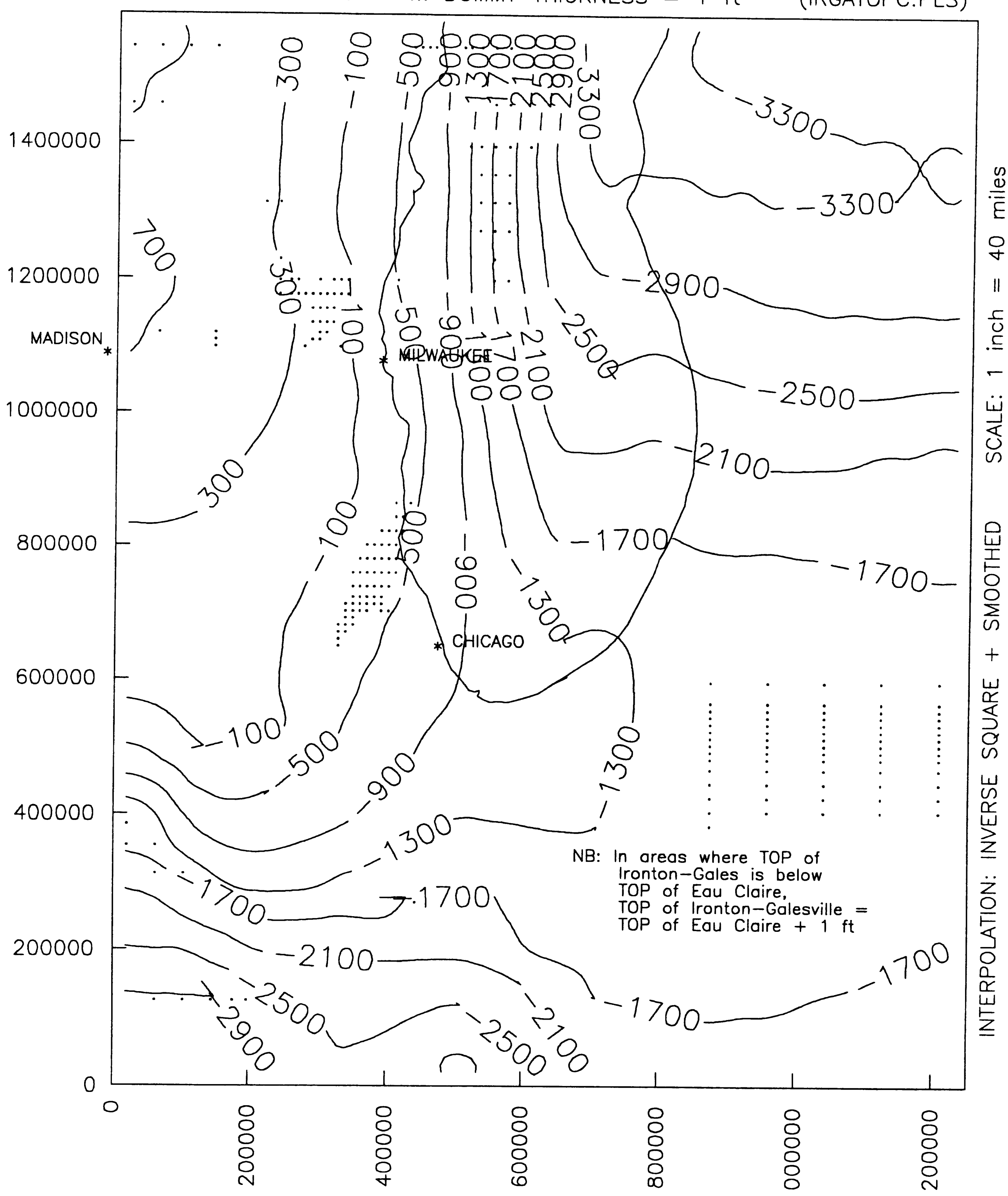


Fig. A-14

THICKNESS OF IRONTON–GALESVILLE based on digitized maps

CONTOURS = 100, 200, 300 ft ::: DUMMY THICKNESS = 1 ft (IRGA–THK.PLS)

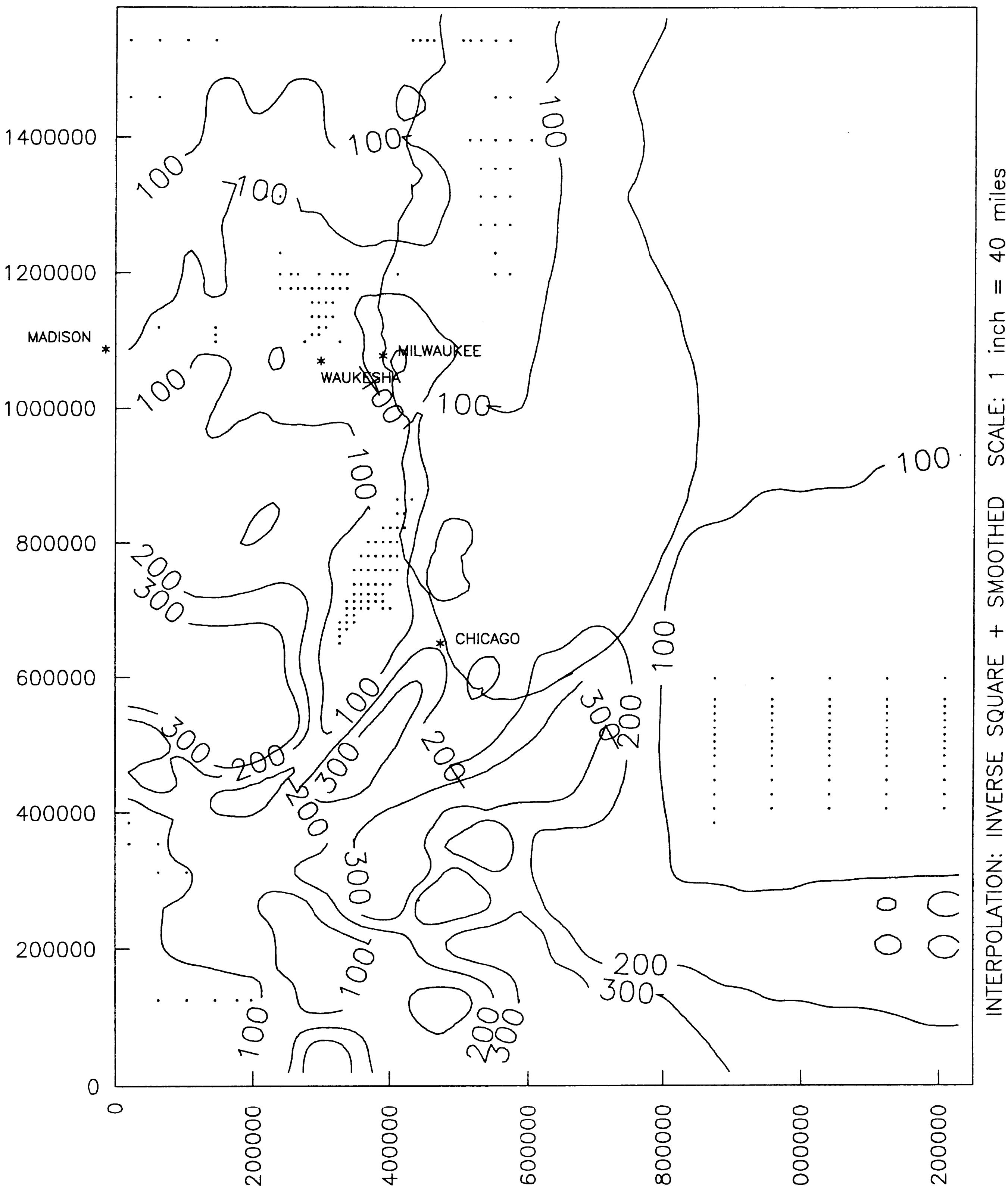


Fig. A-15

IMPLIED Kh OF IRONTON–GALESVILLE from RASA MODEL and DIGITIZED MAPS

CONTOURS= 2, 10 ft/day ::: DUMMY THICKNESS = 1 ft (IRGA–K.PLB)

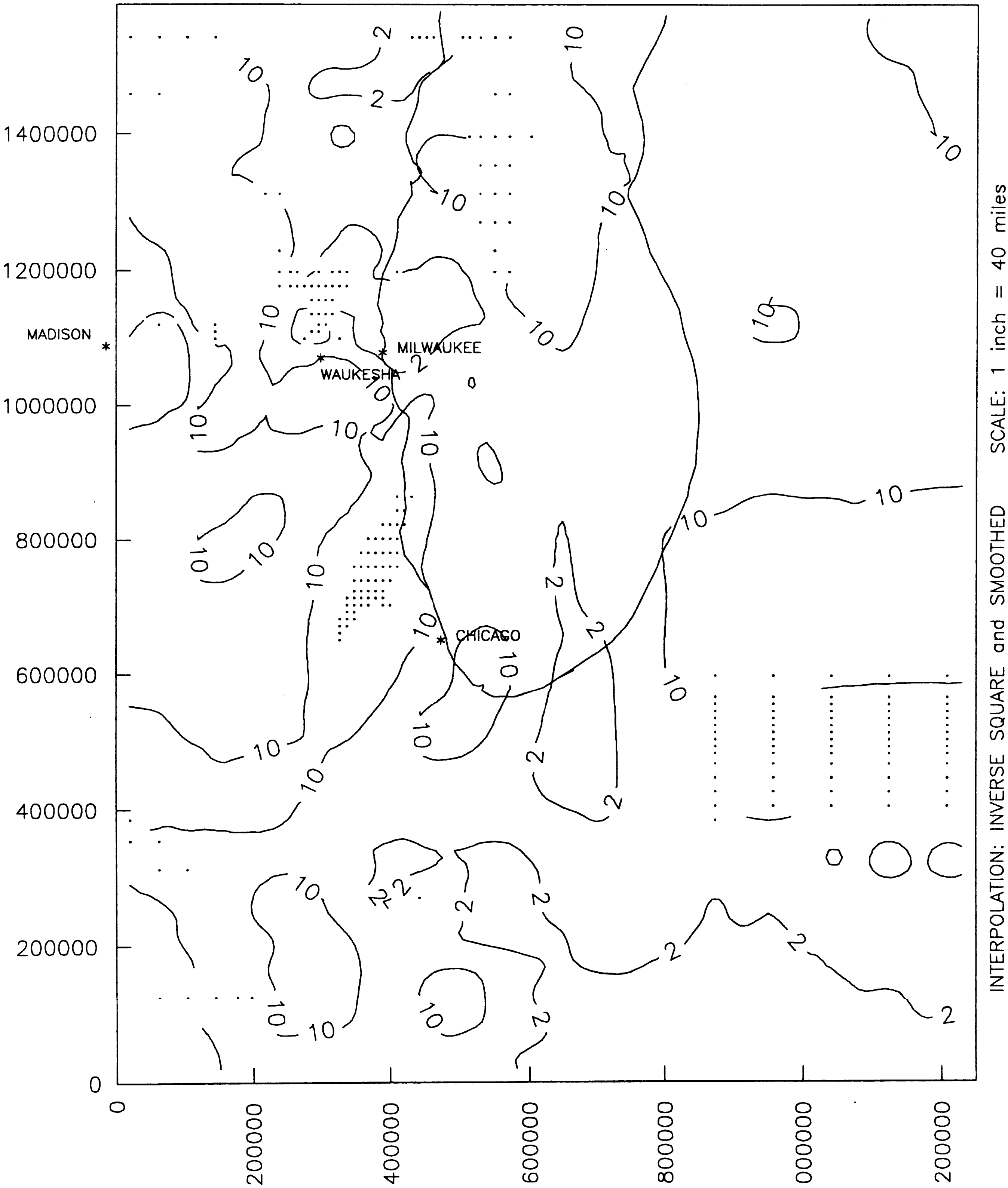


Fig. A-16

LEAKANCE (=VCONT) of ST. LAWRENCE/FRANCONIA in RASA Model

LOGARITHMIC CONTOURS in 1/DAY (STLW-LK.PLS)

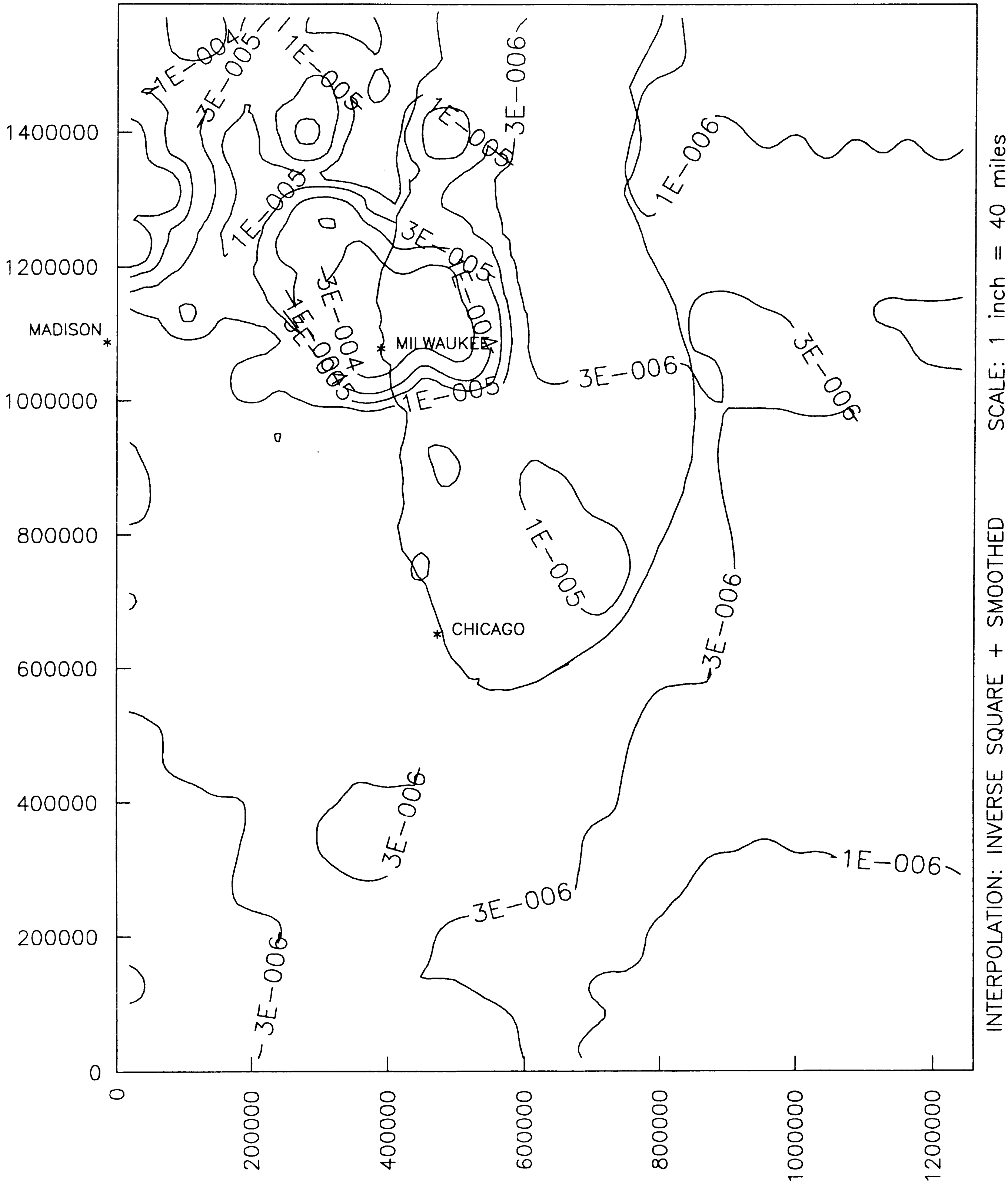


Fig. A-17

TOP of ST. LAWRENCE = BOT of ST. PETER AQUIFER based on digitized maps

VARIABLE CONTOUR INTERVAL (STLW-TOP.PLS)

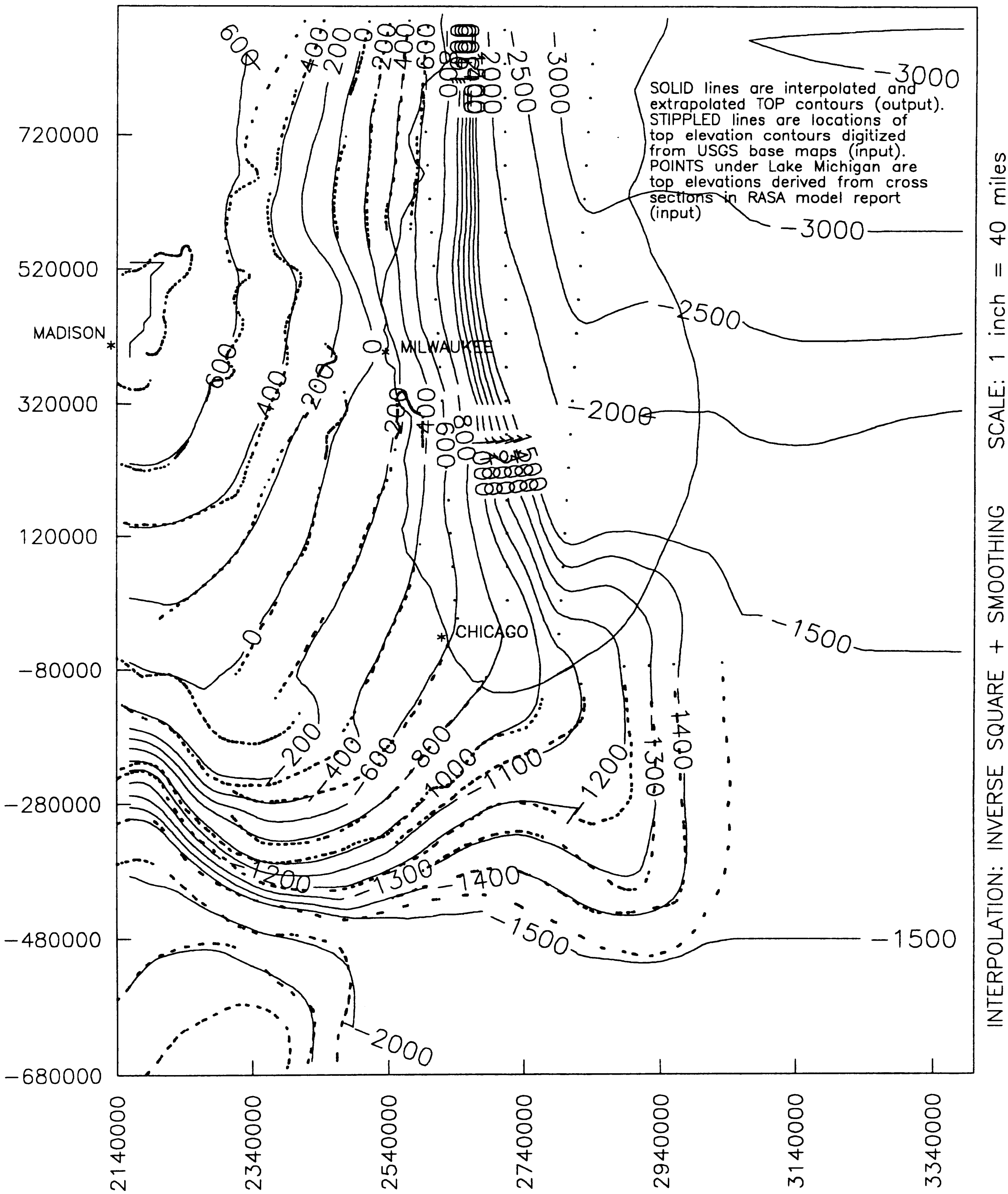


Fig. A-18

"CORRECTED" TOP of ST. LAWRENCE AQUITARD = BOT of ST. PETER AQUIFER

CONTOUR INTERVAL = 400 ft ::: DUMMY THICKNESS = 1 ft (STLWTOPC.PLS)

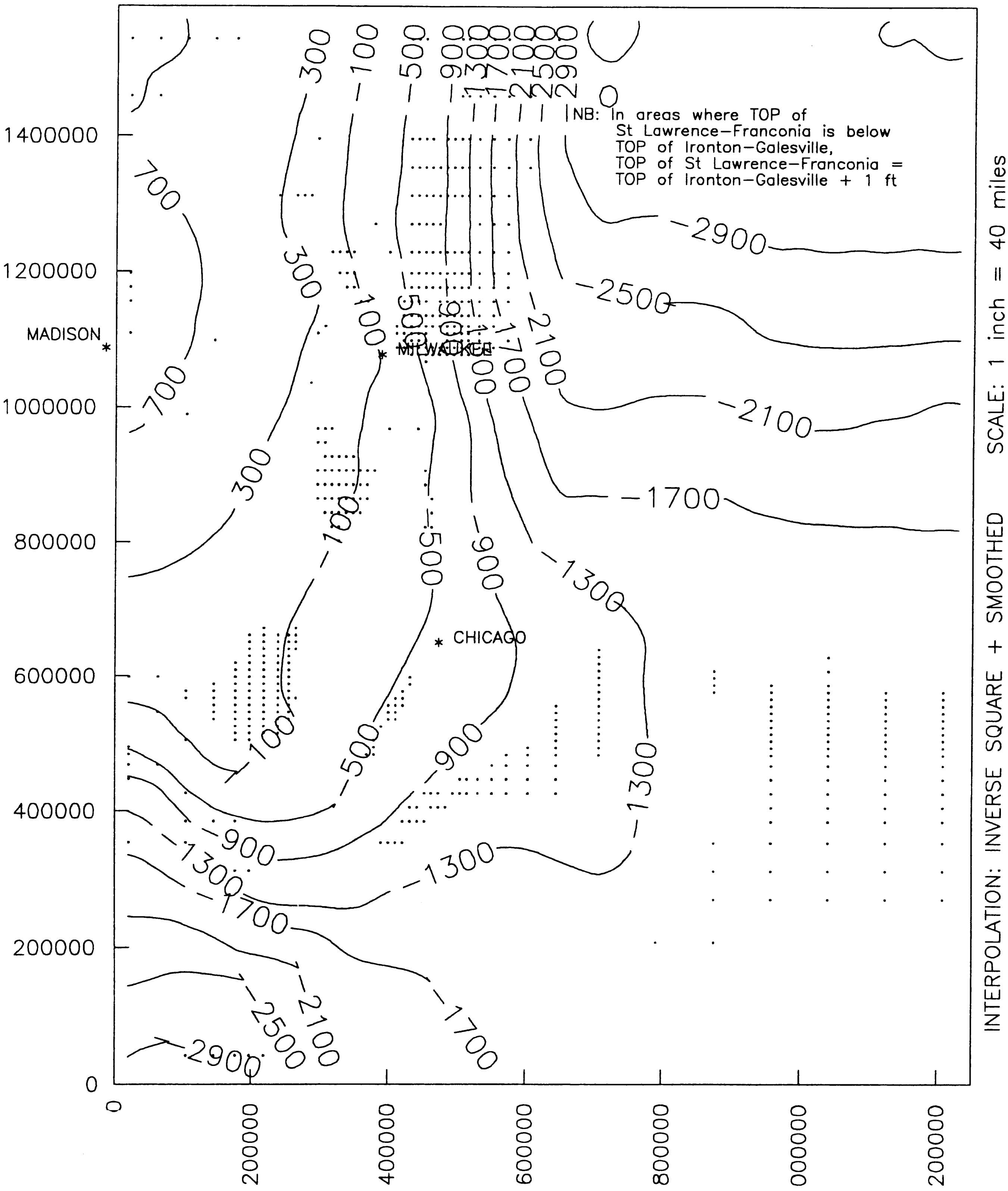


Fig. A-19

THICKNESS OF ST. LAWRENCE/FRANCONIA AQUITARD based on digitized maps

CONTOURS = 100, 200, 300 ft ::: DUMMY THICKNESS = 1 ft (STLW-THK.PLS)

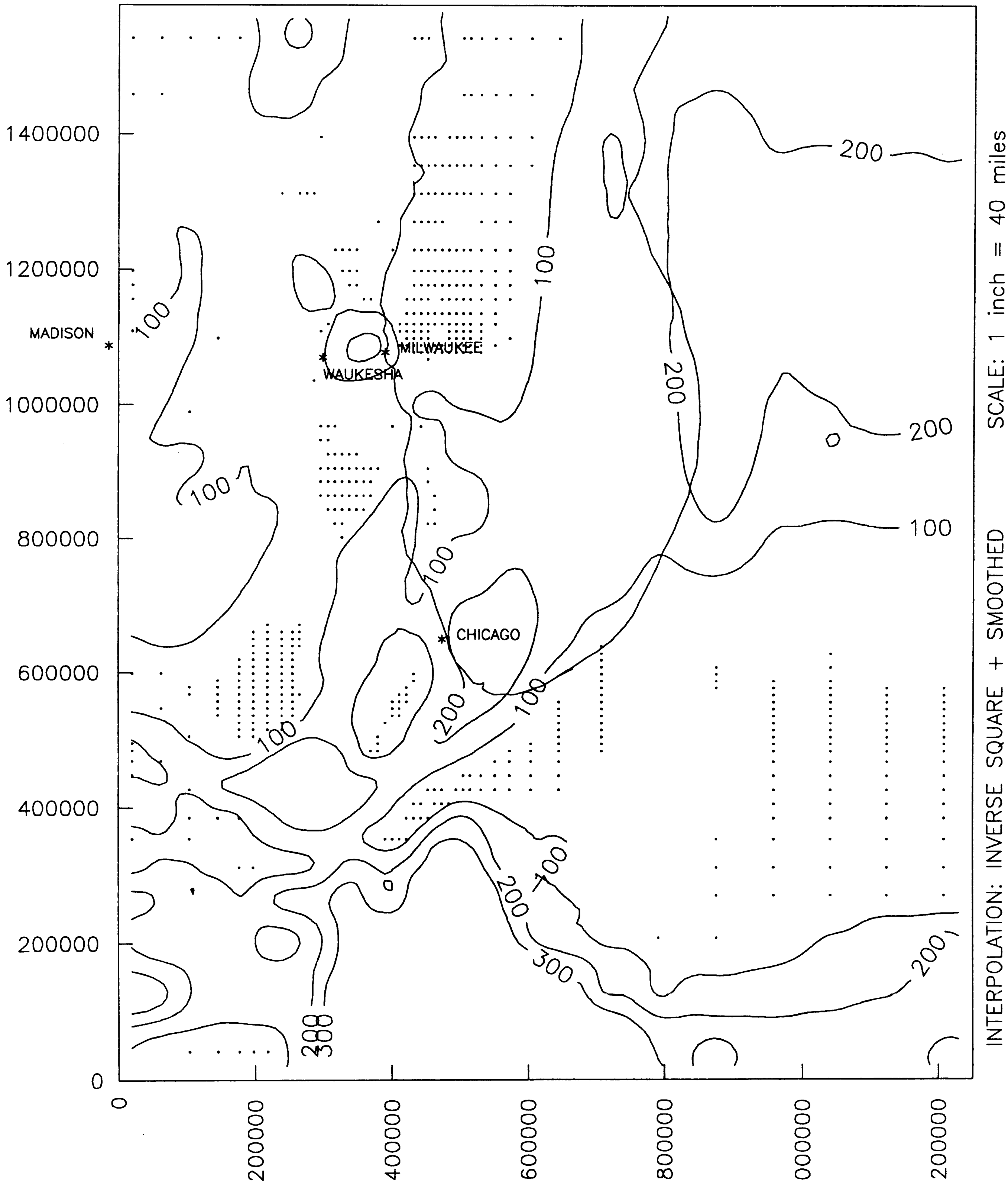


Fig. A-20

IMPLIED Kv OF ST. LAWRENCE/FRANCONIA AQUITARD from RASA MODEL and DIGITIZED MAPS

LOGARITHMIC CONTOURS in ft/day ::: DUMMY THICKNESS = 1 ft (STLW-KV.PLB)

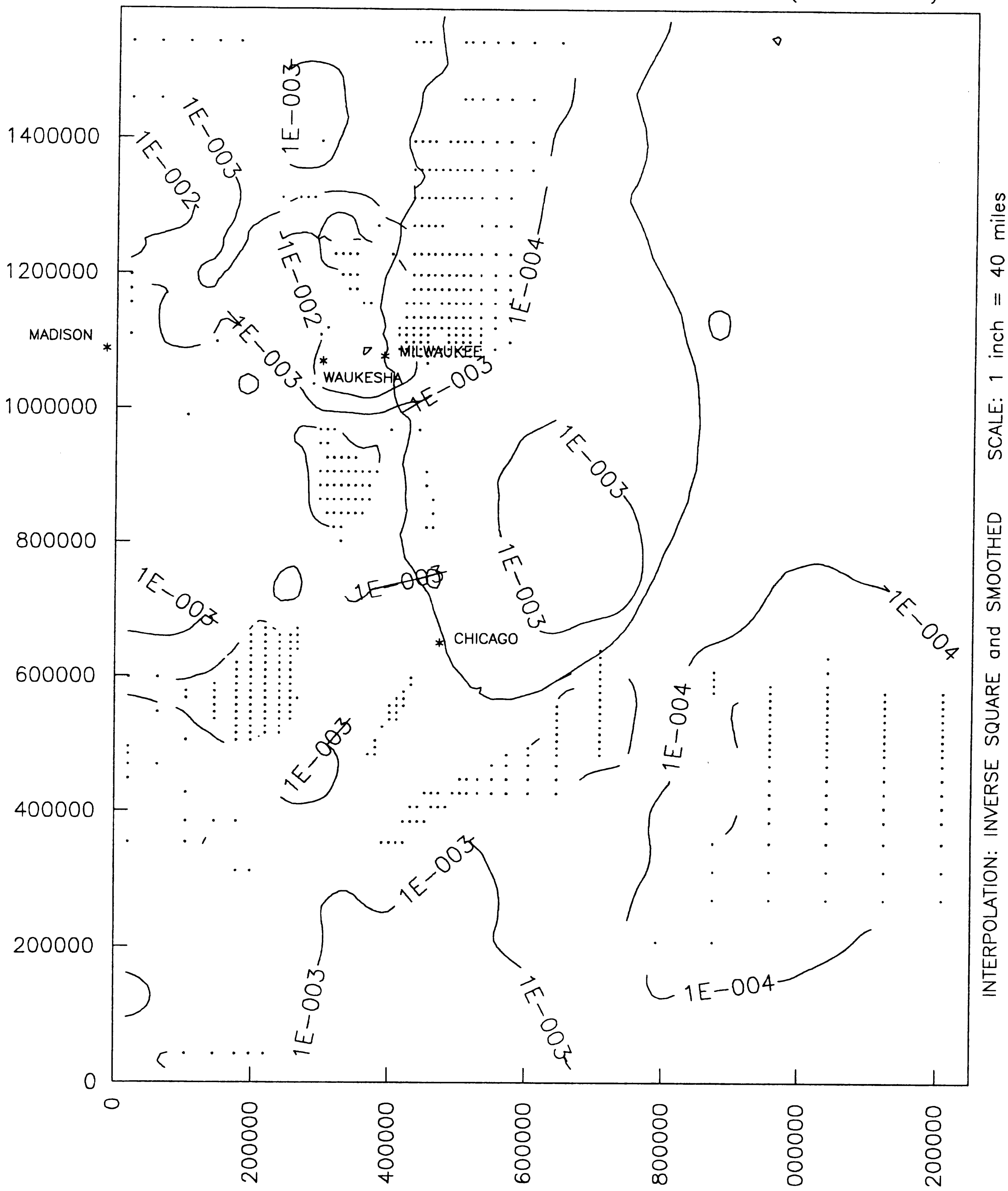


Fig. A-21

Transmissivity of St. Peter (+ Prairie du Chien + Jordan) in RASA Model

CONTOURS = 10, 100, 500, 1000, 2000 ft**2/day (STPTTRAN.PLS)

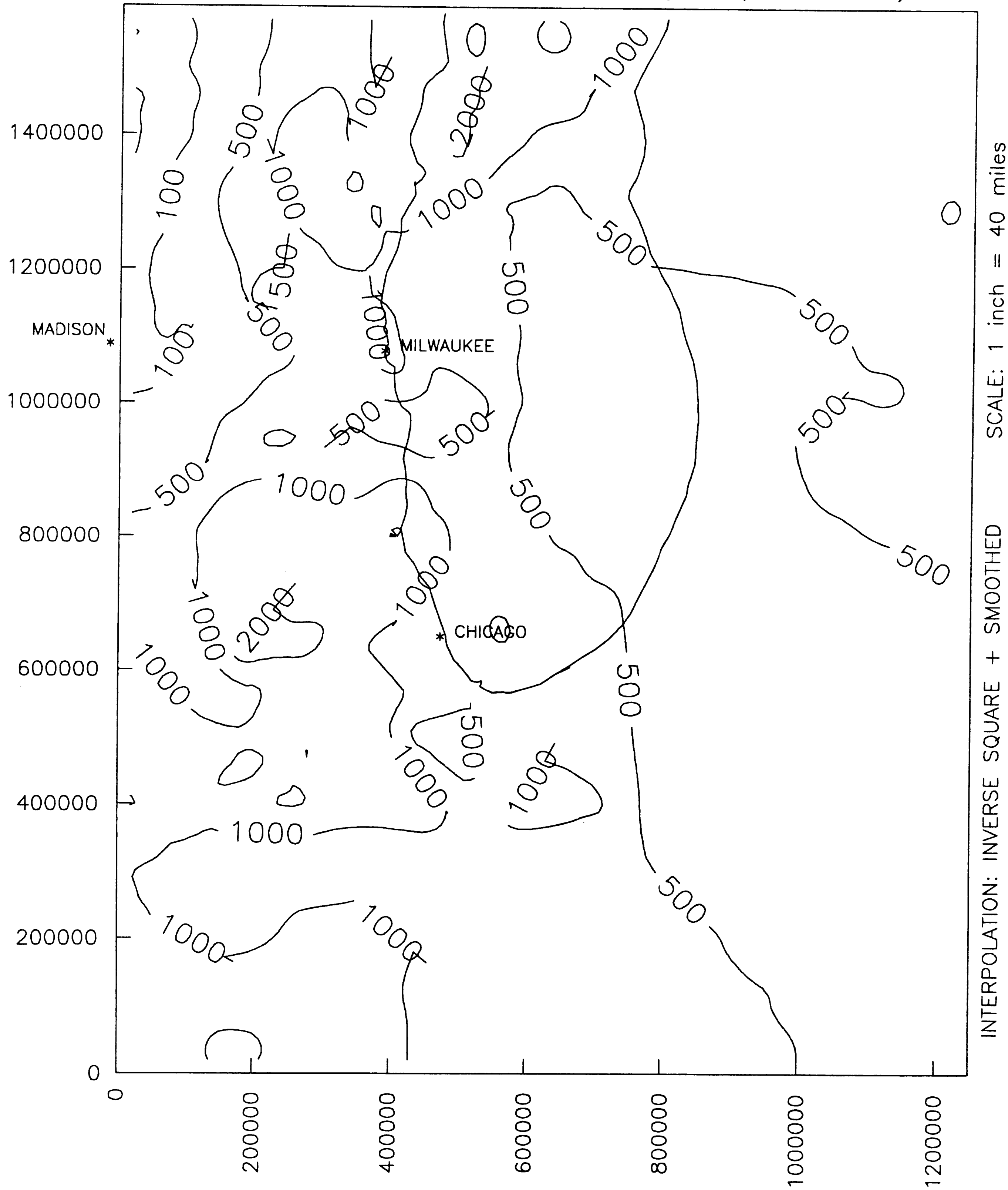


Fig. A-22

TOP of ST, PETER AQUIFER = BOT OF SINNIPEE based on digitized maps

VARIABLE CONTOUR INTERVAL (STPT-TOP.PLS)

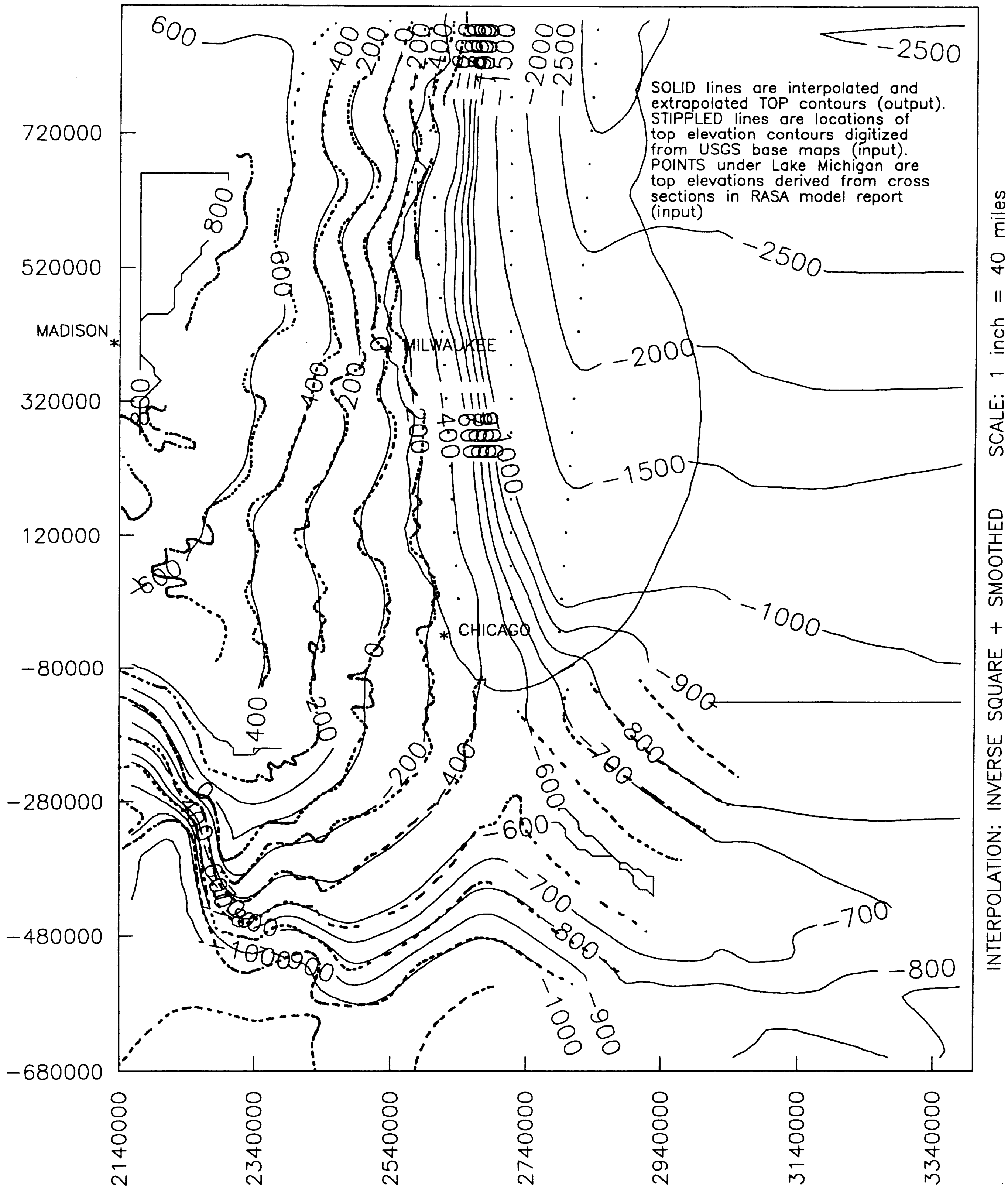


Fig. A-23

"CORRECTED" TOP of ST. PETER AQUIFER = BOT of SINNIPEE

CONTOUR INTERVAL = 400 ft ::: DUMMY THICKNESS = 1 ft (STPTTOPC.PLS)

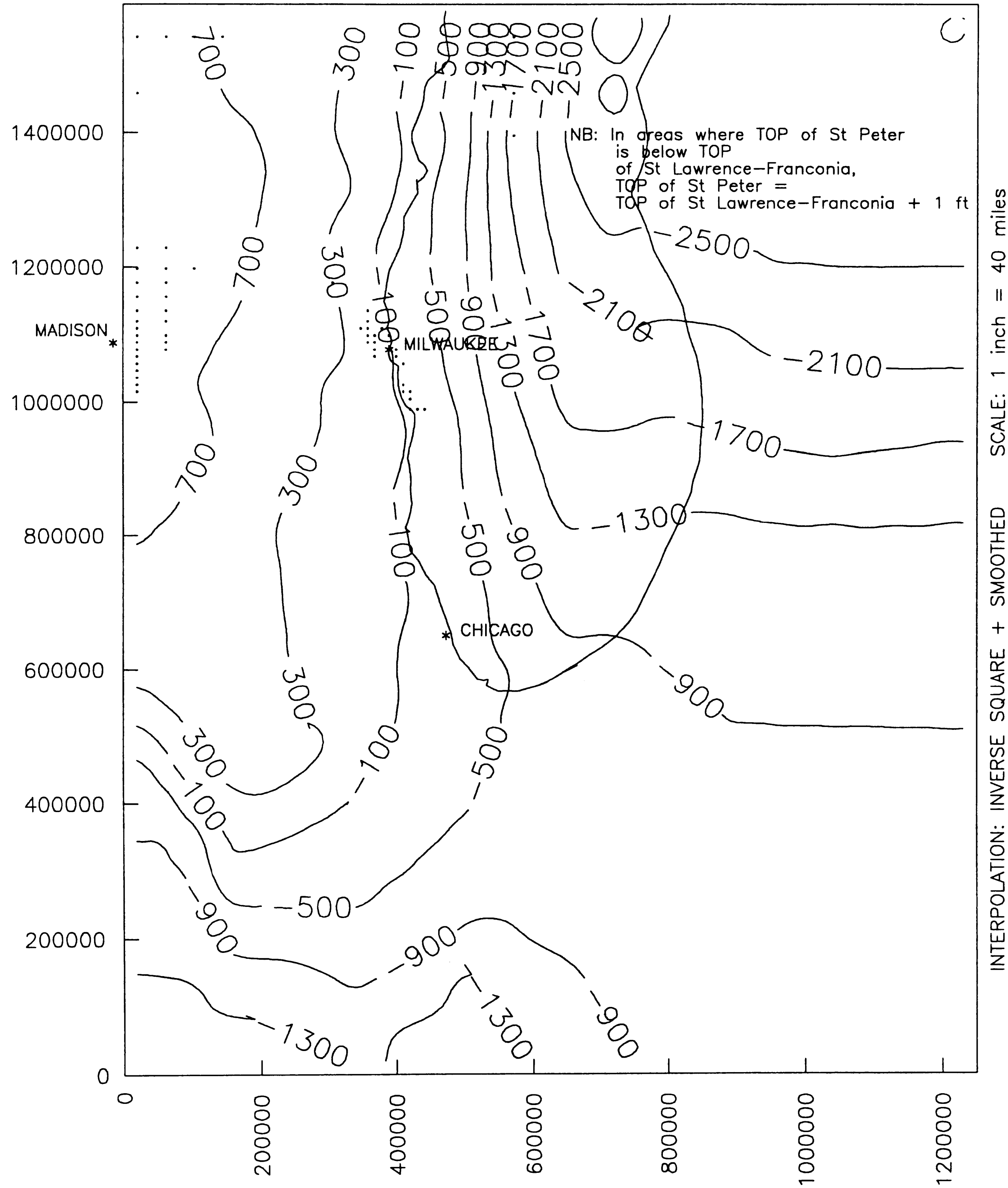


Fig. A-24

THICKNESS OF ST. PETER (+PRAIRIE DU CHIEN+JORDAN) based on digitized maps

CONTOURS = 100, 300, 500, 700 ft ::: DUMMY THICKNESS = 1 ft (STPT–THK.PLI)

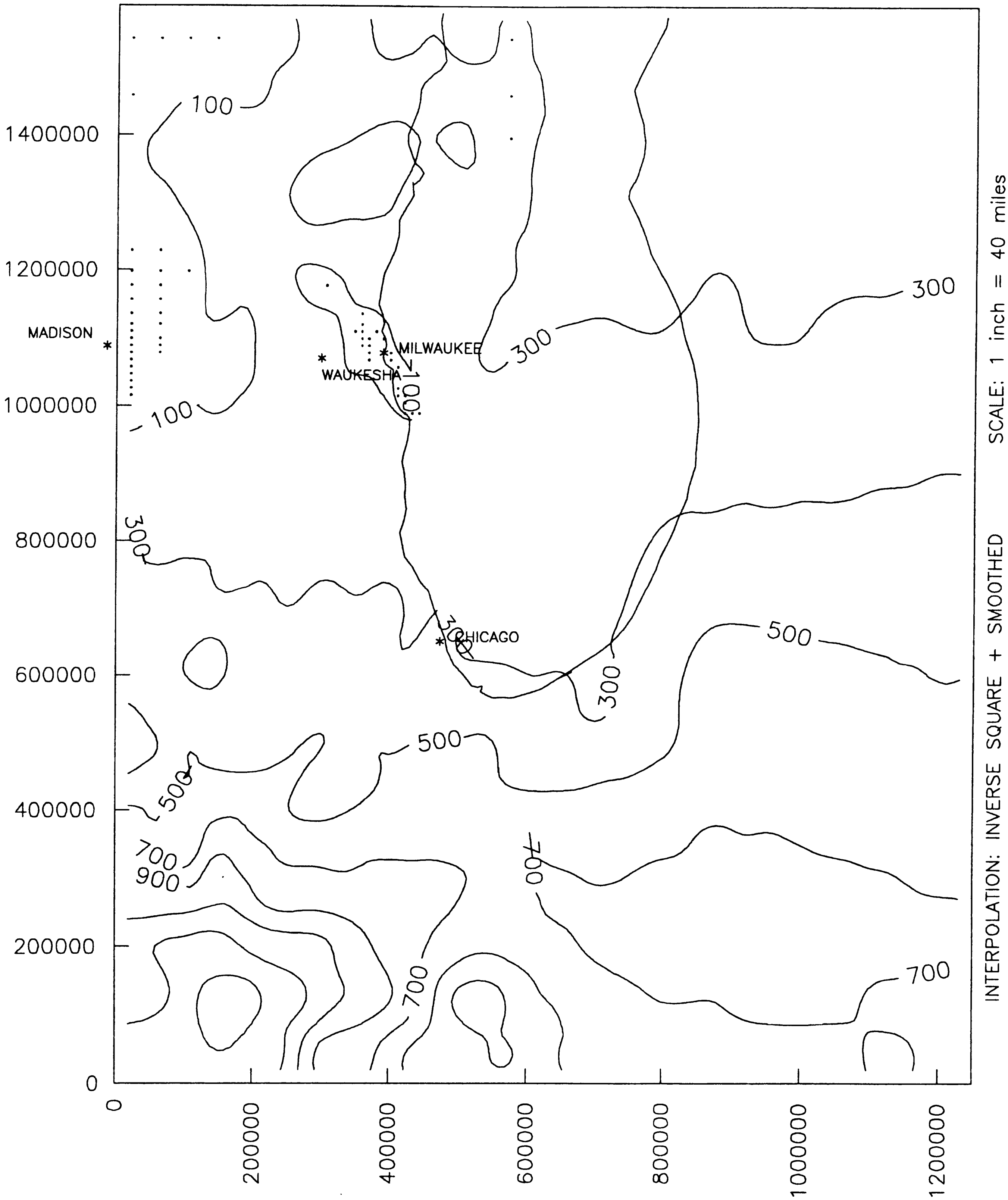


Fig. A-25

IMPLIED Kh OF ST. PETER AQUIFER from RASA MODEL and DIGITIZED MAPS

CONTOURS= 1, 4, 10 ft/day ::: DUMMY THICKNESS = 1 ft (STPT-K.PLB)

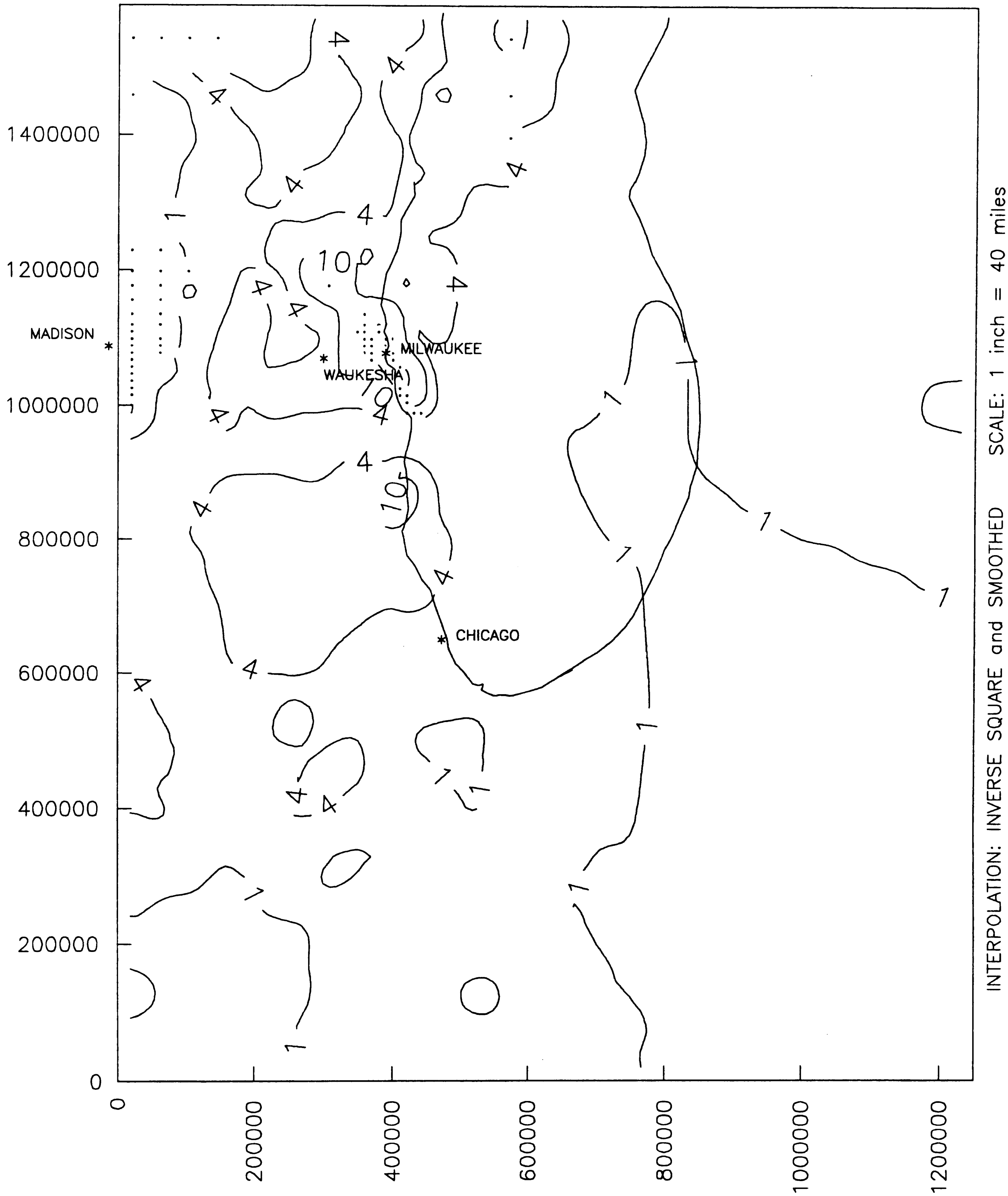


Fig. A-26

LEAKANCE (=VCONT) of MAQUOKETA/SINNIPEE AQUITARD in RASA Model

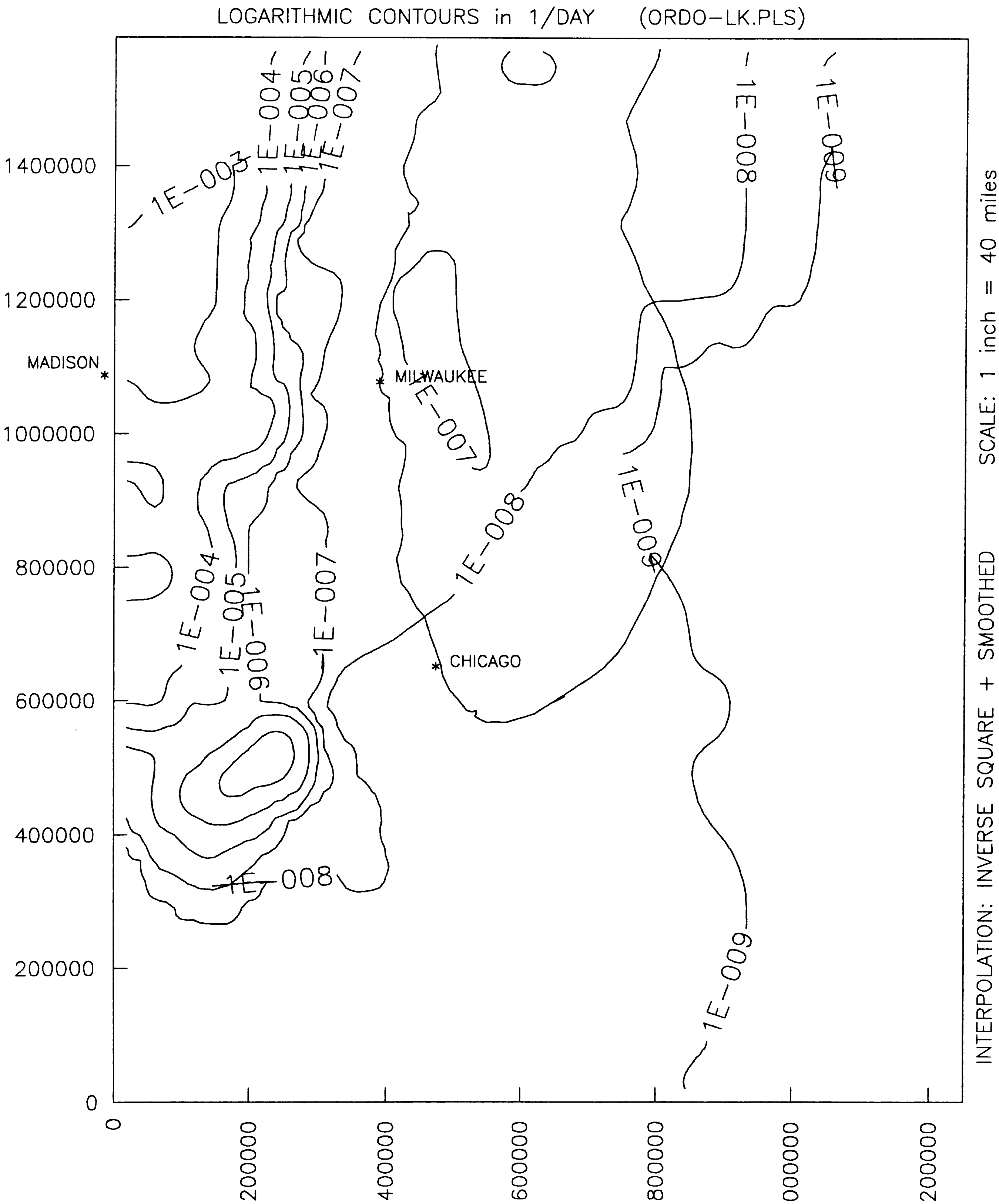


Fig. A-27

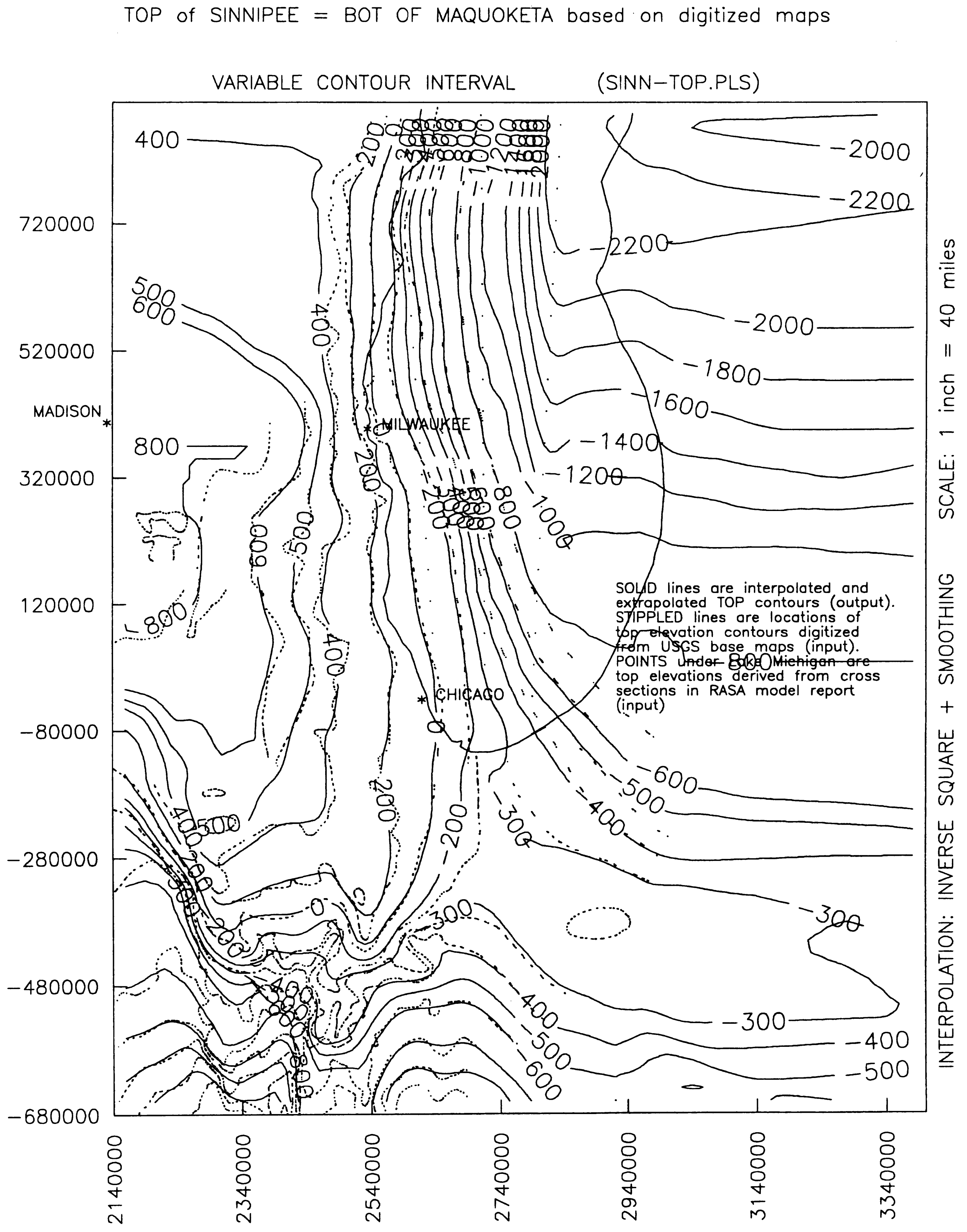

TOP of SINNIPEE = BOT OF MAQUOKETA based on digitized maps
VARIABLE CONTOUR INTERVAL (SINN-TOP.PLS)
MADISON
MILWAUKEE
CHICAGO
SOLID lines are interpolated and extrapolated TOP contours (output). STIPPLED lines are locations of top elevation contours digitized from USGS base maps (input). POINTS under Lake Michigan are top elevations derived from cross sections in RASA model report (input)
INTERPOLATION: INVERSE SQUARE + SMOOTHING SCALE: 1 inch = 40 miles
720000
520000
320000
120000
-80000
-280000
-480000
-680000
2140000
2340000
2540000
2740000
2940000
3140000
3340000

Fig. A-28

"CORRECTED" TOP of SINNIPEE = BOT of MAQUOKETA

CONTOUR INTERVAL = 400 ft ::: DUMMY THICKNESS = 1 ft (SINNTOPC.PLS)

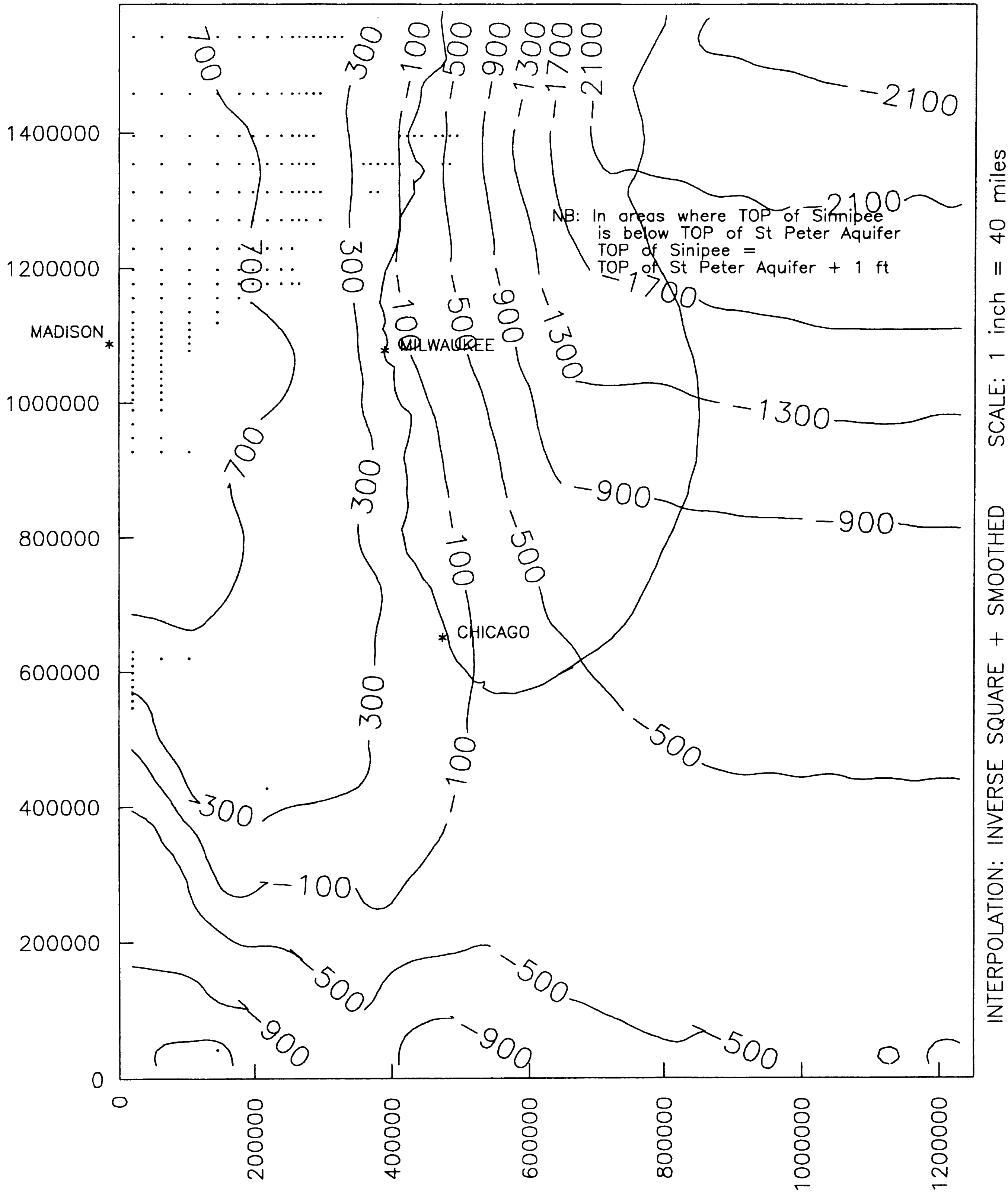


Fig. A-29

THICKNESS OF SINNIPEE based on digitized maps

CONTOURS = 100, 200, 400, 600 ft ::: DUMMY THICKNESS = 1 ft (SINN-THK.PLS)

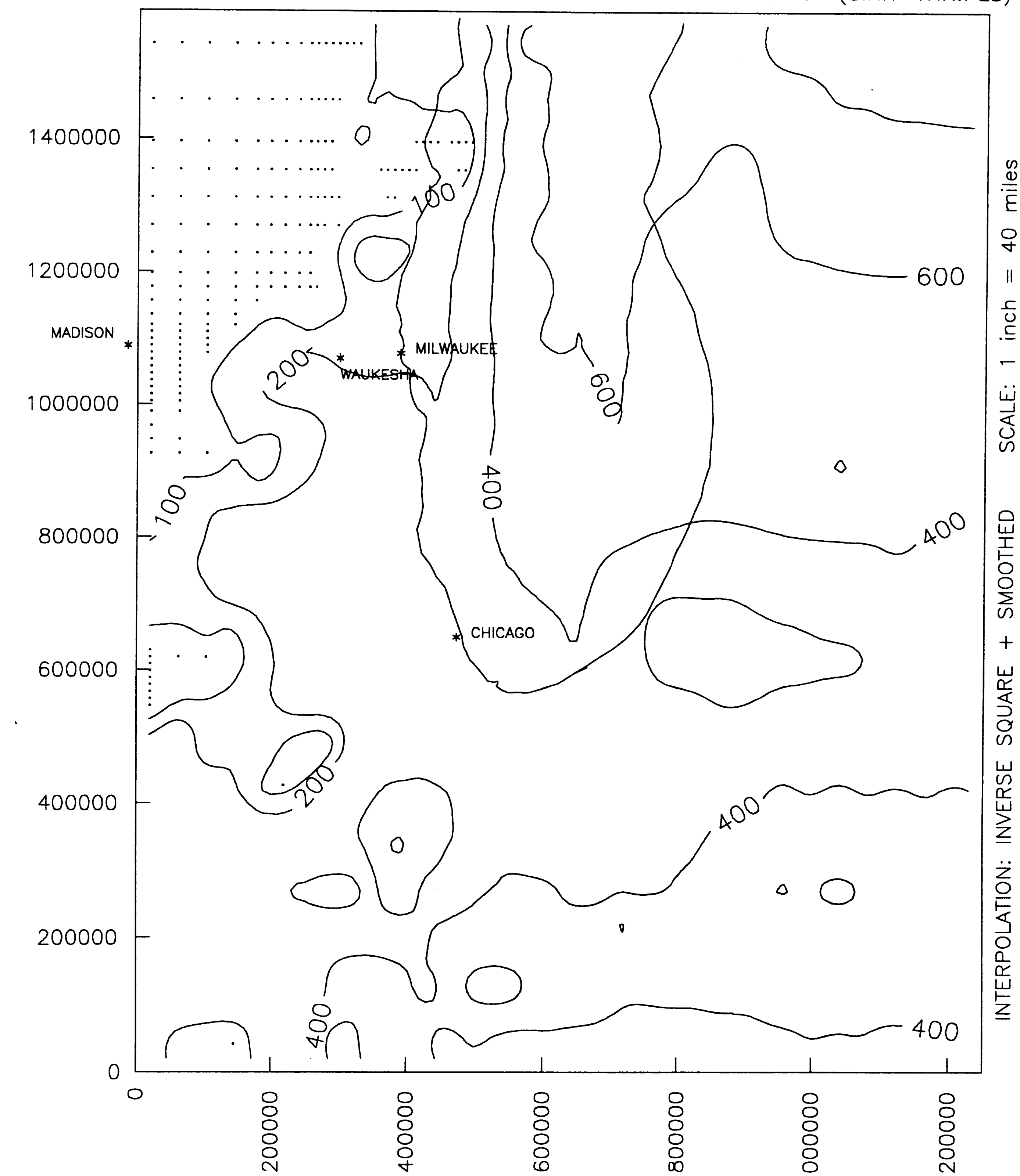


Fig. A-30

TOP of MAQUOKETA = BOT OF SILURIAN based on digitized maps

VARIABLE CONTOUR INTERVAL (ORDO-TOP.PLS)

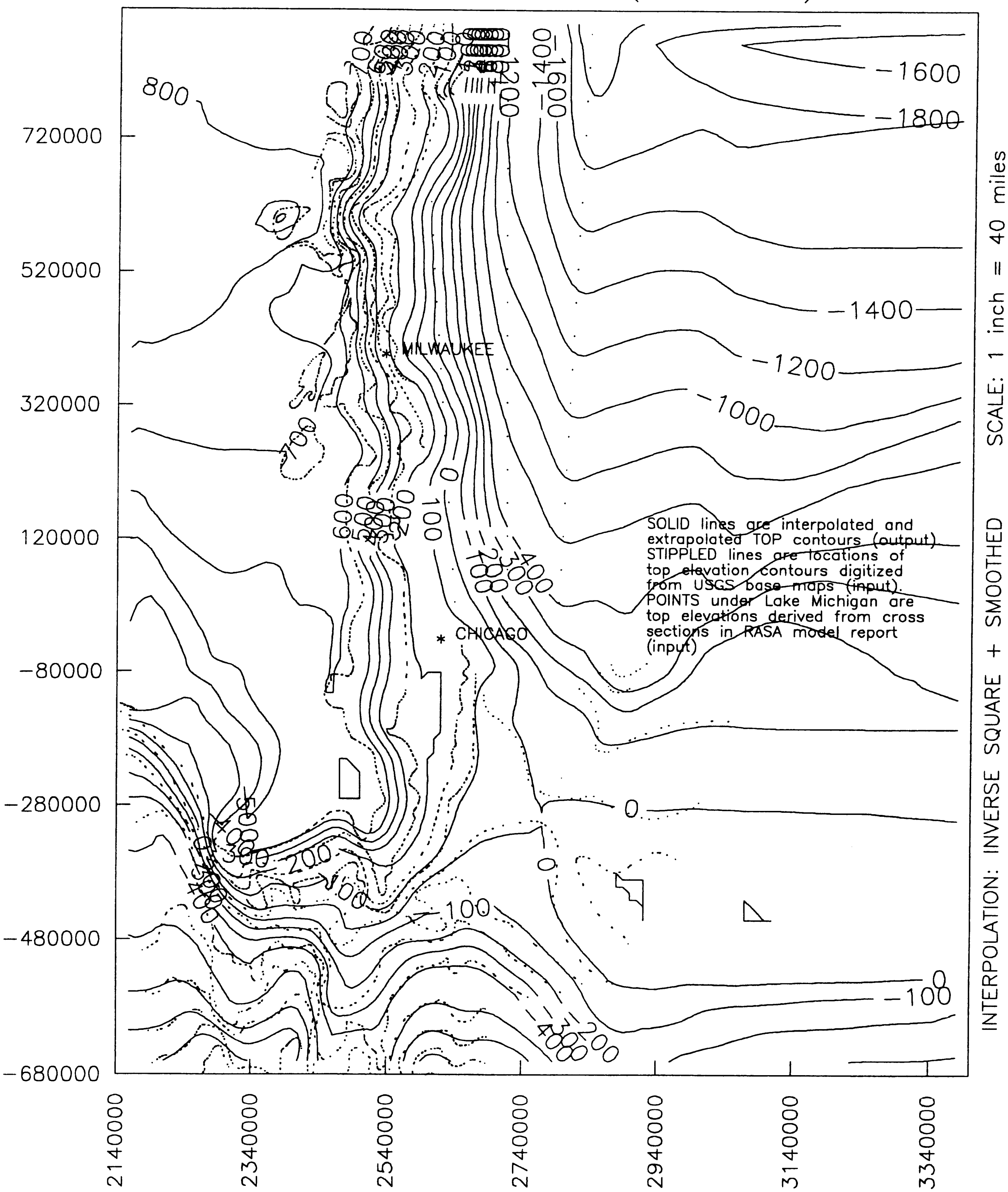


Fig. A-31

"CORRECTED" TOP OF MAQUOKETA = BOT OF SILURIAN based on digitized maps

CONTOUR INTERVAL = 400 ft ::: DUMMY THICKNESS = 1 ft (ORDOTOPC.PLS)

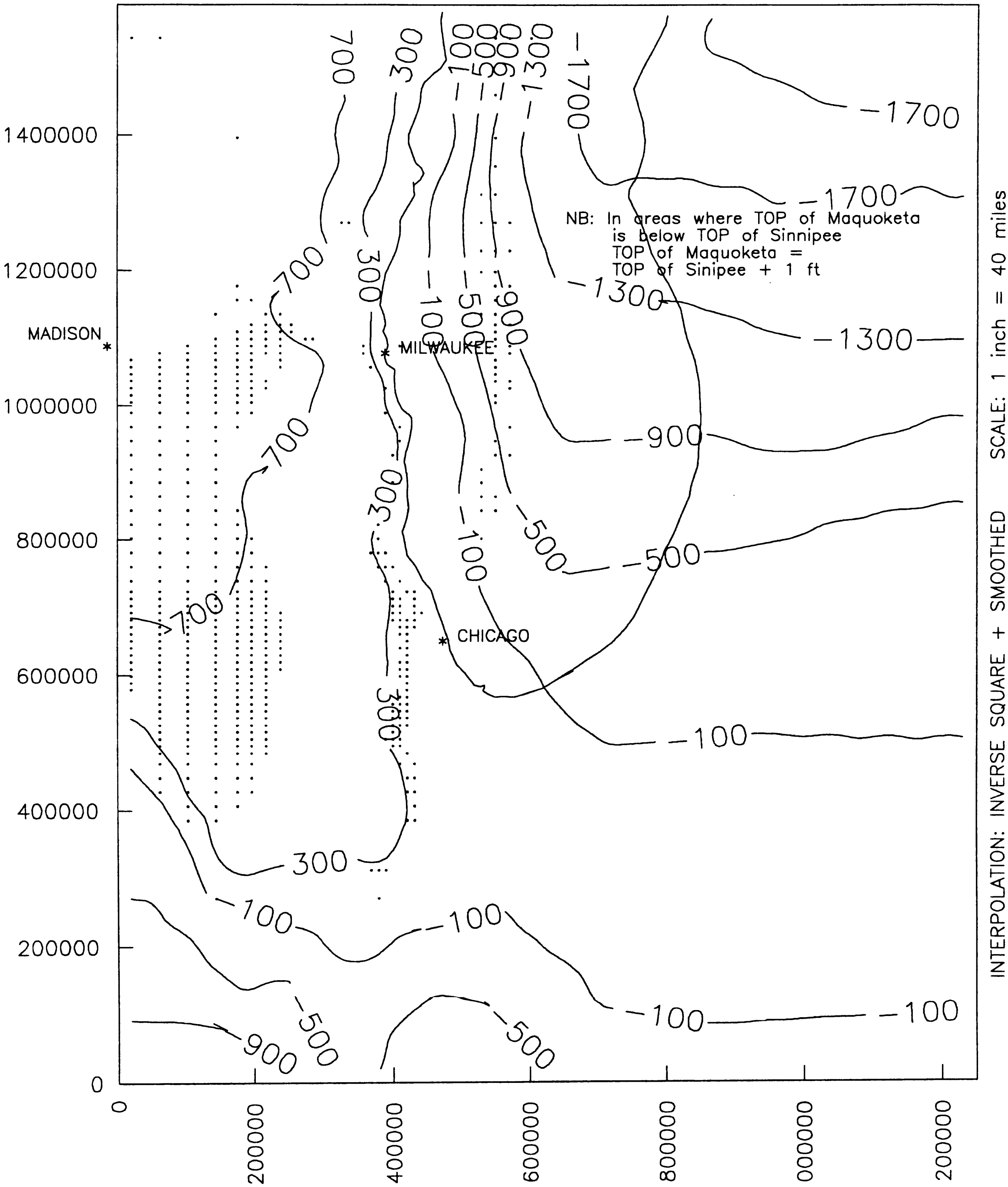


Fig. A-32

THICKNESS OF MAQUOKETA based on digitized maps

CONTOUR INTERVAL = 200 ft ::: DUMMY THICKNESS = 1 ft (MAQU–THK.PLS)

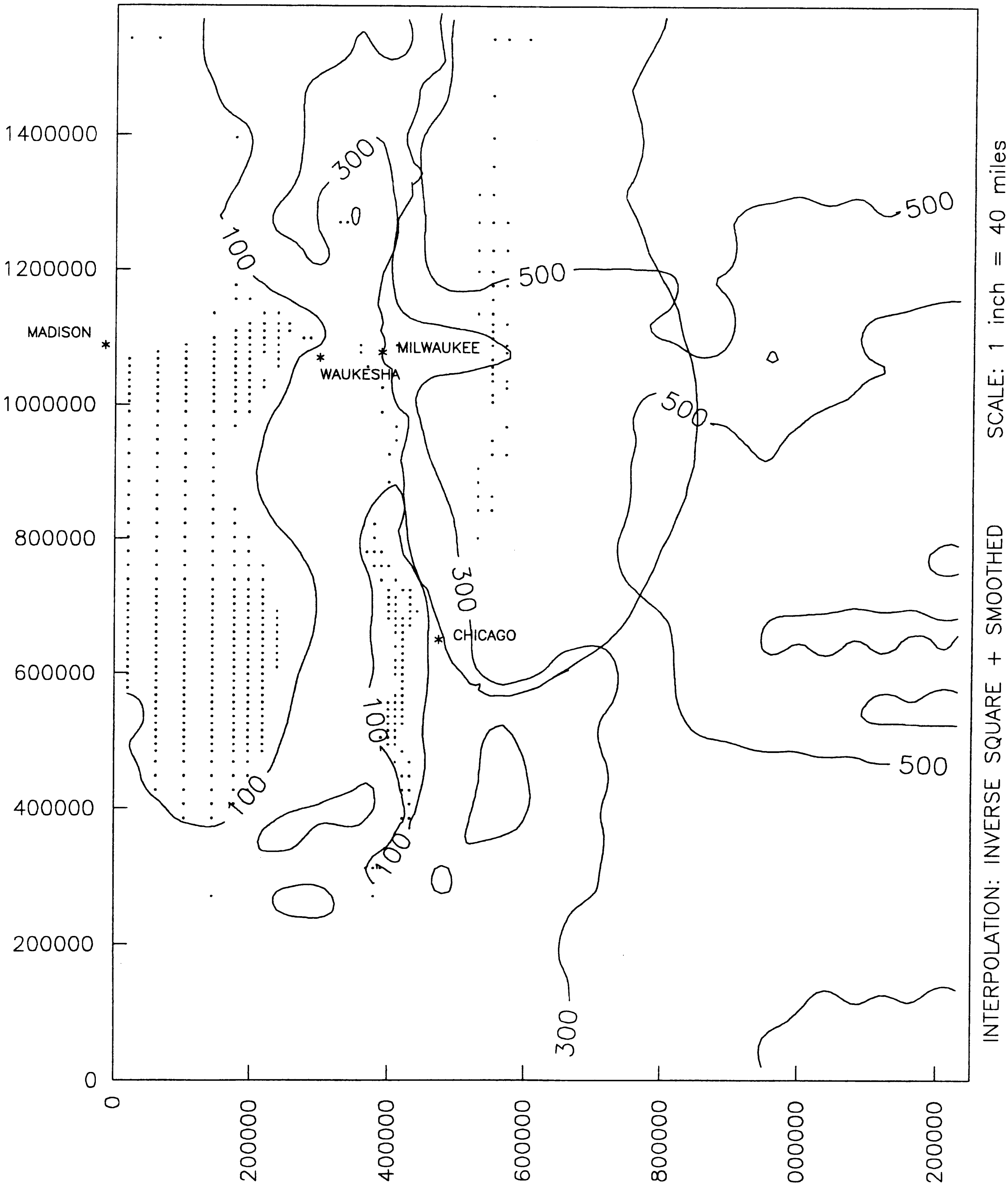


Fig. A-33

THICKNESS OF MAQUOKETA + SINNIPEE based on digitized maps

CONTOUR INTERVAL = 300 ft ::: DUMMY THICKNESS = 1 ft (ORDO-THK.PLS)

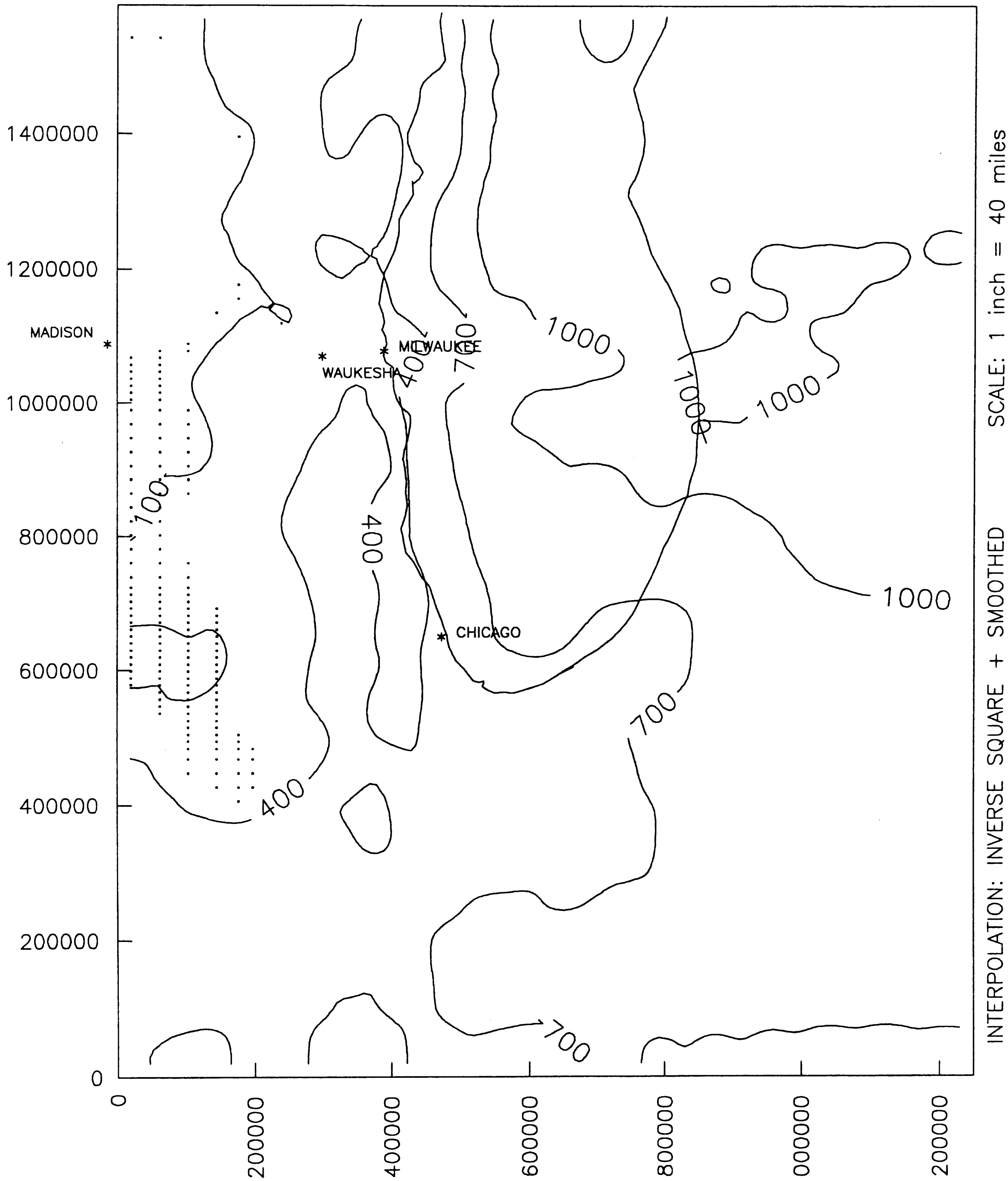


Fig. A-34

IMPLIED Kv OF MAQUOKETA/SINNIPEE Aquitard from RASA MODEL and DIGITIZED MAPS

LOGARITHMIC CONTOURS in ft/day ::: DUMMY THICKNESS = 1 ft (ORDO-KV.PLB)

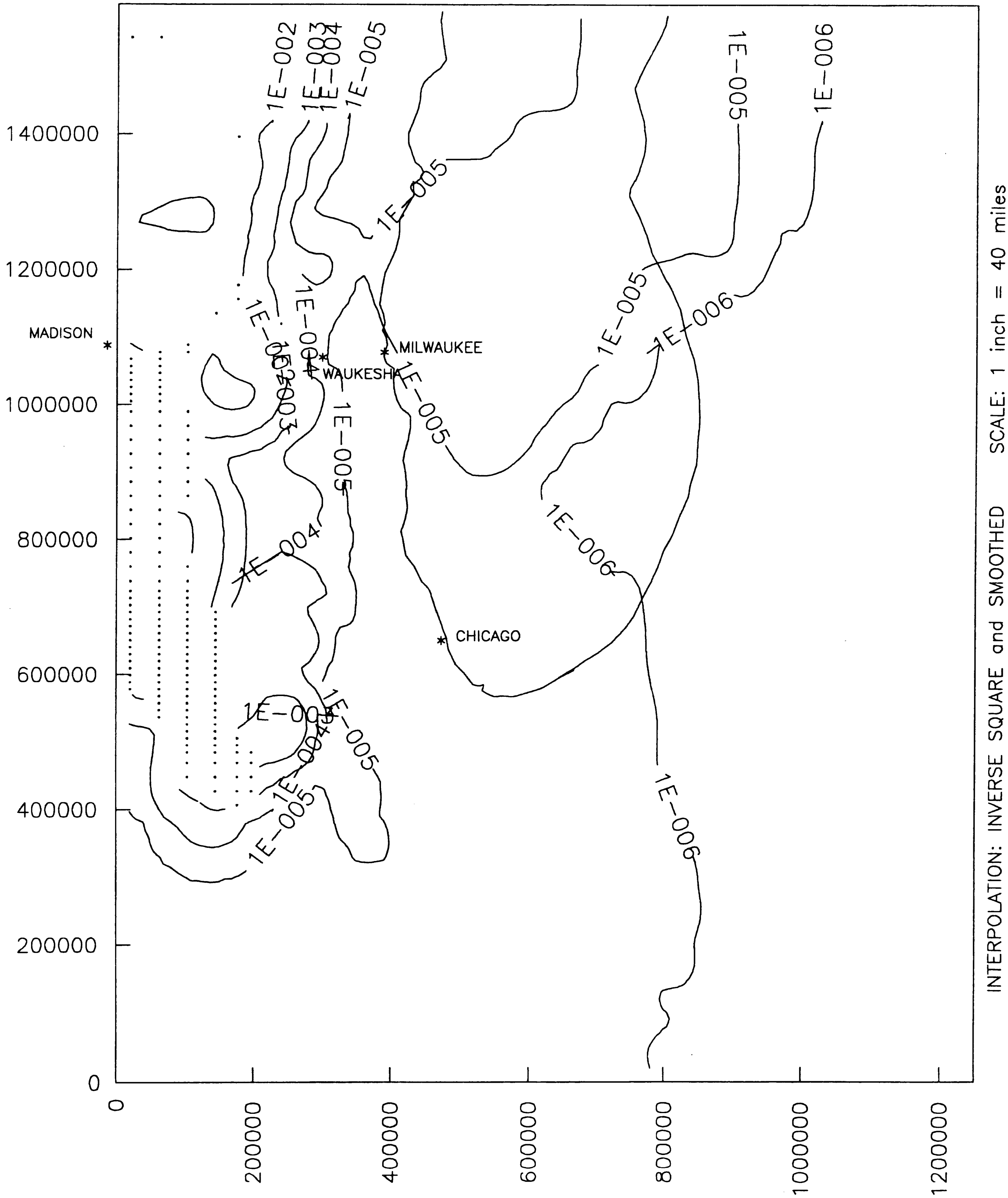


Fig. A-35

Transmissivity of SILURIAN AQUIFER in RASA Model

CONTOURS = 10, 100, 500, 1000 ft**2/day (SILUTRAN.PLS)

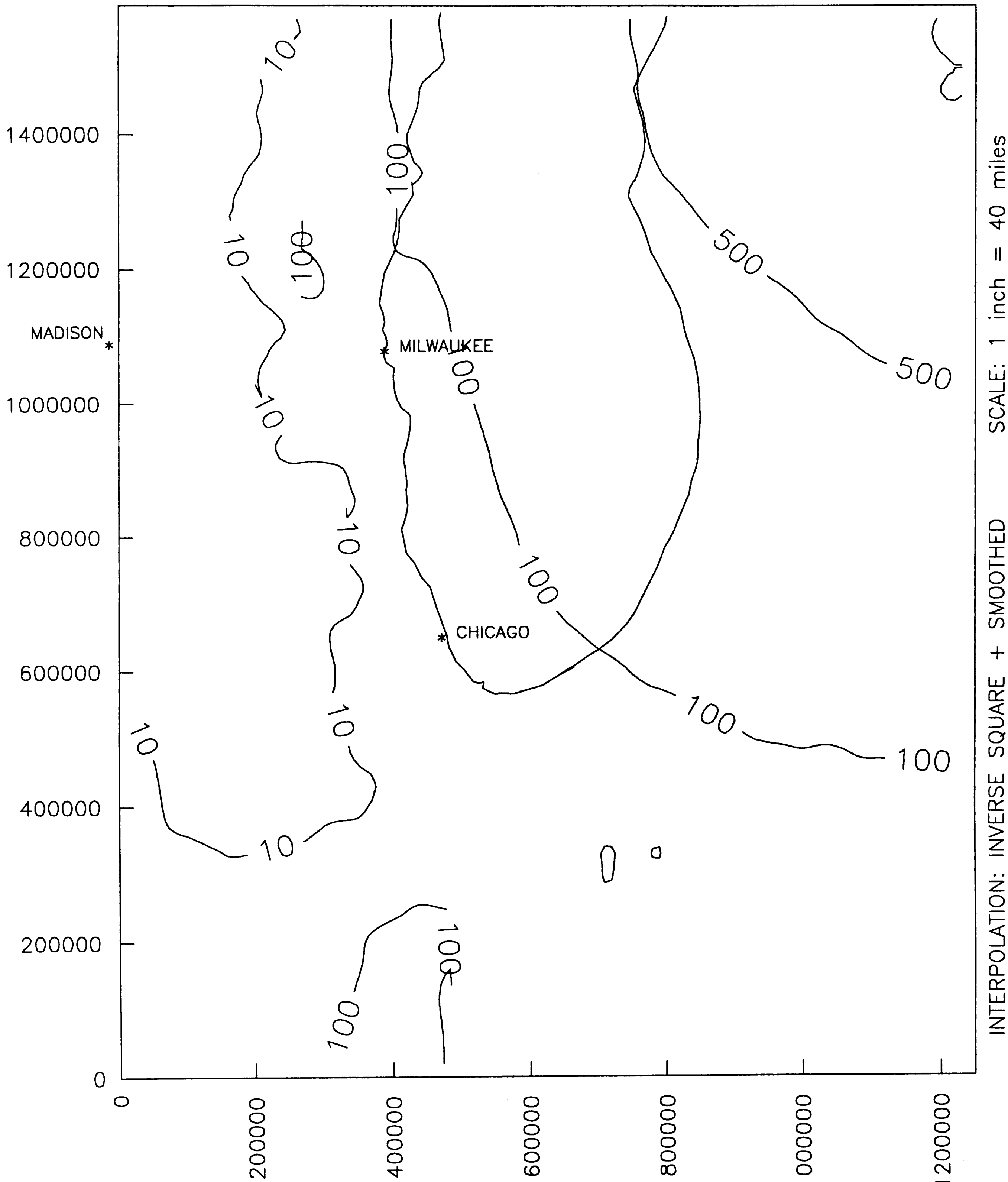


Fig. A-36

TOP of SILURIAN AQUIFER = BOT OF DRIFT or MESOZOIC based on digitized maps

VARIABLE CONTOUR INTERVAL (SILU-TOP.PLS)

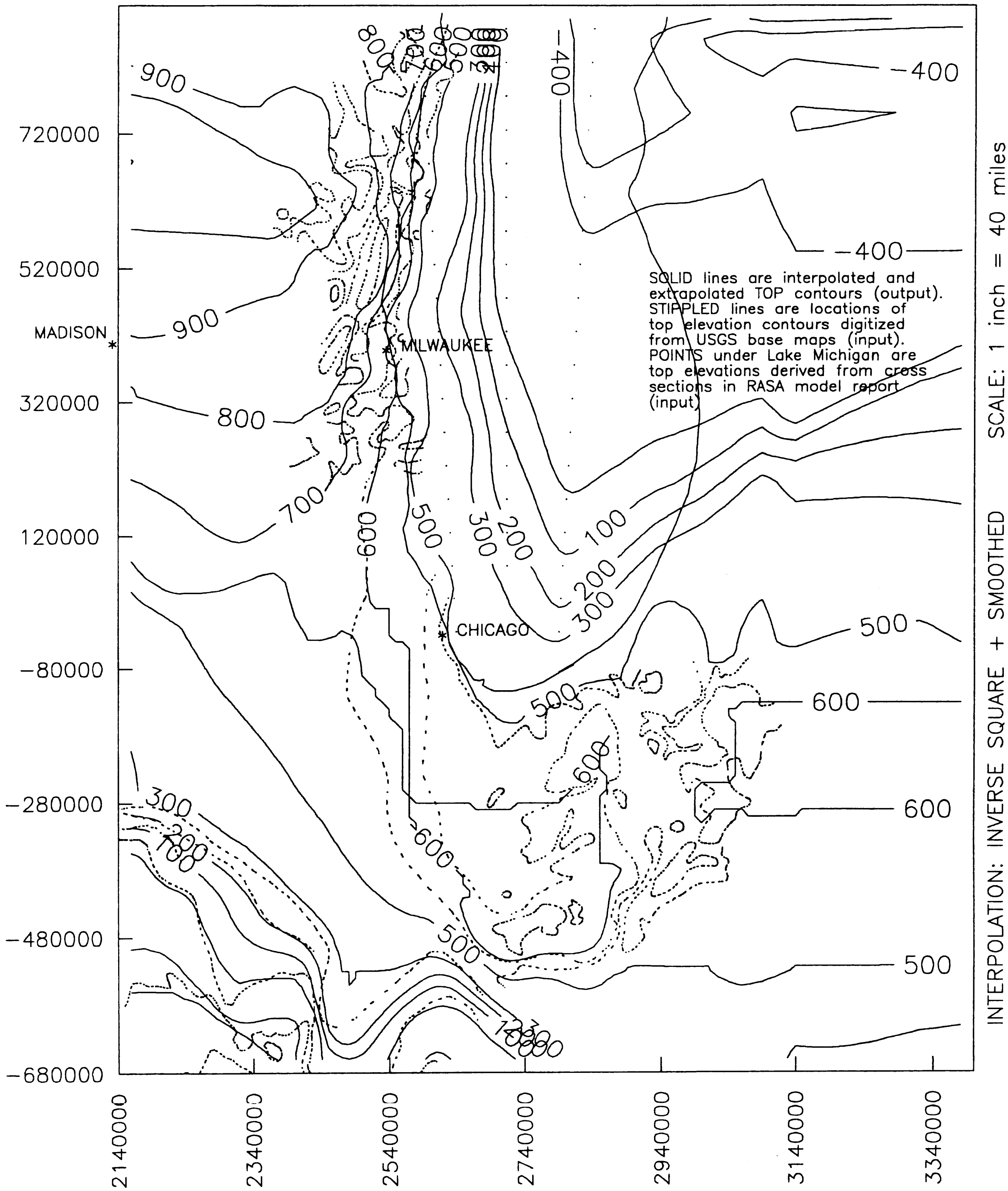


Fig. A-37

"CORRECTED" TOP of SILURIAN AQUIFER = BOT OF GLACIAL or MESOZOIC

CONTOUR INTERVAL = 400 ft ::: DUMMY THICKNESS = 1 ft (SILUTOPC.PLS)

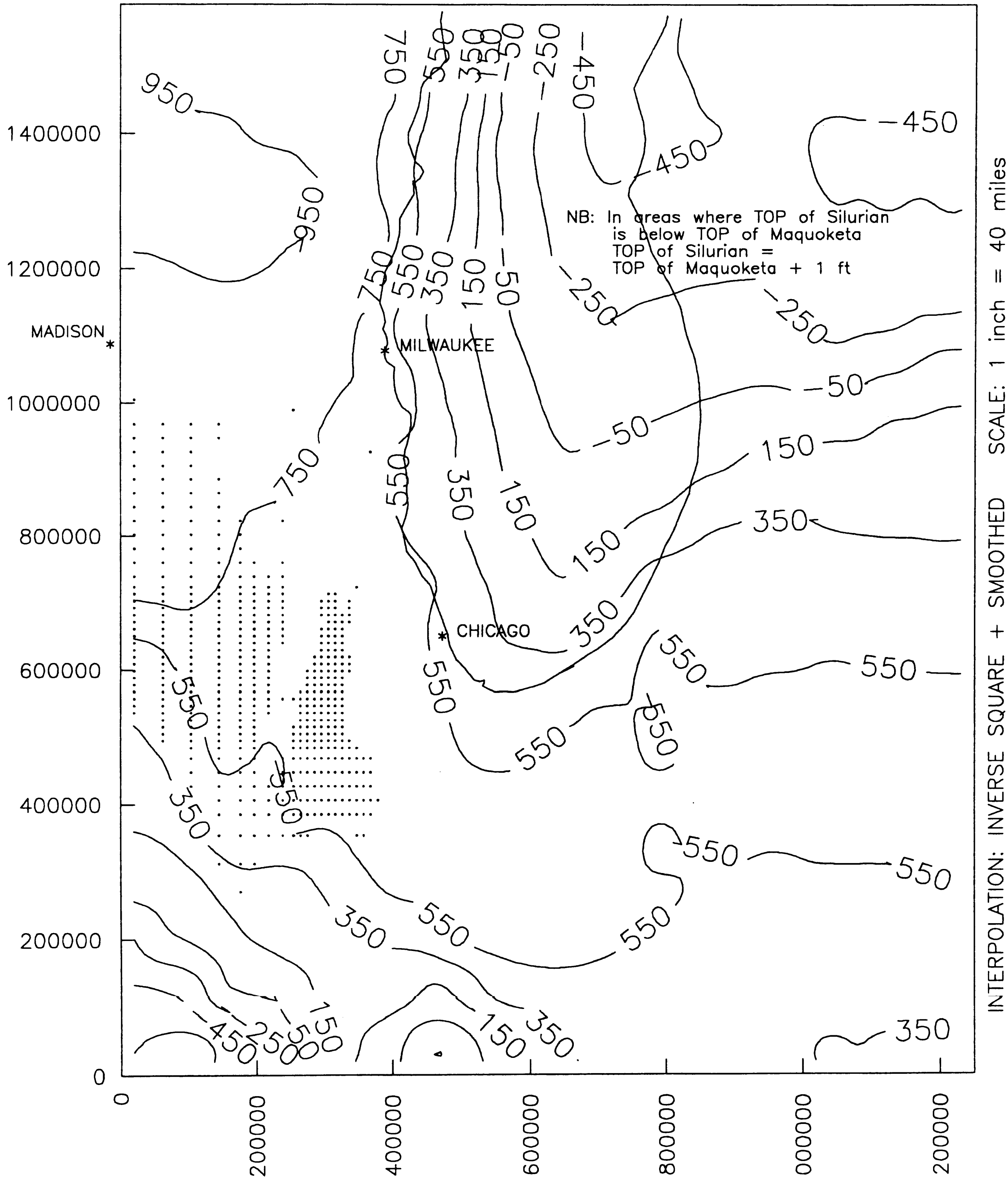
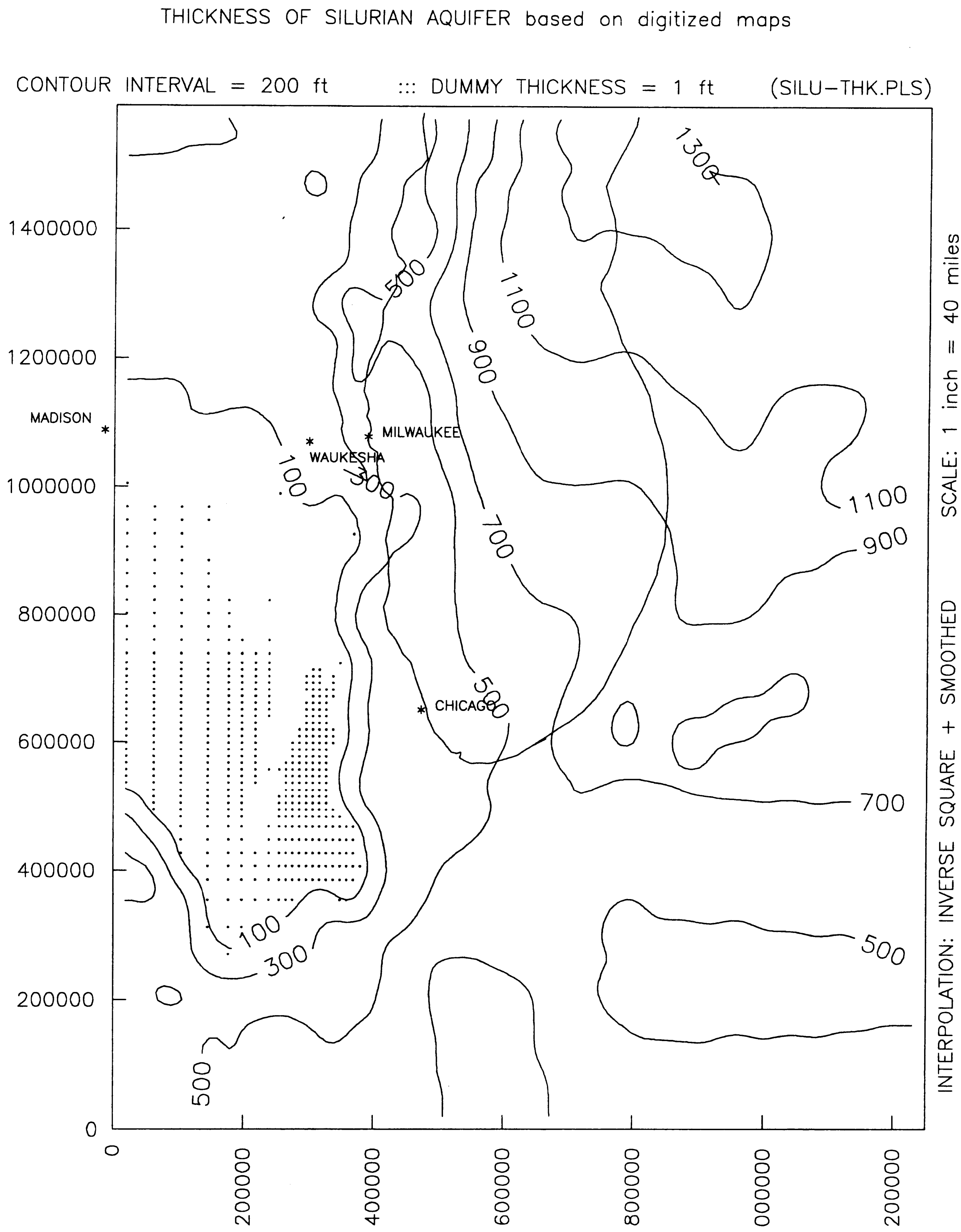


Fig. A-38



THICKNESS OF SILURIAN AQUIFER based on digitized maps
CONTOUR INTERVAL = 200 ft ::: DUMMY THICKNESS = 1 ft (SILU-THK.PLS)
SCALE: 1 inch = 40 miles
INTERPOLATION: INVERSE SQUARE + SMOOTHED
MADISON
MILWAUKEE
WAUKESHA
CHICAGO
1300
1100
900
700
500
300
100
0
200000
400000
600000
800000
1000000
1200000
1400000

Fig. A-39

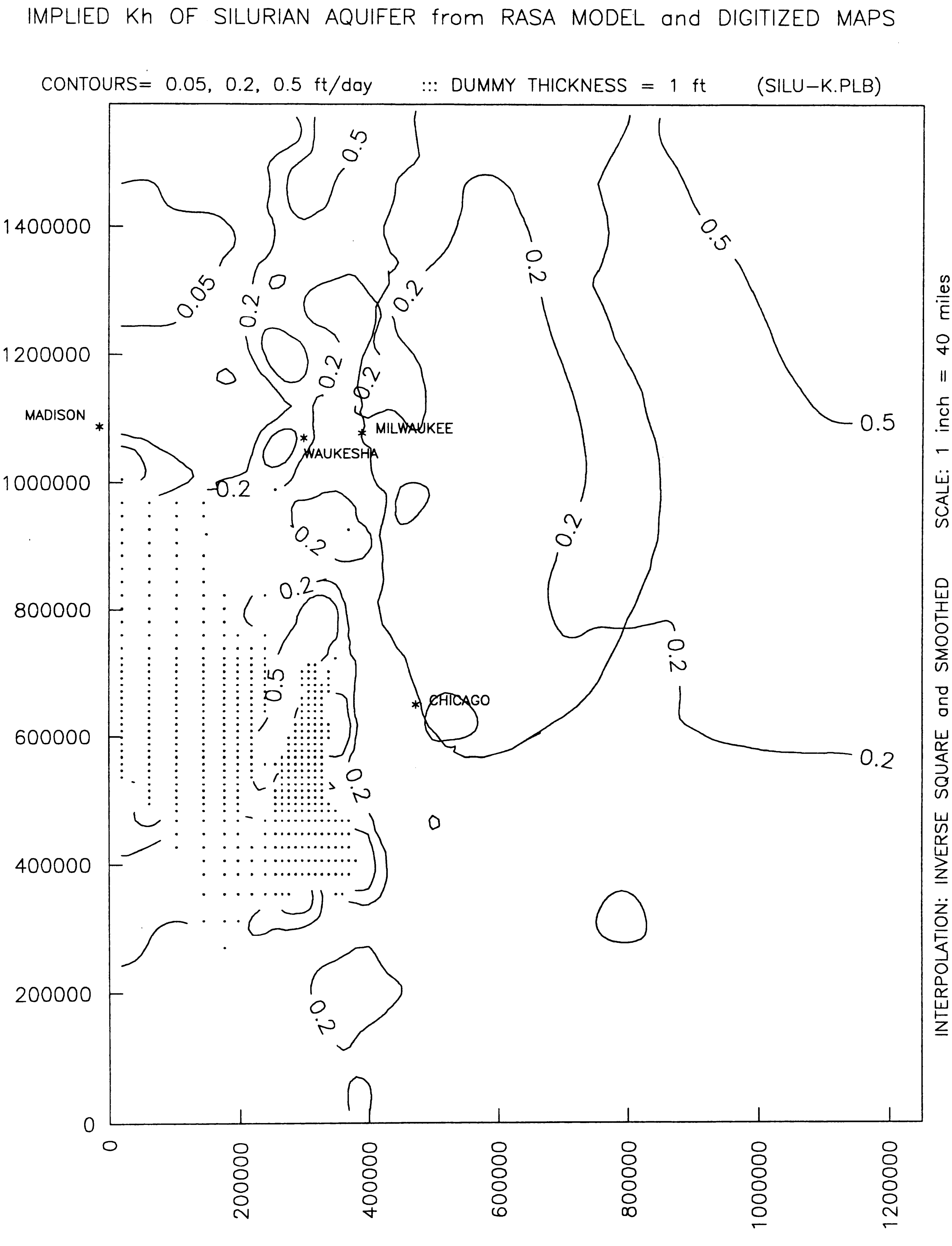

IMPLIED Kh OF SILURIAN AQUIFER from RASA MODEL and DIGITIZED MAPS
CONTOURS= 0.05, 0.2, 0.5 ft/day ::: DUMMY THICKNESS = 1 ft (SILU-K.PLB)
MADISON
WAUKESHA
MILWAUKEE
CHICAGO
0.05
0.2
0.5
1400000
1200000
1000000
800000
600000
400000
200000
0
200000
400000
600000
800000
1000000
1200000
INTERPOLATION: INVERSE SQUARE and SMOOTHED SCALE: 1 inch = 40 miles

Fig. A-40

LEAKANCE of MESOZOIC AQUITARD (PENN.+MISS.+DEVON.) based on digitized maps

LOGARITHMIC CONTOURS in 1/DAY (MESO-LK.PLS)

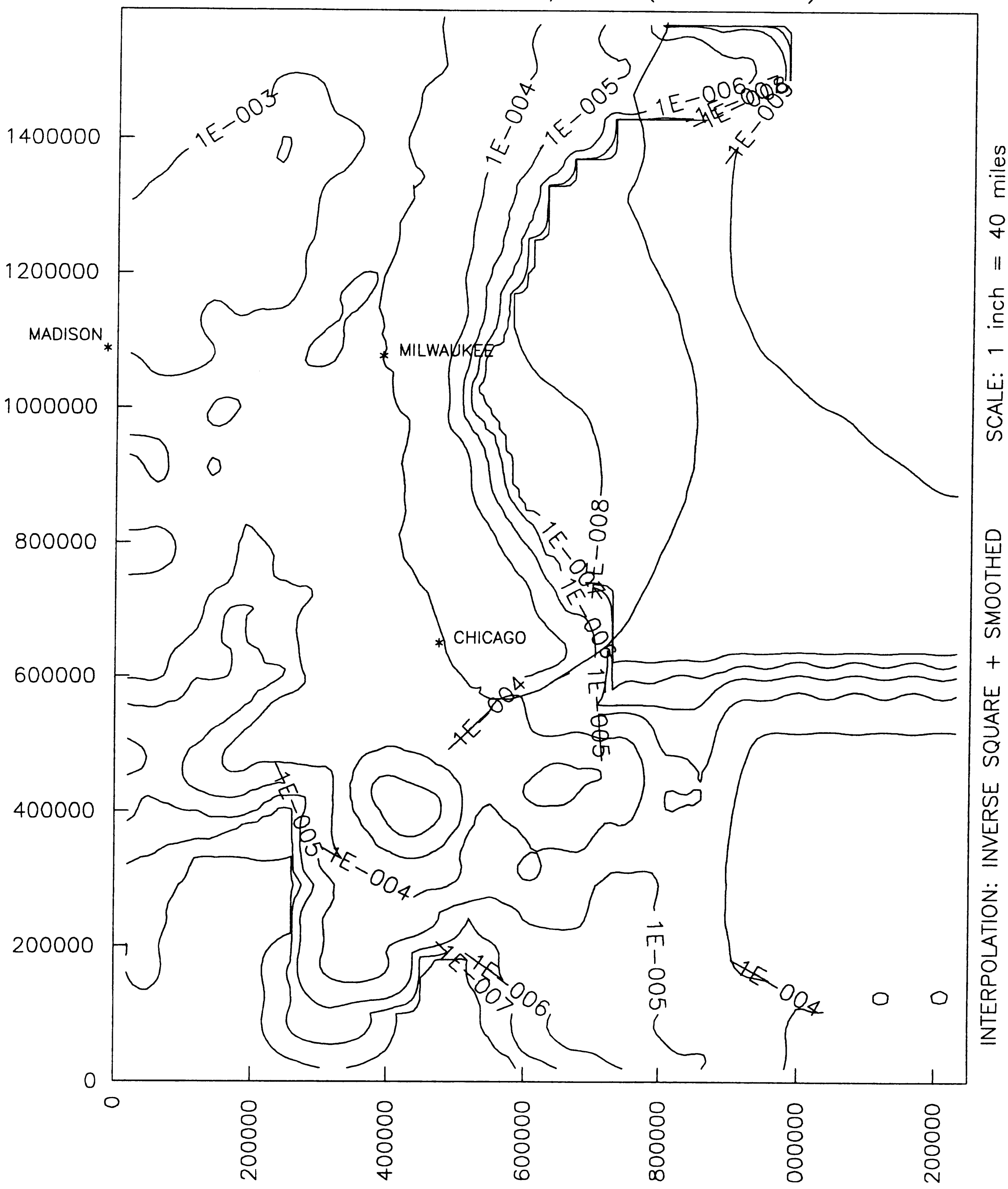


Fig. A-41

TOP of MESOZOIC AQUITARD = BOT OF UNLITHIFIED DEPOSITS based on digitized maps

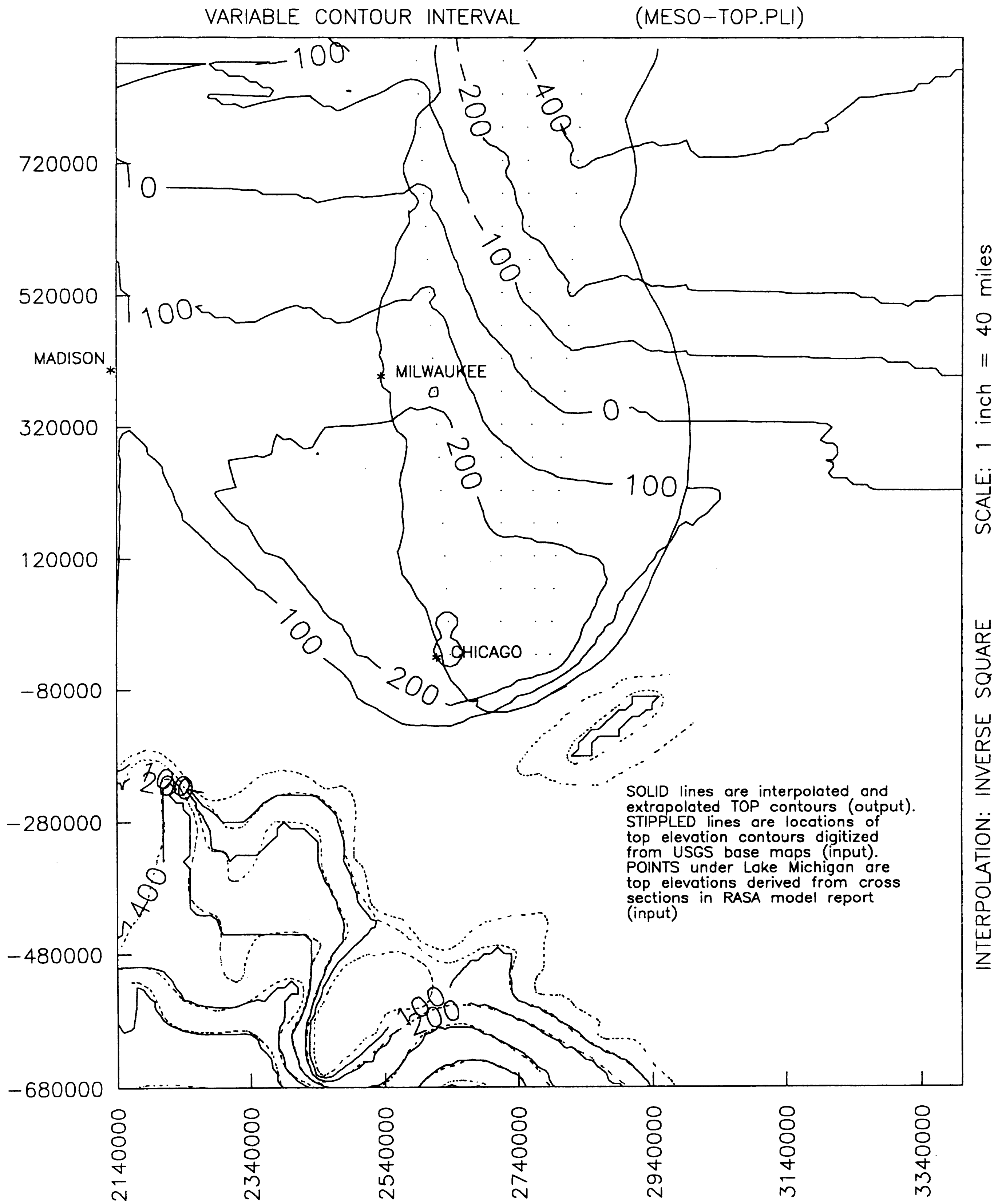


Fig. A-42

"CORRECTED" TOP of MESOZOIC AQUITARD = BOT OF UNLITHIFIED DEPOSITS

CONTOUR INTERVAL = 400 ft ::: DUMMY THICKNESS = 1 ft (MESOTOPC.PLS)

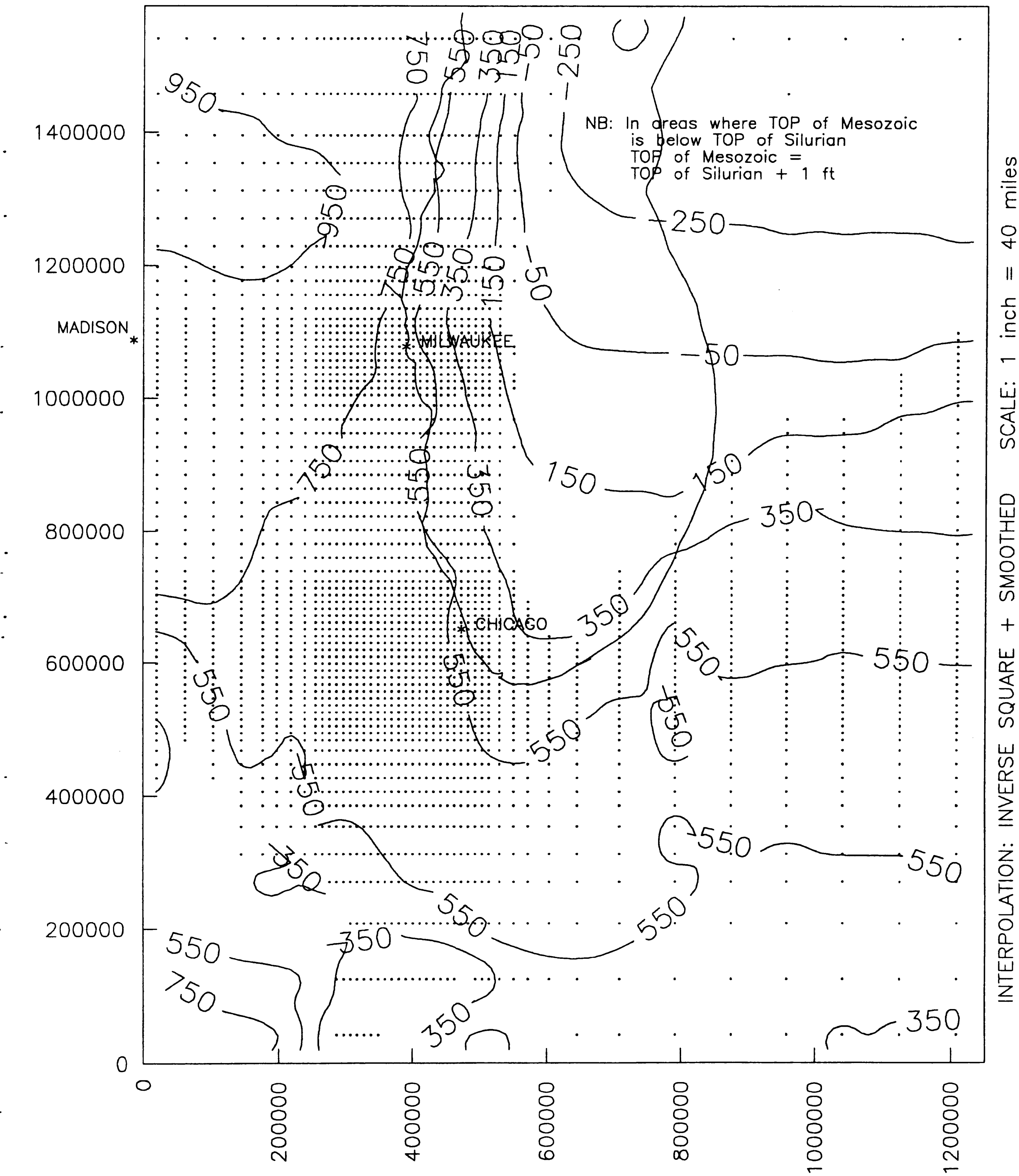


Fig. A-43

THICKNESS OF MESOZOIC AQUITARD based on digitized maps

CONTOUR INTERVAL = 200 ft ::: DUMMY THICKNESS = 1 ft (MESO-THK.PLS)

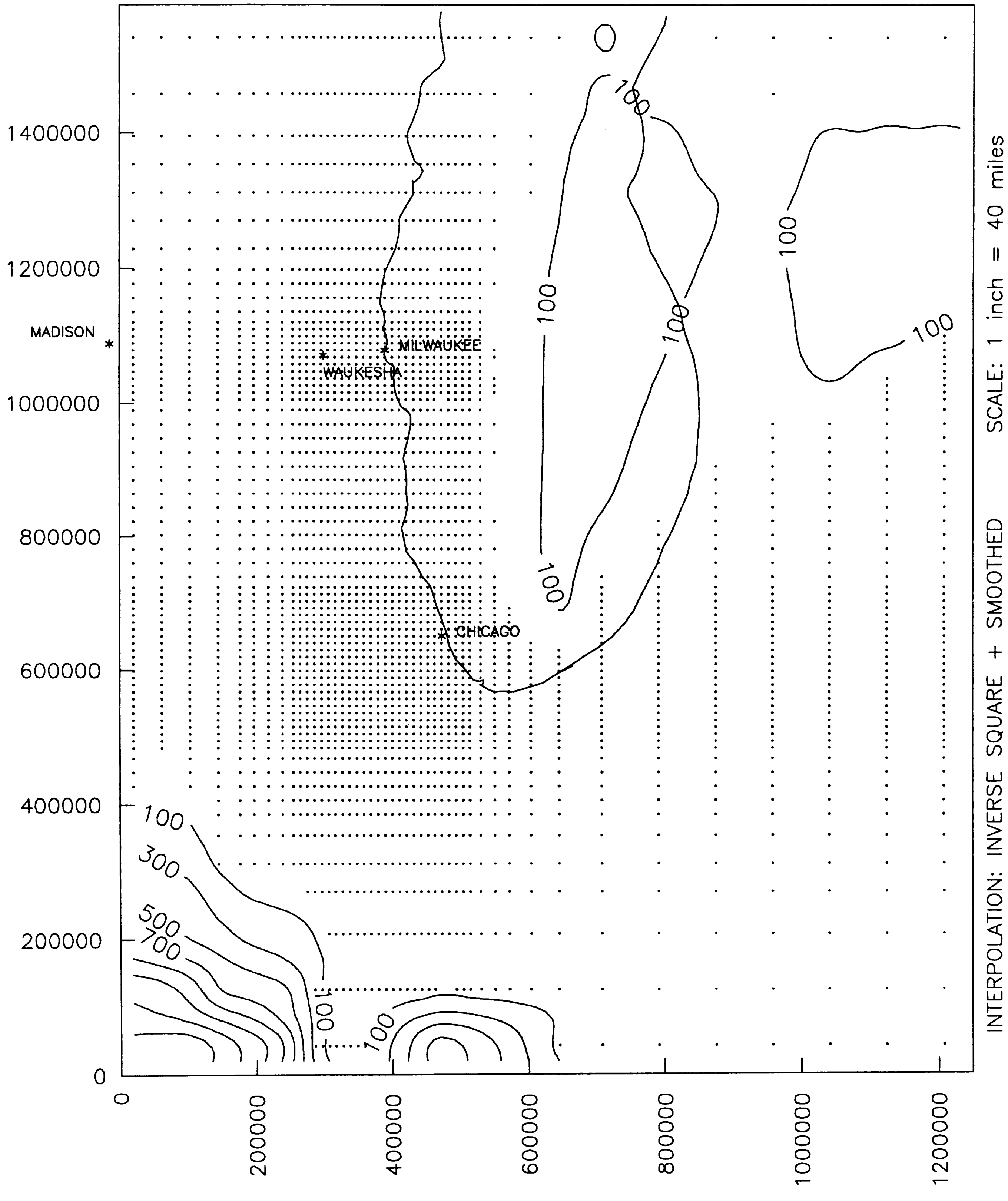


Fig. A-44

IMPLIED Kv OF MESOZOIC AQUITARD from RASA MODEL and DIGITIZED MAPS

CONTOURS = 5E-6, 1E-7 in ft/day ::: DUMMY THICKNESS = 1 ft (MESO-KV.PLS)

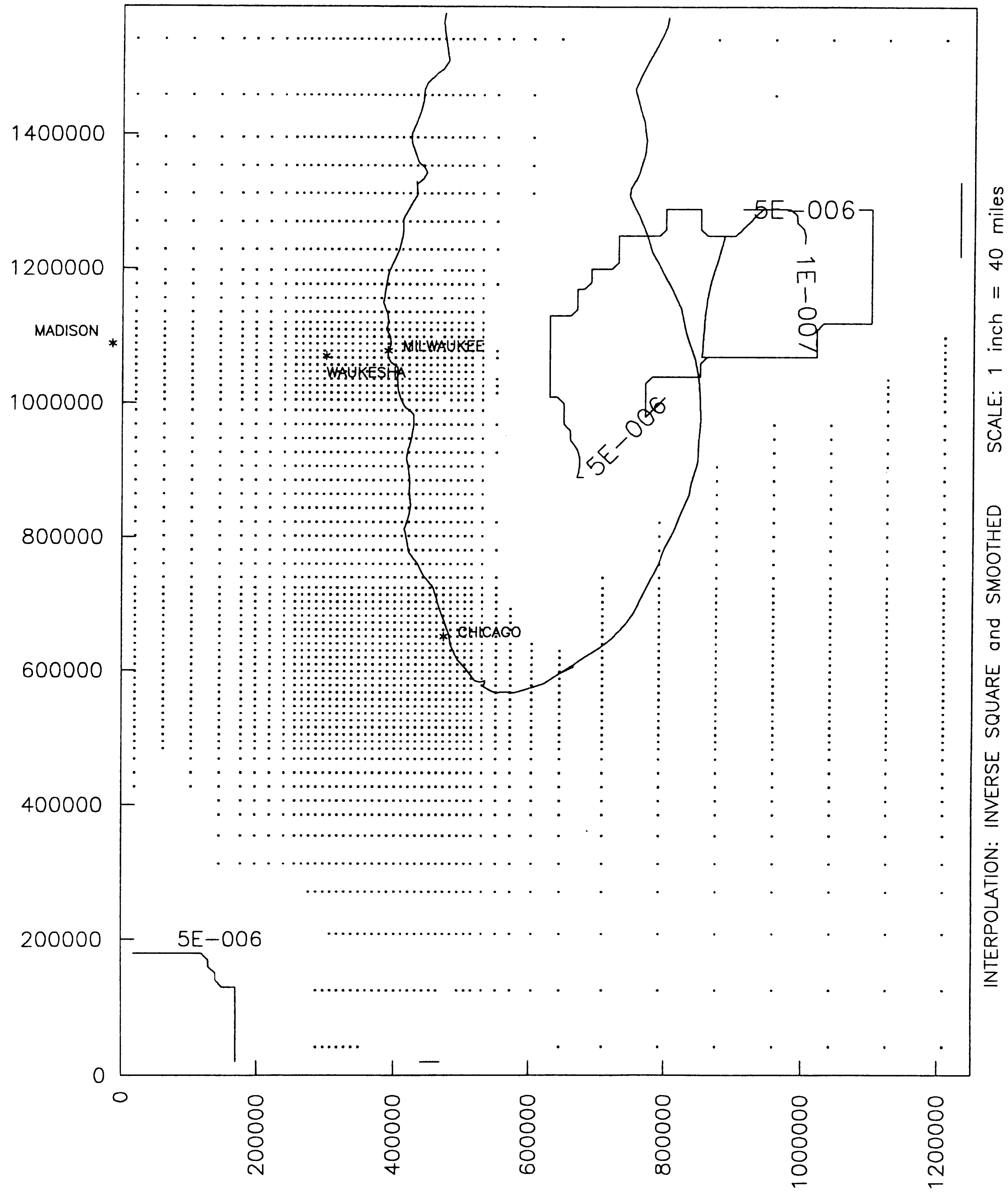


Fig. A-45

CORRECTED" TOP of UNLITHIFIED DEPOSITS to account for water table location

CONTOUR INTERVAL = 400 ft ::: DUMMY THICKNESS = 1 ft (UNCOTOPC.PLS)

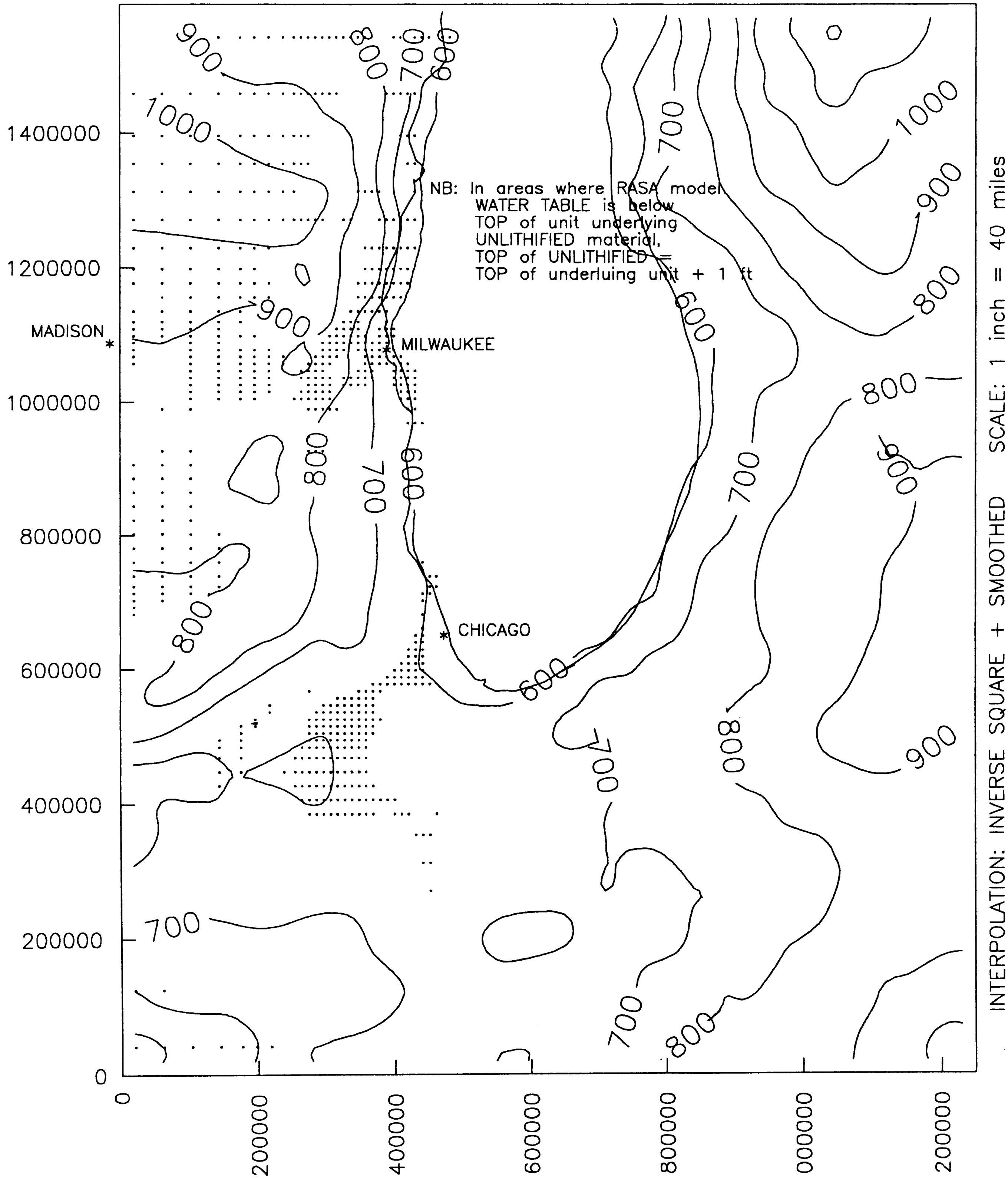


Fig. A-46

SATURATED THICKNESS of UNLITHIFIED DEPOSITS based on RASA MODEL WATER TABLE

CONTOUR INTERVAL = 200 ft ::: DUMMY THICKNESS = 1 ft (UNCO-THK.PLS)

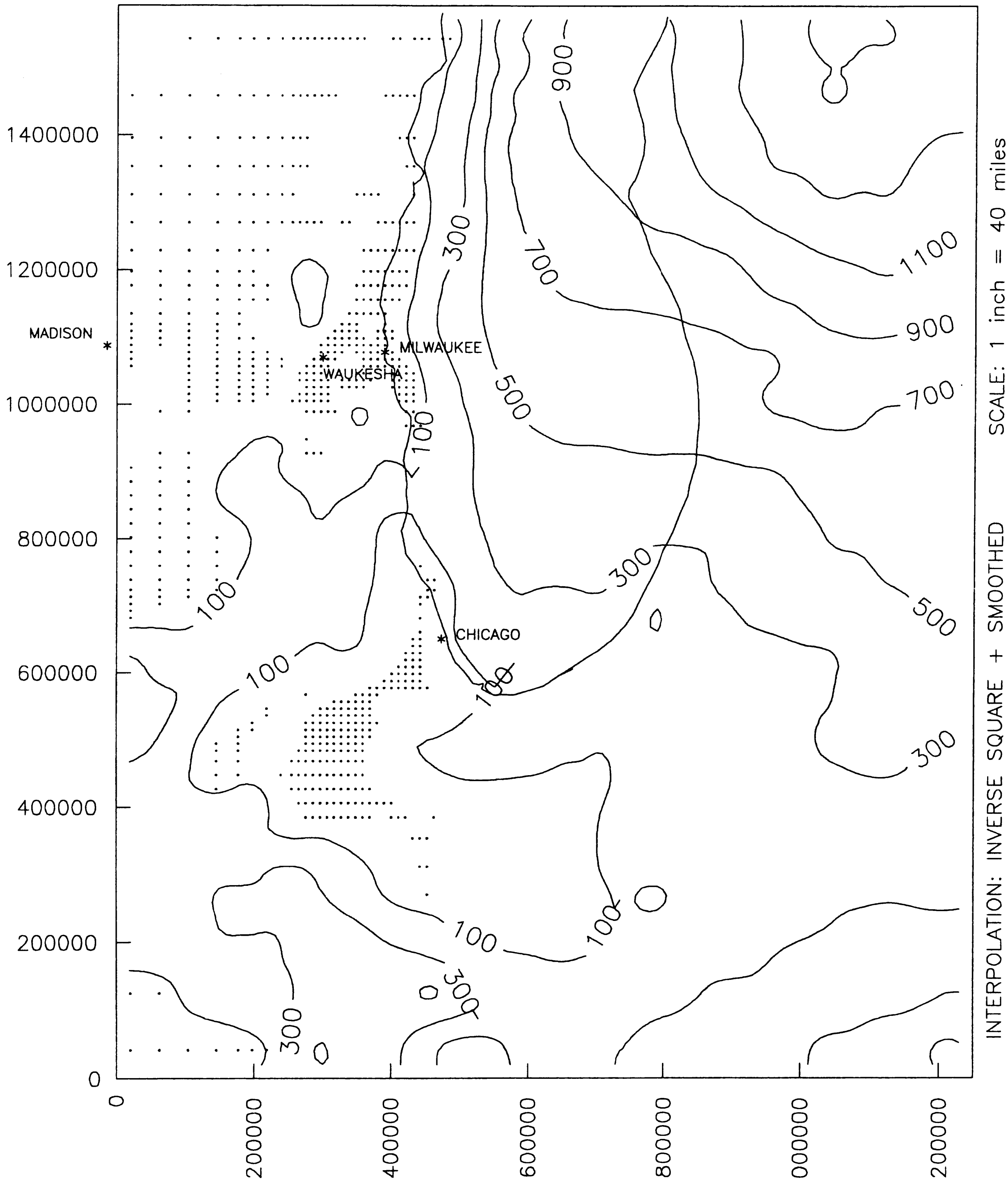


Fig. A-47

Part II

Literature Review for the Sandstone Aquifer System in Southeastern Wisconsin

TABLES

1. Summary of results for permeameter tests listed in Rodenback's (1988) study, which lie within the southeastern Wisconsin model study area.

2. Summary of results for permeameter tests listed in Simpkins' (1989) study, which lie within the southeastern Wisconsin model study area.

3. Summary results for permeameter tests listed in Simpkins' (1989) and Rodenback's studies which lie within the southeastern Wisconsin model study area

4. Summary of results for permeameter tests listed in Schulze-Makuch's (1996) study, which lie within the southeastern Wisconsin model study area.

5. Summary of permeameter test results for Chicago's deep tunnel project as listed in Harza Engineering Company (1975ab) which lie in southeastern Wisconsin model study area.

6. Permeameter test results for a series of studies that tested the Ordovician and Cambrian rock in or near the southeastern Wisconsin model study area.

7. Summary of results from slug/bail test noted in Rodenback's (1988) study, which lie within southeastern Wisconsin.

8. Summary of results from slug/bail tests noted in Simpkins' (1988) study that lies within southeastern Wisconsin.

9. Summary of results from slug/bail tests noted in Carlson's (in progress) study that lies within southeastern Wisconsin model.

10. Composite of results listed in 6, 7 and 8 (Carlson, in progress).

11. Summary of results for generally 10 ft packer tests conducted at the Haven's power plant site three miles north of Sheboygan, Wisconsin (Carlson, 1998a).

12. Summary of results for generally 20 ft packer tests conducted along the path of Milwaukee's deep tunnels (Carlson, in progress).

13. Summary of results for generally 40 ft packer tests conducted along the path of Chicago's deep tunnels collected from Harza Engineering Company (1975a) (Carlson, 1998a).

14. Summary of results for generally 15-20 ft packer tests conducted along the path of the Superconductor Super Collider, which lies near Auora, Illinois. Results from Kempton and others (1987ab) and Curry and others (1988) were compiled for the below results by stratigraphic unit (Carlson, 1998a).

15. Confidence of difference between adjacent unit's hydraulic conductivity using the T-test. The data set analyzed is M.M.S.D.'s packer test data.

16. Confidence of difference between adjacent unit's hydraulic conductivity using the T-test. The data set analyzed is Chicago's deep tunnel project packer test data

17. Summary of previous studies that determined hydraulic conductivity of various units by analyzing specific capacity tests.

18. Carlson's (1998b) hydraulic conductivity values determined for various units by analyzing specific capacity tests.

19. Confidence of difference of hydraulic conductivity between adjacent units determined by analysis of specific capacity data for adjacent units using the T-test method.

20. Previous works that included aquifer tests of various units in or near southeastern Wisconsin model region.

21. Summary of aquifer test results from Carlson (in progress) and Carlson (1998c) for a variety of units in Ozaukee, Milwaukee, and Waukesha counties that are from analysis of test results in generally unpublished documents of M.M.S.D. or the Wisconsin D.N.R. Note number of observations is larger than the number of tests because some of the tests are multiple-well-aquifer tests: 10 in Pleistocene materials, 5 in Devonian-Silurian and 35 in Silurian.

22. Summary of horizontal anisotropy of hydraulic conductivity results from analysis of multiple-well-aquifer tests conducted throughout southeastern Wisconsin.

23. Model results in terms of horizontal hydraulic conductivity and vertical anisotropy of hydraulic conductivity (Kh/Kv) for a variety of models of Pleistocene to Cambrian units in or near southeastern Wisconsin or northeastern Illinois.

24. Summary of point results for porosity from the combined data sets of Schulze-Makuch (1996) and Carlson (in progress).

25. Porosity for various unconsolidated units in southeastern Wisconsin for only a part of Rodenback's (1988) study area of eastern Wisconsin that lies in southeastern Wisconsin.

26. Porosity for various unconsolidated units in eastern Racine Co. and southern Milwaukee Co. in Simpkins' (1989) study area.

27. Porosity for various unconsolidated units in and around Milwaukee, Wisconsin. Results are from analysis of water content tests conducted by M.M.S.D.

28. Porosity values as determined from core-volume-displacement method for six major studies in southeastern Wisconsin.

29. Porosity values as determined from core-volume displacement method for Chicago's deep tunnel project (Harza Engineering Company, 1975a).

30. Porosity for a variety of studies completed in St. Peter Fm. down to Mt. Simon Fm. throughout southern Wisconsin and northern Illinois.

31. Bulk porosity determined in Carlson (in progress) from the examination of M.M.S.D. neutron logs.

32. Bulk porosity determined in Carlson (in progress) from the examination of M.M.S.D. density logs. The base reference for material density is that of limestone for Silurian units and Sinnipee units. For the Maquoketa Group base density used was that of limestone for Ft. Atkinson and shale for Brainard and Scales.

33. Bulk porosity determined in Carlson (1998d) from the examination of Chicago deep tunnel (sonic logs).

34. Confidence of the difference of porosity for adjacent units for the analysis of neutron logs in Milwaukee as listed in 31. Statistical analysis is completed by the use of a T-test.

35. Confidence of the difference of porosity for adjacent units for the analysis of sonic logs in Chicago as listed in 33. Statistical analysis is completed by the use of a T-test.

36. Average recharge rate for previous ground water models used for studies in or near southeastern Wisconsin.

37. Average baseflow "recharge rate" for watersheds that are at least partially in the southeastern Wisconsin groundwater model study area: and have at least 10 years of gaging records for Wisconsin watersheds and 5 years for Illinois watersheds.

38. Summary of analysis to determine Shale/clay content for various units from Lindwurm Member of the Milwaukee Fm. to St.Peter Fm. in the Ancell Group for M.M.S.D. natural gamma logs.

39. Summary of analysis to determine Shale/clay content for various units from Racine Fm. to Eau Claire Fm. for Chicago deep tunnel natural gamma logs (Carlson, 1998f).

40. Summary of analysis to determine Shale/clay content for various units from Racine Fm. to Mount Simon Fm. for Wisconsin Geological and Natural History Survey logs natural gamma logs (Carlson, 1998f).

41. Results of determining the confidence of difference for shale/clay content for the various pairs of adjacent units listed in 38. This M.M.S.D. natural gamma data is from borings in Milwaukee, Wisconsin.

42. Result of determining the confidence of difference for shale/clay content for the various pairs of adjacent units listed in 39. This Chicago deep tunnel natural gamma data are from borings in Chicago, Illinois.

43. Result of determining the confidence of difference for shale/clay content for the various pairs of adjacent units listed in 40. This WGNHS natural gamma data is from borings in Kenosha, Milwaukee, Racine and Washington Counties, all of which are in the southeastern Wisconsin model region.

FIGURES

Executive Summary

After examination of existing data there are several general statements that can be made about the hydrogeology of the southeastern Wisconsin groundwater model area (fig. 1):

1. In southeastern Wisconsin the abundance of available hydraulic conductivity data decreases greatly below Silurian rock. In fact, below the Galena-Platteville (Sinnipee) there are very few formation specific values of hydraulic conductivity.

2. In northeastern Illinois the abundance of available hydraulic conductivity data decreases greatly below the base of the Platteville Fm. In fact, below the St.Peter Sandstone there are very few formation specific values.

3. In general for the clastic units of the St. Peter Fm. through the Mt. Simon Fm., the units become thicker and finer grained from north to south and west to east across the southeastern Wisconsin groundwater model area.

4. It appears that from southeastern Wisconsin hydraulic conductivity data the following stratigraphic units or combinations of units have significantly different hydraulic conductivity from adjacent unit(s): Racine Fm., Manistque Fm., Mayville Fm., Maquoketa Group, Galena-Platteville Fms. and St. Peter Fm.

5. It appears that from hydraulic conductivity and/or clay content data the following stratigraphic units should be the focus of study to see if they are significantly different from adjacent unit(s): Prairie du Chien Group, Jordan Fm., St. Lawrence Fm., Tunnel City Group, Wonewoc Fm., Eau Claire Fm. and Mt. Simon Fm. In fact given Mt Simon's great thickness, over 1000 ft. (330m), and variable clay content and possible variable hydraulic conductivity, it should be examined to see if there are layers within the Mt. Simon that are significantly different in terms of their hydraulic conductivity.

Hydraulic Conductivity

There are six different techniques that have been used to determine hydraulic conductivity of stratigraphic units within southeastern Wisconsin; from smallest size of sample tested to largest size of sample tested they are: permeameter tests, slug tests, packer tests, specific capacity tests, aquifer tests, and ground water models. The largest of these data sets is specific capacity data, which number in the 1000's for some of the units. Data sets of 100's by unit exist for permeameter tests, slug tests and packer tests. Generally aquifer tests are for a composite of Silurian, Ordovician-Cambrian or unconsolidated units. The smallest data set is groundwater models. However, for this study they probably yield the best values for starting horizontal hydraulic conductivities (Kh), vertical hydraulic conductivities (Kv), and vertical anisotropy of hydraulic conductivities (Kh/Kh) for development of the southeastern Wisconsin groundwater model. In general, hydraulic conductivity values increase with the increasing volume of a sample examined in the list of tables that follow. This is why use of previous model results is probably the best for initial values used in the development of this study's model.

Permeameter Tests

There are two different types of permeameter tests, constant head and falling head. Both of these tests are conducted on small samples, in the laboratory, that are generally a few inches in length and diameter. In general, constant head permeameter tests are conducted on unconsolidated material or rock, which has larger values of hydraulic conductivity. On the other hand falling head tests are conducted on rock or unconsolidated material which has smaller values of hydraulic conductivity (Fetter, 1980)

For the constant head permeameter test the head is held at a constant level, ideally no more than one half of the length of the sample, and water is driven through the sample at a constant rate. As a result the simple equation that follows can be used to calculate the resulting hydraulic conductivity (Fetter, 1980):

$$K = VL/Ath$$

Where V is the volume of water discharging in time t, L is the length of the sample, A is the cross-sectional area of the sample, h is the hydraulic head and K is the hydraulic conductivity.

For the falling head permeameter test as the name suggests the head is changing throughout the test. The resulting equation is somewhat more complex than the one for the constant head test, see the equation below for calculating K from the results of a falling head permeameter test:

$$K = [(d_t^2 L)/(d_c^2 t)]\ln(h_o/h)$$

Where h_o is the head at the start of the test, h is the head at time t, t is the length of time of the test, d_t is the diameter of the tube the head is measured in, d_c is the diameter of the sample and K is the hydraulic conductivity (Fetter, 1980).

For studies in southeastern Wisconsin model area both types of permeameter tests have been conducted. For unconsolidated materials, Rodenbeck's (1988) data are about 28% constant-head tests and 30% falling-head tests; for the remainder of tests the type of permeameter test was not noted. For unconsolidated materials, Simpkins' (1989) data are about 37% constant-head tests and 41% falling-head tests; for the remainder of tests the type of permeameter test was not noted. For rock the share of falling-head tests is larger. For example, Schulze-Makuch's (1996) data are about 65% falling-head tests and only 35% are constant-head tests. Schulze-Makuch (1996) conducted falling-head tests whenever the hydraulic conductivity was less than 8.6×10^{-4} m/day.

There are seven major studies of hydraulic conductivity in southeastern Wisconsin using permeameter tests and two in nearby northeastern Illinois, see Tables 1 to 5. These tests are usually falling head tests but also include constant head tests as well. Two of these studies are of unconsolidated materials (Rodenbeck, 1988; and Simpkins, 1989) and seven are of Devonian-Cambrian rock (Harza Engineering Company, 1975a,b; Milwaukee Metropolitan Sewerage

District, 1981, 1984ab, and 1989; Schulze-Makuch, 1996). In addition, a number of smaller studies that usually tested one or two formations within Silurian-Cambrian rock in or near the study area are noted in Table 6 (see Figure 2 for location of studies). In general, permeameter test results are concentrated in Silurian-Ordovician units, that is from Racine Fm. down to St Peter Fm., see Figure 3.

Slug Tests

Slug tests are field tests developed to test low to moderately high hydraulic conductivity material in-situ by either the addition or withdrawal of a known amount of water and then observe the change in water level through time in response to the impact of the slug of water (Fetter, 1980, Domenico and Schwartz, 1990). For studies in southeastern Wisconsin rising head tests, often bail tests, are the most common: 81% of the tests noted by Rodenbeck (1988), 76% tests noted by Simpkins (1989), only about 50% of tests noted by Carlson (in progress)

The resulting data is plotted on a change in head versus time plot where the ratio of change in head (H) versus the original change in head (H_o) is plotted along the log axis of a semilog plot while the time is plotted on the linear axis of the semilog plot for both the Hvorslev (1951) technique and Bouwer and Rice technique used for analysis of resulting data. These two techniques are by far the most commonly used in analysis of slug tests results in southeastern Wisconsin studies. About 55% of slug tests were analyzed by the Hvorslev (1951) technique, 33% of slug tests were analyzed by the Bouwer and Rice (1976) technique and the remaining 12% the technique used for analysis is unknown except for 2 tests (0.4%) analyzed by another technique.

The equation used for calculating the hydraulic conductivity by the Hvorslev (1951) technique is shown below:

$$K = [R^2/(2L(t_2 - t_1))]\ln(L/R)\ln((H_1/)/(H_2/H_o))$$

Where K is hydraulic conductivity, R is the radius of casing, L is the length of screen, H_o is the initial change of head at the start of the test, H_1 and H_2 are the change of head at later times, t1 and t_2 is time after the start of the slug test. The Hvorslev (1951) technique is the only technique directly used by Carlson (in progress) for analysis of M.M.S.D. piezometer sensitivity (slug tests) given these tests were short in length of time, typically less than 60 minutes. In addition Carlson (in progress) used the Hvorslev method for analysis of bail tests on UWM piezometers. Altogether these two sets of data account for about 150 slug test results.

The other major technique for analysis of slug tests included in Simpkins (1989) and Carlson (in progress) is the Bouwer and Rice (1976) technique. For Bouwer and Rice (1976) the below equation is used to calculate hydraulic conductivity:

$$K = [(R^2 \ln(R_e/r_w))/2Lt]\ln(H_o/H_t)$$

Where K is hydraulic conductivity, L is the length of screen, H_o is initial change of head at time equal to zero, H_t is change of head at time greater than zero, R_e is effective radius over which H_t is dissipated, r_w is well radius (casing plus filter pack for a borehole), R is radius of casing.

The most common field test in southeastern Wisconsin for hydraulic conductivity of unconsolidated materials is the slug test. There are three studies noted below, Tables 7 to 10 which include large numbers of slugs by compiling data from existing hydrogeologic studies often associated with placement of landfills or other structures or groundwater monitoring associated with chemical spills or leaky underground storage tanks that may impact groundwater, see Figure 4 for location of slug test sites.

Packer Tests

In general, a packer test involves isolating a given section of rock by inflating a series of packers at either end of the section to be tested. Water is then pumped into the section of interest only. Pressure is measured during the interval of the pumping. Then by using the below equation it is possible to calculate hydraulic conductivity (Rovey and Cherkauer, 1994).

$$K = 0.0679\ Q[\ln(L/r)/H2\delta L]$$

Where K is hydraulic conductivity in cm/s, Q is flow rate in gpm, H is differential pressure in PSI, L is length of packed off region in ft., r is radius of borehole in ft. and 0.0679 is a conversion factor which allows K to be expressed in cm/s.

Generally M.M.S.D. conducted several tests at each packed off interval for time intervals of 1, 2, and 4 minutes after which a geometric mean of results was calculated and used as the single value noted for the given packed off interval. Chicago deep tunnel packer tests were generally 5 minutes in length and they typically conducted three tests at each site, 3, 5 and 8 minutes (Harza Engineering Company, 1975b). Packer test length of time was not noted for the Haven site tests. The length of packer test was the longest for Superconductor Super Collider (SSC) project tests, 15 minutes (Schumacher, 1990). In general, five tests were conducted at each interval at typical pressures of 35, 70, 100, 70 and 35 PSI (Schumacher, 1990). As with the M.M.S.D. data, the geometric mean was calculated for inclusion in the data set for Table 14.

The packed off interval was usually about 15-20 ft (4.5-6.1 meters) for M.M.S.D. packer tests and SSC packer tests (Schumacher, 1990; Carlson, in progress) , while for Chicago's deep tunnel project test intervals were generally about 40 ft in length and for the Haven's power plant study packer tests intervals were generally about 10 ft in length (Harza Engineering Company, 1975a; Carlson, 1998a).

In general, hydraulic conductivity was attributed to a single unit if either the whole packed off region lied within a single unit or if it is a highly conductive unit then it was acceptable if over 75% of the packed off region was the highly conductive unit. In general, most of the tests meet the first criteria.

There are four major sets of packer test data within or close to southeastern Wisconsin, Tables 11 to 14 see Figure 5 for location of test studies. Packer test results include only Silurian and Ordovician units, Racine Fm. down to St. Peter Fm., see Figure 6. This data is along the paths of both Chicago and Milwaukee deep tunnels and along the path of Superconductor Super Collider west of Chicago and near the Haven's power plant near Sheboygan, Wisconsin. In general, the Wisconsin sites are tests mainly from Silurian or Devonian rock while Illinoian sites are tests mainly from Ordovician rock.

As can be seen in Tables 11 to 14 there is a wide range of geometric mean values of hydraulic conductivity for the various Devonian through Ordovician units, with a high value of 0.59 m/day for the Thiensville Fm in Milwaukee area to a low value of 5.6×10^{-4} m/day for the Lindwurm member of Milwaukee Fm in the Milwaukee area. The question for this study is: what units are significantly different in terms of their hydraulic conductivity? With this in mind using a T-test determine the confidence of difference of hydraulic conductivity between each adjacent pair of units for the two largest data sets, data for Milwaukee's and Chicago's deep tunnel projects, see Tables 15 and 16.

Specific Capacity Tests

There is a large body of specific capacity data present in many areas because usually when a private household well is constructed there is not a full aquifer test but a simpler specific capacity test completed. These tests generally include a few hours of pumping where only a yield and maximum drawdown are noted (Fetter, 1994). For this study one can see that previous workers have analyzed about 6400 specific capacity tests in or close to the southeastern Wisconsin model region. However, only three workers have included analysis on most of these tests: Carlson (1998b) about 3100 tests, Gonthier (1975) about 800 tests and Young and Batten (1980) about 550 tests.

The method used for analyzing specific capacity tests in Carlson (1998b) and often by other workers (Carmen, 1988; Wehrheim, 1989; Clite, 1992; Pearson, 1993; and Schulze-Makuch, 1996) is that developed by Bradbury and Rothschild (1985). The method is a refinement on an earlier method developed by Theis (1963) which did not take into account well loss and for partially penetrating wells (Fetter, 1994). The equation that Bradbury and Rothschild (1985) developed to calculate transmissivity from specific capacity data is shown below:

$$T = \{Q/(4ð(S - S_w))\}[\ln((2.25Tt)/(r_w^2\_)) + 2s_p]$$

Where T is transmissivity, S is drawdown, S_w is well loss, t is pumping time, r_w is radius of well, _ is the storativity, s_p is partial penetration factor. Transmissivity is on both sides of the equation so the solution involves an iterative process that requires a first guess at transmissivity (T). Convergence generally occurs within three to four iterations. However, for the spreadsheet developed for solution by Carlson (1998b) analysis included seven iterations to be sure of the closure on a solution.

Generally in most studies in southeastern Wisconsin the resulting transmissivity or hydraulic conductivity is assigned to just the Silurian dolomite. However, for Carlson (1998b) hydraulic conductivity is determined for a specific unit. This involves selecting only a part of the specific capacity tests in a given area. This is done by first determining the geologic unit that is the top of the rock by examining geologic maps developed by Rovey (1990), Gonthier (1975) or Mai and Dott (1985) depending on the unit considered: Milwaukee Fm. down to St. Peter Sandstone. Second, from isopach maps in Rovey (1990) or Mai and Dott (1985) or developed from Wisconsin Geological and Natural History Survey unpublished geologic logs there is a determination of the thickness of the top unit in an area of interest. Third, select only specific capacity tests, which have a borehole length generally less than 80% of the thickness of the unit of interest. This means that generally the small private wells in an area are used. Fourth and last, calculate transmissivity using the Bradbury and Rothschild (1985) method and divide result by unit thickness to yield hydraulic conductivity, see Table 18 for results from Carlson (1998b). As a final note for values from: LeRoux (1957), Walton and Csallany (1962), Csallany and Walton (1963), Prickett and others (1964), Cline (1965), Hoover and Schicht (1967) and Hutchinson (1970) were calculated from their raw specific capacity data provided. Generally it was assumed that the borings were fully penetrating except for Walton and Csallany (1962) and Csallany and Walton where unit thickness was determined from isopach maps in Csallany and Walton (1963) or Viscosky (1985) or examination of Chicago Deep Tunnel borings in Harza Engineering (1975a).

In general, in the past most workers have considered specific capacity tests as dolomite only, but more recently studies have considered specific capacity tests by unit or groups of units. Table 17 is a summary list of results before Carlson (1998b) while Table 18 is a summary list of results from Carlson (1998b). In general most of the solutions, ~75%, for hydraulic conductivity were determine with the use of the Bradbury and Rothschild (1985) method. See Figures 7a, b, and c for the location of various specific capacity studies in and near southeastern Wisconsin model area. In general, because specific capacity tests which test single units are from shallow domestic wells only units from Racine Fm. down to St. Peter Fm. are included in results noted in Table 18 and Figure 8.

As with packer test results there is a wide range of geometric mean values for the specific capacity data as noted in Table 18, range is 1.7 orders of magnitude. Again as with packer test data there is a check to see which units can be considered statistically significantly different in terms of their hydraulic conductivity, see Table 19.

Aquifer Tests

For this study aquifer tests were analyzed for determination of hydraulic conductivity (K) within a variety of units in southeastern Wisconsin and northeastern Illinois. Given the generally short tests, a few hours or less, it was decided that only basic Cooper and Jacob (1946) and Theis (1935) methods should be used for the determination of K values. For the Cooper and Jacob (1946) method the drawdown data is plotted on semi-log paper with time on the log axis and drawdown on the linear axis. Using the below equation can complete calculation of transmissivity:

$$T = 2.3Q/(4\eth m)$$

Where Q is pumping rate, m is slope of line noted as change in drawdown per log cycle and T is transmissivity. Finally K is calculated by dividing transmissivity by unit thickness or openhole length, assuming the openhole is open to a single unit. When using the Theis (1935) curve matching technique for the determination of transmissivity, it is necessary to plot drawdown data on log-log paper where one axis is time from the start of drawdown or recovery and the other axis is the value of drawdown or recovery from the start of the test. Then the field curve is matched with the Theis (1935) type curve. Then using an arbitrary match point the transmissivity can be calculated. The only requirement for a match point is that it must fall on both the type curve plot and the field data plot. If this is true then transmissivity can be calculated using the below equation:

$$T = QW(u)/4\eth s$$

Where Q is pumping or recovery rate, W(u) is the Theis well function value for type curve match point, s is drawdown or recovery from field curve match point and T is transmissivity (Theis, 1935). Again as with the Cooper and Jacob (1946) method as described before, K can be calculated by dividing transmissivity by the unit thickness. After the two values of K were calculated a geometric mean was calculated and included within Carlson's (in progress) data set. Sources for the various aquifer tests are unpublished data sets of M.M.S.D. (1980 to 1994), U.S.G.S. (1994) and a few Environmental Rehabilitation Projects (ERP) studies.

Generally, aquifer tests were analyzed by Carlson (in progress) using both the Theis (1935) and Cooper and Jacob (1946) methods. Another method used by M.M.S.D. (1981a) and Schulze-Makuch (1996) to analyze aquifer tests was the Hantush, (1956) method. This method is similar to the Theis (1935) method except it includes leakage through a confining unit and allows the determination of vertical hydraulic conductivity of overlying confining beds.

Lastly there are a limited number of multiple-well-aquifer tests analyzed by Carlson (in progress) and Jansen (1995) to determine direction of maximum transmissivity and the magnitude of anisotropy of horizontal transmissivity (hydraulic conductivity). The determination of horizontal anisotropy requires at least three observation wells at different azimuths from the pumping well. In general, for Carlson's (in progress) study of multiple-well-aquifer tests in Mequon, Wisconsin each test has between three and seven observation wells which have transmissivity determined by both the Theis (1935) and Cooper and Jacob (1946) methods as well as a geometric mean of these two results which was used as the transmissivity at that observation well. The method developed by Maslia and Randolph (1987) was used to solve a matrix of information that included transmissivity at observation wells and the distance east or west and distance north or south of the pumping well for each of the observation wells. Jansen (1995) determined maximum and minimum transmissivity plus the orientation of the transmissivity ellipse using the Hantush and Thomas method (Kruseman and Ridder, 1991).

Aquifer tests have been completed in all units: unconsolidated materials, Silurian-Devonian dolomite and the Ordovician-Cambrian sandstone, Tables 20 and 21, see Figures 9a ,b and c for location of aquifer tests. However, the vast majority are completed in Silurian-Devonian because of the ease of accessing this aquifer versus the Ordovician-Cambrian. Typical aquifer depths of wells completed in the Silurian-Devonian and Ordovician-Cambrian are 300 ft. to 500 ft. to over 1500 ft respectively. In general, the unconsolidated materials are not tested because as a source of water they are relatively unreliable. The vast majority of aquifer tests are single well tests, for cost reasons, but occasionally multiple-well-aquifer tests are conducted. These can provide information on horizontal anisotropy of transmissivity, which is noted in Table 22.

Ground Water Models

In general, when modeling there is an effort to match model generated results with observations by adjusting various properties of the model. The properties that are typically adjusted are recharge rates and distribution and the hydraulic conductivity both horizontal and vertical. For most models the exercise is to match model generated water levels with observed water levels. If one is fortunate there is the possibly of matching model generated fluxes into or out of rivers or lakes with observed fluxes into or out of rivers or lakes. The addition of flux data will increase the confidence of the model solution as being physically reasonable and probably closer to reality (Anderson and Woessner, 1992).

For most modeling projects there is a calibration of a model to match model water levels and fluxes with observed fluxes and water levels. This involves reducing the difference between model generated and observed values to a minimum while still using reasonable fluxes and hydraulic conductivities. Often local aquifer test results can be used as a reference for reasonable hydraulic conductivities while baseflow study results or climatological data can provide a set of values possible for recharge.

If one is fortunate there is a second set of conditions in which to verify the model against. Here the fluxes and heads are different from the calibration conditions due to additional or less pumpage or other withdrawals of groundwater. The verification usually involves refinement of calibration results to determine values of hydraulic conductivity, which generate reasonable, results for both calibration and verification conditions. A successful calibration and verification of a model usually indicates the model results are probably a more correct determination of hydraulic conductivities than if only calibration is possible.

There are two general types of groundwater models used: finite-difference and finite-element. Of the 19 models developed within the southeastern Wisconsin region only Plomb (1989), M.M.S.D. (1992) and Camp Dresser and McKee (1995) are finite-element models all of the rest are finite-difference models. In addition, except for Prickett and Lonnquist (1971), McLeod (1975ab), Young (1976), Ladwig (1981) and Rovey (1983) all of the finite-difference models used MODFLOW (MacDonald and Harbaugh, 1984, and 1988) the most widely used finite-difference model in the world (Osiensky and Williams, 1997).

For the studies of southeastern Wisconsin models range in size from small cross-sections of Camp Dresser and McKee (1995) that cover less than one square kilometer or Carlson (in progress) that cover less than five square kilometers to Mandle and Kontis' (1992) model that includes tens of thousands of square kilometers covering all of southeastern Wisconsin and northeastern Illinois. For southeastern Wisconsin most of the models include only a calibration. However, verification was completed by Rovey (1983), Nader (1990), Clite (1992), Mueller (1992) and for two of three models by Carlson (in progress)

For this section the horizontal hydraulic conductivity is noted for each unit considered in the model and where present the vertical anisotropy of hydraulic conductivity (Kh/Kv) is also noted, see Table 23. For locations of models see figures 10a, b and c.

Porosity

Porosity has been determined in the southeastern Wisconsin groundwater model area by four different methods: point-count analysis, water-content analysis, core volume displacement analysis and geophysical log analysis. The location of these studies can be seen in Figures 11 and 12.

Point-Count Analysis

Point-count analysis involves counting points on a thin section of rock and noting whether the point is a pore or rock in this case. There are only two studies at this scale (Schulze-Makuch, 1996; Carlson, in progress). Typically about 1000 to 2000 points on each slide were examined. On average for the 15 slides examined by Schulze-Makuch 1490 points were examined, while on the average for the 12 slides examined by Carlson (in progress) 1914 points were examined.

Water-Content Analysis

Porosity for unconsolidated units was derived from conversion of water content values available from data collected for various M.M.S.D. studies (MMSD, 1981, 1984ab, 1989). Water content can be calculated using the below equation (Bouwer, 1978)

$$W_c = (W_w - W_d)/W_d$$

Where W_w is the wet weight of a sample, W_d is the dry weight of a sample and W_c is the water content value of a sample. For this study water content values have been converted to porosity values by use of the below equation:

$$P = (P_s W_c)/(P_w + W_c P_s)$$

Where P is porosity, W_c is the water content, P_s is the density of solid particles and P_w is the density of water. For this conversion three assumptions are made. One, all pores are filled with water that has been removed by the drying process. Two, the density of water is 1 g/cm^3. Three, the density of soil material is that of quartz 2.65 g/cm^3 (Schlumberger, 1972). With the above equation and the above assumptions approximately 4100 values of porosity were calculated (Carlson, in progress).

Water-content analysis has been completed for 1000s of unconsolidated samples in southeastern Wisconsin. Five large studies have been conducted where porosity values have been determined from water-content results (M.M.S.D. 1984ab; Rodenbeck, 1988; Simpkins, 1989; and Carlson, in progress).

Core Volume Displacement

The core volume displacement porosities were determined by use of the Principle of Archimedes (Schulze-Makuch, 1996). The porosity is determined by following the three steps described below. One, dry the sample for at least 8 hours at 105°C until a constant mass has been reached as described by (ASTM, 1992). Two, weigh and record the final weight for each sample and then put sample into the permeameter. Three, saturate the sample and weigh and record this value of weight (Schulze-Makuch, 1996).

The porosity of the sample can be determined by using the below equation.

$$n = y^*(m_s - m_d)/m_d$$

Where n is porosity, y is apparent density of the sample, m_s mass of saturated sample and m_d mass of dry sample. Apparent density is a result of dividing the mass of the dry sample by the volume of the dry sample which is the volume of a cylinder, length times square of radius times pi.

Porosity determinations by the Principle of Archimedes are susceptible to errors because often not all the pores have been fully saturated by water. However, through analysis of the measured values of density it has been determined that in general Archimedes porosities are valid (Schulze-Makuch, 1996).

There have seven major studies to determine porosity from using the core-volume-displacement method (Harza Engineering Company, 1975a,; M.M.S.D., 1981, 1984a,b, 1989; Palispis, 1985; and Schulze-Makuch, 1996). Given that the number of observations in southeastern Wisconsin are limited there is only one table to note observations by stratigraphic unit for each study as well as a composite value.

In addition a limited number of porosity results are noted for studies in or near southeastern Wisconsin that examined only one or two formations, see Figure 11 for location of studies. Porosity values from core-volume displacement studies include analysis of all Silurian-Cambrian units, but are mainly of Racine Fm. down to St. Peter Fm., see Figure 13.

Geophysical Log Analysis

For this study there are three different geophysical logs which were included as sources of in-situ porosity values for Silurian-Cambrian rock and Pleistocene sediments in the southeastern Wisconsin groundwater model study area. The logs included are formation density logs otherwise known as gamma-gamma logs, neutron logs otherwise know as neutron-neutron logs and sonic logs. What follows is a brief description of these logs used and how porosity is derived from the log results. Location of studies is shown in Figure 9.

Formation density logs

The formation density log, or sometimes referred to as gamma-gamma log, is used to determine the lithologic make up of rock units and their porosity (Dyck and others, 1972; Schlumberger, 1972; Chapellier, 1992). For this study, the formation density log is simply called a density log. In this study, the density log was one of three logs used for the determination of porosity. The density values were recorded on a continuous record, but porosity was calculated only every 2ft (0.6 m) in Silurian rock, and every 4 ft (1.2 m) in Ordovician rock using the below equation for MMSD (1980a) density logs (Schlumberger, 1972):

$$n = (d_m - d_b)/(d_m - d_f)$$

Where n is porosity, d_f is water's density, d_b bulk density recorded and d_m is matrix density which is a combination of limestone and shale using the equation below:

$$d_m = (1 - f_s)d_L + f_s d_s$$

Where d_L is limestone density, d_s is shale and f_s is fraction of rock that is shale as determined from analysis of natural gamma ray logs. The density for limestone is 2.71 g/cm^3 (Schlumberger, 1972) and the density used for shale is 2.38 g/cm^3 which is the median value for shale density as listed in Telford (1976). The reason for using limestone as the main matrix mineral rather than dolomite is because early MMSD (1979) boring logs associated with the Northside Interceptor project identify the rock below the unconsolidated material as limestone rather than correctly as dolomite. This misidentification will impact the calibration of the density log because the values listed on the log are lower than they should be.

Density log functions in the following manner. The gamma ray source within the probe emits a certain quantity of gamma ray radiation. The gamma rays then back scattered and attenuated by the rock leaving a smaller intensity of gamma ray radiation to be detected by the detector on the probe. The amount of radiation reaching the detector is inversely proportional to the electron density of the environment (Dyck and others, 1972; Schlumberger, 1972; and Hilchie, 1982), which is generally for most common rock types proportional to bulk density (Schlumberger, 1972; and Dyck and others, 1972).

M.M.S.D.'s (1980a) density logs have a source to detector distance of 8 inches (20 cm) which yields a depth of investigation that would be slightly under 15 cm which is the depth of investigation when the source to detector distance is 25 cm (Chapellier, 1992). In general, borehole corrections are insignificant for boreholes with diameters less than 10 inches (25 cm) (Schlumberger, 1972), which is the case for all of the M.M.S.D. boreholes logged with the density log probe (MMSD, 1980a).

Neutron-neutron logs

The neutron-neutron log is the second geophysical log used in this study for determination of porosity. This log, for this study is referred to as simply a neutron log. In general, neutron logs can be used for determining lithology, porosity, specific yield, moisture content and moisture fronts (Dyck and others, 1972), but for this study only porosity has been considered. Given that all the dolomite is saturated, the determination of moisture content, moisture fronts and specific yields is precluded since these measurements require the rock at times to be unsaturated. In general, neutron logs respond to hydrogen content which is mainly either petroleum, natural gas or water (Dyck and others, 1972; Schlumberger, 1972, Hilchie, 1982; and Chapellier, 1992). In particular, for the purposes of this study the only fluid present, which contains hydrogen, is water.

Neutron logs have a source of neutrons, which in the case of MMSD (1980) logs is Americium-Beryllium. The neutrons are emitted and are involved in collisions with nuclei of various minerals and hydrogen nuclei (Dyck and others, 1972). In general, a collision with heavy nuclei, anything other than hydrogen causes only a small change in a neutron's energy. Only a collision with hydrogen causes a major reduction in the speed, energy, of a neutron (Schlumberger, 1972). The number of these slow" moving neutrons is proportional to hydrogen content present (Hilchie, 1982; Schlumberger, 1972). The depth of investigation is dependent on hydrogen content (Hilchie, 1982); in general, depth of investigation increases as porosity (hydrogen content) decreases (Schlumberger, 1972; and Hilchie, 1982).

For this study, the raw counts per second (CPS) were recorded every 2 ft (0.6m) along the log record. These values were converted into porosity by setting up a regression relationship between core-volume-displacement porosity and neutron log CPS value. The regression relationship includes an adjustment to take into account core-volume-displacement values of porosity, which in general are smaller than the porosity determined from geophysical logs. The core-volume-displacement porosity values used for this study's correlation with neutron CPS values are a set of porosity results from Schulze-Makuch (1996) for boring sites where there are neutron logs. There are five core results that meet these criteria. These five values were plotted on a log CPS versus porosity plot for porosity calibration curve. The reason for a log plot is that the relationship between porosity and resulting neutron log CPS value is given by the below equation (Dresser Atlas, 1982):

$$\log(n) = C - KNÜ$$

Where C and K are constants, n is porosity and NÜ is the neutron log response value (CPS). It is clear that four of the five points lie on a regression line and one point is an outlier. For the regression equation the outlier is ignored. The result is the below regression equation:

$$n = (3.246 - \log(CPS)))/0.0396$$

Where n are the raw porosity results for a neutron log and CPS is the raw neutron log count.

It has been observed that geophysical log porosities are larger than core-volume-displacement porosities (Birdwell Seismic Service Corporation (BDSSC), 1968). Keeping this in mind for this study, a conversion constant between core and geophysical log porosity was calculated. Three values were included when creating the constant, which was used in this study. One is the three-percent addition noted by BDSSC (1968) for their study of Silurian dolomite around Chicago, Illinois. Two, is the composite average difference of 2.62% between this study's porosity results from analysis of density logs for Silurian units and the average of Schulze-Makuch's (1996) core-volume-displacement porosity values for common units for these two data sets. Three, is the 3.85% porosity difference from Schulze-Makuch (1996) plot that compares point-count, core-volume-displacement and geophysical porosity for the Mayville Fm. The resulting conversion constant from a geometric mean of these three values is 3.12%. So with the conversion constant the complete conversion equation from raw neutron CPS count to geophysical log porosity is completed as the below equation:

$$n_g = 3.12 + (3.246 - \log(CPS))/0.0396$$

Where n_g is the porosity as determined by a geophysical log for a sample that is considerably larger than a core. For neutron log porosity, only calculations for boreholes with a diameter of 3.5 inches were analyzed, for two reasons. One, neutron logs are sensitive to borehole size (Chapellier, 1992). Two, the only boreholes that had cores used for this correlation were those with diameters of 3.5 inches.

Generally calibration of raw neutron CPS values is not necessary since most neutron log results are presented as values of porosity (Schlumberger, 1972). Once porosity values have been determined from analysis of neutron logs it is possible then to compare them with density log results. For this study neutron log porosity values are significantly smaller than density log porosity values. With this porosity difference it is possible then to calculate the chert content for these logs. This was done for the Silurian dolomite below the Waubakee Fm. given that both Rovey (1990) and MMSD (1981, 1984ab, and 1989) noted that there is a significant chert content for the Manistique, Byron and Mayville Formations.

Chert has a low density, 2.19 g/cm^3 (CRC, 1979) which in turn inflates porosity of density log results relative to porosity of neutron log results. This is because chert has no impact on a neutron log's response, but being lighter than limestone or shale, chert increases the porosity value for a density log. The calculation completed for a density log porosity earlier assumes a system that contains only limestone or shale, both of which are denser than chert. If chert is present the resulting density log porosity result will increase by 0.3% for every 1% of chert present in the carbonate rock. This is a result of chert's density difference of 0.5 g/cm^3 with limestone versus water which has a density difference of 1.7 g/cm^3 with limestone.

Sonic logs

For Chicago deep tunnel logs, porosity was compiled from their rock property logs (Birdwell Seismic Service Corporation, 1968 and 1971) which among other things notes the porosity. This porosity was derived from sonic logs. Values of porosity were generally noted every 2ft (0.6m). This set of logs is noted as 3-D velocity logs with travel time recorded in 100s of microseconds. The 3-D velocity log is then split into shear and pressure wave travel times and noted among other properties of the rock in the rock property log (Birdwell Seismic Service Corporation, 1968 and 1971).

The sonic log sends out a series of pulses between two and ten per second (Keys, 1997) that travel through the rock and arrive at receivers within the probe that record the travel time of the pulse. By noting the travel times and resulting velocities given the known source to receiver distance, usually about two to three feet (Dresser Atlas, 1985), it is possible to determine porosity given knowledge of the lithology at a given point. The below equation can be used to calculate porosity:

$$n = (Ät_{log} - Ät_m)/(Ät_f - Ät_m)$$

Where n is porosity, $Ät_{log}$ is reading on sonic log in ìsec/ft, $Ät_m$ is transit time of matrix, $Ät_f$ is transit time in fluid, about 189 ìsec/ft (Schlumberger, 1971; Hilchie, 1982; Dresser Atlas, 1985; and Keys, 1997). As a note of comparison, the transit times for rock are far lower than fluid transit time: sandstone 50-55.5 ìsec/ft, limestones 43.5-47.6 ìsec/ft, and dolomites 38-43.5 ìsec/ft (Schlumberger, 1972; Hilchie, 1982). Shales are generally far less elastic and hence transit times are far larger than for other rock, 62.5 ìsec/ft to 167 ìsec/ft (Keys, 1997). The rock velocities appear to be independent of type of fluid filling the pores: water, petroleum, or natural gas, or the presence of disseminated shale (Schlumberger, 1972). However, for this study only water is filling the pores for all units through the study area.

The typical depth of investigation for a sonic log is about 8-12 inches (20-30 cm) (Hilchie, 1982). The depth of investigation is less for unconsolidated materials about 9 inches (23 cm) and for very solid rock the depth of investigation is larger about 44 inches (110 cm) (Keys, 1997)

Geophysical log porosity values have been determined for both the Milwaukee and Chicago deep tunnel projects. For the Milwaukee project, values of porosity from neutron and density logs were determined every two feet in Silurian rock and every four feet in unconsolidated sediments and Ordovician rock. The reason for the differences in the number of observations is due to the fact that a smaller number of borings have neutron logs than density logs. Lastly the Chicago deep tunnel project has porosities from sonic logs determined every 2 ft in Silurian rock and between 2 and 4 ft in Ordovician and Cambrian rock. As with many of the other data sets geophysical porosity results are concentrated in the upper rock units, Racine Fm. down to St. Peter Fm., see Figure 14

As with hydraulic conductivity the question is what units have significantly different values of porosity? This may not be a concern for steady-state modeling but for any unsteady-state modeling it is necessary to have an understanding of porosity since it is a factor that influences storativity which is an important parameter to know just as hydraulic conductivity when developing a ground-water model which will simulate present and future conditions for the aquifers for southeastern Wisconsin. With this in mind, what follows are two tables, which include results of statistical significance of difference between porosities of adjacent units.

Recharge

Recharge has been determined in this area by two different methods: ground water models and baseflow analysis. The location of these studies can be seen in Figures 10, 15 and 16.

Ground Water Models

Model recharge values are determined by completing the calibration and verification procedure, which is briefly described in the section on determining hydraulic conductivity by use of groundwater models. Once the model has been calibrated then one can determine the recharge rate by dividing the recharge flux as listed in a model's output by the land surface area within a model. It is generally considered that recharge is a result of rainfall so recharge is only applied to the surface area of a model that is neither a lake nor river. For ease of understanding for this study all recharge rates are expressed in cm/yr which involves conversion of flux in models which are generally noted as volume per second or volume per day. This allows one to check if the model recharge is reasonable, that is, equal to or somewhat less than local baseflow and less than precipitation which for the Milwaukee area is about 32 inches/year (81 cm/yr) (Carlson, in progress).

There have been 19 models in the study area that ~~which~~ included recharge as input. In general values from these models range from 1 cm/yr to 7 cm/yr. There appears to be a trend where recharge rate increases westward across the study area. In addition, models, which focus on the lower sandstone aquifer, tend to have lower recharge values, average 1 cm/yr, than models, which simulate solely Silurian dolomite, average 3.9 cm/yr. This is mainly a result of areas where the Maquoketa shale is present, which has a very low recharge rate, typically about 0.2 cm/yr.

Baseflow Analysis

Baseflow is that component of stream flow supplied by groundwater discharging into the stream (Bouwer, 1978). For this study, baseflow was determined by hydrograph separation. This involves determining the slope of a line defining a recessional period of baseflow which is during a long time of decreasing stream discharge (Fetter, 1994). The discharge data is plotted on semilog paper where discharge is on the log axis and time of year is on the linear axis. For this study the longest period of recession usually occurs roughly at the mid-point of the typical hydrologic year, defined as October 1st to the following September 30th. The mid-point is the annual spring snowmelt, which generally happens in early March to early April. From this slope other shorter baseflow recession regions were determined by drawing lines parallel to the longest baseflow recessional line. Lastly, areas without a baseflow recessional line were filled in with lines between flat and roughly the inverse of the baseflow recessional line's slope. Once a baseflow curve is defined then the area under each trapezoid or rectangle is calculated. The resulting volume of water is in turn divided by the watershed area to yield a recharge rate. Generally for this solution, the size of the spring snow melt, the main recharge event, will largely determine the value of baseflow "recharge rate" calculated. Within this calculation is the assumption that, in general, groundwater movement is confined within a surface watershed. This is probably not true, but it does allow one to calculate at least approximately recharge in a given watershed.

In addition to ground water models there have been 44 watersheds where recharge has been determined from baseflow studies that lie fully or partially within the southeastern Wisconsin groundwater model area. There are 20 watersheds in southeastern Wisconsin and 24 in northeastern Illinois, see Figure 15 and 16 for locations. In general, recharge rate from baseflow studies is about 2.5 to 3 times larger than recharge from ground water models for the same study area. In addition, there maybe a trend in recharge rate of an increase westward across the study area.

Mineral Content from Geophysical Logs

For this study natural gamma ray logs of MMSD (1980a), Birdwell Seismograph Service (1968, 1971) and WGNHS (1997) where analyzed. Natural gamma ray logs in general provide information on sediment composition, in particular clay/shale content (Dyck and others, 1972, Schlumberger, 1972 and Chapellier, 1992). Shale content results can be used within the calculation of porosity from density logs as described earlier in this report.

The percentage of clay was calculated using the below equation (Chapellier, 1992):

$$V_c = (G_x - G_s)/(G_c - G_s)$$

Where V_c is fraction of clay, G_x is gamma ray response at a given point of observation, G_s is gamma ray response for a clean sand and G_c is gamma ray response for a clay (Chapellier, 1992). For this study the maximum and minimum responses are such that either a clean sandstone or clean carbonate (limestone, dolostone) is the minimum response instead of a sand while a pure shale is the maximum response instead of clay. Generally the minimum gamma log response occurs in the Mayville Fm., Waukesha and Franklin members of Manistique Fm., Racine Fm., Potosi Fm. , Prairie du Chien Group or St. Peter Fm., while the maximum response occurs in the Scales Fm. of the Maquoketa Group, Franconia Fm. or Eau Claire Fm. For this study, the value of shale content was calculated every 2 ft (0.6m), except below the Mayville Fm. (bottom of Silurian rock), then measurements were calculated every 4 ft. (1.2 m). A borehole correction for MMSD's and Chicago Deep Tunnel gamma logs is not needed given gamma logs are generally insensitive to borehole size if the borehole diameter is under 13 inches (Hilchie, 1982), which is the case for almost all boreholes considered in this study. As Hilchie (1982) notes, only if the drilling mud is a heavy Barite mud or the borehole size is over 13 inches in diameter is there a significant need for a borehole correction for gamma logs. Neither of these conditions is the case for most of these boreholes, which are generally 3 to 8 inches in diameter (Birdwell Seismograph Service, 1971; MMSD, 1980a), with the vast majority between 3 and 4 inches, and where clean water is the drilling fluid used during the boring of these holes (MMSD, 1980a).

What follows is a brief description of gamma ray log respondence and the mechanism and the nature of the observation. A gamma ray log responds to the intensity of gamma ray radiation from naturally occurring radioactive isotopes in either rock or soil (Dyck and others, 1972; Hilchie, 1982; Schlumberger, 1972; and Chapellier, 1992). In general, the main isotopes that generate gamma ray radiation are potassium 40, and uranium-radium series (Schlumberger, 1972; Chapellier, 1992). Typically, the count of gamma ray radiation is done with a scintillation counter, but older logs may have Geiger-Mueller counters (Schlumberger, 1972). The depth of investigation for a gamma log is about 40 cm (16 inches) for a rock with a density of 2.5 g/cm^3 (Chapellier, 1992). The gamma ray log responds to a sphere of influence around the probe; so for this study's gamma ray logs, the volume of rock investigation was about 0.25 m^3 (8.8 ft^3) and varied depending on borehole size, which for MMSD logs ranges from 8.9 cm to 20 cm diameter (3.5 inches to 8 inches), while Chicago deep tunnel logs are between 7.6 cm to 27.9 cm (3 inches and 11 inches) and the WGNHS logs have diameters of 25.4 cm to 43.2 cm (10 inches to 17 inches).

The clay/shale content is an important factor in determining hydraulic conductivity. In fact, for sandstones a number of workers have developed equations relating hydraulic conductivity to clay content among other properties of a rock (Yao, 1992; and Yao and others, 1993). So with this in mind, clay content was determined by analysis of natural gamma logs for three sets of geophysical logs: M.M.S.D. logs, Chicago deep tunnel logs, and WGNHS logs in the model region (Tables 38 to 40).

Geophysically derived values of hydraulic conductivity are important because unit specific field scale values of hydraulic conductivity are limited to St. Peter Fm. and above with only a few lab measurements of hydraulic conductivity for units down to Eau Claire Fm. Hydraulic conductivity values for the Mt. Simon Fm. are a result of test where Mt Simon is it is either lumped with others units above or from measurements in central Illinois with the possibility of facies changes causing Mt. Simon Fm. to be significantly different than it is in Waukesha Co. So with this in mind shale/clay content was determined for each unit in southeastern Wisconsin, see Tables 38, 39 and 40.

Lastly the statistical significance to determine if adjacent units are different in clay/shale was completed. For clastic units this result probably indicates they are different in hydraulic conductivity as well, see Table 41 to 43 for statistical results.

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Table 1. - Summary of results for permeameter tests listed in Rodenback's (1988) study, which lie within the southeastern Wisconsin model study area.

		Hydraulic Conductivity		
Unit	Observations	Mean (m/day)	Log K (m/day)	Std Dev (m/day)
Ozaukee Till	3	3.89×10^{-5}	-4.41	0.28
Oak Creek Till	76	3.55×10^{-5}	-4.45	0.68
New Berlin Till	1	3.16×10^{-5}	-4.50	0.00
Zenda Till	1	1.82×10^{-5}	-4.74	0.00
Tiskilwa Till	1	8.71×10^{-5}	-4.06	0.00
Lacustrine	20	3.39×10^{-4}	-3.47	1.47
Outwash	3	5.13×10^{-3}	-2.29	1.36

Table 2. - Summary of results for permeameter tests listed in Simpkins' (1989) study, which lie within the southeastern Wisconsin model study area.

		Hydraulic Conductivity		
Unit	Observations	Mean (m/day)	Log K (m/day)	Std Dev (m/day)
Oak Creek Till	112	2.82×10^{-5}	-4.55	1.04
New Berlin Till	2	1.23×10^{-4}	-3.91	0.64
Lacustrine	12	3.31×10^{-3}	-2.48	1.80
Outwash	3	2.63×10^{-2}	-1.58	2.33

Table 3. - Summary results for permeameter tests listed in Simpkins' (1989) and Rodenback's studies which lie within the southeastern Wisconsin model study area.

Unit	Observations	Hydraulic Conductivity Mean (m/day)	Log K (m/day)	Std Dev (m/day)
Ozaukee Till	3	3.89×10^{-5}	-4.41	0.28
Oak Creek Till	188	3.16×10^{-5}	-4.50	0.91
New Berlin Till	6	7.94×10^{-5}	-4.10	0.60
Zenda Till	1	1.82×10^{-5}	-4.74	0.00
Tiskilwa Till	1	8.71×10^{-5}	-4.06	0.00
Lacustrine	32	7.94×10^{-4}	-3.10	1.67
Outwash	6	1.15×10^{-2}	-1.94	1.94

Table 4. - Summary of results for permeameter tests listed in Schulze-Makuch's (1996) study, which lie within the southeastern Wisconsin model study area.

Unit	Observations	Hydraulic Conductivity Mean (m/day)	Log K (m/day)	Std Dev (m/day)
Thiensville	36	9.77×10^{-4}	-3.01	1.68
Racine	10	5.37×10^{-6}	-5.27	0.58
Racine reef	5	5.37×10^{-3}	-2.27	1.96
Romeo beds	10	3.71×10^{-5}	-4.43	0.97
Mayville	11	1.17×10^{-4}	-3.93	1.35

Table 5. - Summary of permeameter test results for Chicago's deep tunnel project as listed in Harza Engineering Company (1975ab) which lie in southeastern Wisconsin model study area.

		Hydraulic Conductivity		
Unit	Observations	Mean (m/day)	Log K (m/day)	Std Dev (m/day)
Racine				
non-reef	14	3.47×10^{-5}	-4.46	2.27
reef	8	9.55×10^{-4}	-3.02	1.39
Joliet	15	3.63×10^{-7}	-6.44	0.72
Kankakee	9	2.40×10^{-7}	-6.62	0.78
Edgewood	6	5.50×10^{-7}	-6.26	1.07
Maquoketa				
Brainard	1	9.12×10^{-8}	-7.04	0.00
Fort Atkinson	4	2.09×10^{-7}	-6.68	0.54
Scales	2	9.12×10^{-8}	-7.04	0.00
Galena	19	8.32×10^{-6}	-5.08	1.68
Platteville	25	5.89×10^{-6}	-5.23	1.63
St. Peter	11	2.63×10^{-3}	-2.58	1.09
Prairie du Chien	2	5.13×10^{-7}	-6.29	0.64
Potosi	1	2.36×10^{-6}	-5.63	0.00
Franconia	5	8.12×10^{-4}	-3.09	0.54
Ironton	4	4.17×10^{-2}	-1.38	0.59
Galesville	3	2.09×10^{-1}	-0.68	0.14
Racine				
non-reef	14	4.57×10^{-6}	-5.34	2.00
reef	8	9.12×10^{-5}	-4.04	1.74
Joliet	15	1.78×10^{-7}	-6.75	0.44
Kankakee	9	2.14×10^{-7}	-6.67	0.49

Table 5. - Below is a summary of permeameter test results for Chicago's deep tunnel project as listed in Harza Engineering Company (1975ab) which lie in southeastern Wisconsin model study area -- continued

Unit	Observations	Hydraulic Conductivity Mean (m/day)	Log K (m/day)	Std Dev (m/day)
Edgewood	6	2.09×10^{-7}	-6.68	0.61
Maquoketa				
Brainard	1	9.12×10^{-8}	-7.04	0.00
Fort Atkinson	4	2.82×10^{-7}	-6.55	0.61
Scales	2	9.12×10^{-8}	-7.04	0.00
Galena	19	1.41×10^{-6}	-5.85	0.95
Platteville	25	5.01×10^{-7}	-6.30	0.99
St. Peter	11	6.31×10^{-4}	-3.20	0.81
Prairie du Chien	2	9.12×10^{-8}	-7.04	0.00
Potosi	1	3.89×10^{-6}	-5.41	0.00
Franconia	5	1.91×10^{-6}	-5.72	1.40
Ironton	4	7.08×10^{-4}	-3.15	1.08
Galesville	3	1.95×10^{-1}	-0.71	0.21

Table 6. - Permeameter test results for a series of studies that tested the Ordovician and Cambrian rock in or near the southeastern Wisconsin model study area.

Author Unit/Location	Observations	Hydraulic Conductivity Mean (m/day)	Log K (m/day)	Std Dev (m/day)
Emrich (1966)				
Galesvile/Herscher, IL	81	4.72×10^{-1}	-0.33	N.A.
Galesvile/Crescent City,IL	40	1.78×10^{-1}	0.75	N.A.
Galesvile/Garfeild, IL	~50	7.80×10^{-1}	-0.11	N.A.
Galesvile/Ancona, IL	~25	5.50×10^{-1}	-0.26	N.A.
Galesvile/Potiac, IL	~25	4.00×10^{-1}	-0.40	N.A.
Galesvile/Mahomet, IL	~35	6.70×10^{-1}	-0.17	N.A.
Illinois State Water Survey (1973)				
Mt. Simon/Anconia, IL	N.A.	4.15×10^{-2}	-1.38	N.A.
Mt. Simon/Pontiac, IL	N.A.	5.41×10^{-3}	-2.27	N.A.
Mt. Simon/Hudson, IL	N.A.	2.33×10^{-2}	-1.63	N.A.
Cutler (1979)				
St Peter/	15	1.41×10^{0}	0.15	0.33
Gross (1980)				
St. Peter/	16	1.70×10^{0}	0.23	0.30
Galesville/	7	1.91×10^{0}	0.28	0.31
Pujol-Rius (1980)				
St. Peter/	62	3.02×10^{0}	0.48	0.16
Heidari and Cartwright (1981)@				
Ironton-Galesville/	1	2.98×10^{0}	0.47	N.A.
Eau Claire/	5	7.25×10^{-7}	-6.14	N.A.
Mt. Simon/	9	1.05×10^{-1}	-0.98	N.A.
Swingen (1981)				
St. Peter/	8	1.73×10^{-1}	-0.76	0.26
Jachim Dolomite/	16	7.59×10^{-3}	-2.12	0.77
Vaticon (1981)				
Mt. Simon/	36	3.00×10^{-1}	-0.53	0.38
Spoerl (1984)				
St. Peter/	18	2.19×10^{0}	0.34	0.14
Schumacher (1990)*				
Maquoketa/	N.A.	7.22×10^{-9}	N.A.	N.A.
St. Peter/	N.A.	5.46×10^{-3}	N.A.	N.A.

@ these values are average of the average values for individual layers noted in report
* geometric median of range noted.

Table 7. - Summary of results from slug/bail test noted in Rodenback's (1988) study, which lie within southeastern Wisconsin.

Unit	Observations	Hydraulic Conductivity Mean (m/day)	Log K (m/day)	Std Dev (m/day)
Kewaunee Till				
Ozaukee Till	5	1.70×10^{-3}	-2.77	0.72
Oak Creek Till	99	2.04×10^{-3}	-2.69	1.08
New Berlin Till	4	7.41×10^{-2}	-1.13	0.47
Tiskilwa Till	5	1.15×10^{-1}	-0.94	0.47
Lacustrine	12	3.80×10^{-2}	-1.42	1.32
Outwash	4	5.01×10^{-2}	-1.30	0.93

Table 8. - Summary of results from slug/bail tests noted in Simpkins' (1988) study that lies within southeastern Wisconsin.

Unit	Observations	Hydraulic Conductivity Mean (m/day)	Log K (m/day)	Std Dev (m/day)
Oak Creek Till	153	1.25×10^{-3}	-2.90	1.17
New Berlin Till	19	1.45×10^{-2}	-1.84	0.55
Alluvium	34	4.37×10^{-2}	-1.36	1.06
Lacustrine	26	5.01×10^{-2}	-1.30	1.34

Table 9. - Summary of results from slug/bail tests noted in Carlson's (in progress) study that lies within southeastern Wisconsin model.

Unit	Observations	Hydraulic Conductivity Mean (m/day)	Log K (m/day)	Std Dev (m/day)
Ozaukee Till	33	3.72×10^{-2}	-1.43	0.90
Oak Creek Till	101	1.26×10^{-2}	-1.90	1.29
New Berlin	14	3.09×10^{-2}	-1.51	1.37
Alluvium	85	1.78×10^{-1}	-0.75	1.35
Esturaine	13	2.04×10^{-2}	-1.69	0.87
Lacustrine	20	2.63×10^{-2}	-1.58	1.18
Outwash	21	7.94×10^{-2}	-1.10	1.01

Table 10. - A composite of results listed in Tables 6, 7 and 8 (Carlson, in progress).

Unit	Observations	Hydraulic Conductivity Mean (m/day)	Log K (m/day)	Std Dev (m/day)
Ozaukee Till	38	2.24×10^{-2}	-1.65	1.04
Oak Creek Till	353	2.82×10^{-3}	-2.55	1.25
New Berlin Till	37	2.29×10^{-2}	-1.64	0.97
Tiskilwa Till	5	1.15×10^{-1}	-0.94	0.47
Alluvium	119	1.20×10^{-1}	-0.92	1.30
Esturaine	13	2.04×10^{-2}	-1.69	0.87
Lacustrine	58	3.80×10^{-2}	-1.42	1.29
Outwash	25	8.13×10^{-2}	-1.09	0.99

Table 11. - Summary of results for generally 10 ft packer tests conducted at the Haven's power plant site three miles north of Sheboygan, Wisconsin (Carlson, 1998a).

Unit	No. of tests	Hydraulic Conductivity Geometric Mean (m/day)	Log K (m/day)	std. dev. (m/day)
Racine	135	1.0×10^{-2}	-2.0	0.8
Romeo beds	18	1.3×10^{-1}	-0.9	0.3
Manistque	75	1.1×10^{-1}	-1.0	0.6
Waukesha	69	9.8×10^{-2}	-1.0	1.1
Brandon Bridge	4	2.6×10^{-1}	-0.6	0.3
Franklin	2	4.7×10^{-1}	-0.3	0.0

Table 12. - Summary of results for generally 20 ft packer tests conducted along the path of Milwaukee's deep tunnels (Carlson, in progress).

Unit	No. of tests	Hydraulic Conductivity Geometric Mean (m/day)	Log K (m/day)	std. dev. (m/day)
weathered zone	54	4.8×10^{-2}	-1.3	1.4
Lindwurm	5	5.6×10^{-4}	-3.3	1.1
Berthelet	11	2.1×10^{-2}	-1.7	1.4
Thiensville	73	5.9×10^{-1}	-0.2	1.0
Waubakee	60	2.4×10^{-3}	-2.6	1.2
Racine	269	4.2×10^{-3}	-2.4	1.4
Romeo beds	34	4.1×10^{-2}	-1.4	1.0
Waukesha-Byron	103	2.9×10^{-3}	-2.5	1.2
Waukesha	29	3.2×10^{-3}	-2.5	1.3
Brandon Bridge	14	1.6×10^{-3}	-2.8	1.2
Franklin	14	2.5×10^{-3}	-2.6	1.1
Mayville	77	3.2×10^{-2}	-1.5	0.9
Maquoketa	25	6.9×10^{-3}	-2.2	2.6
Galena	1	8.6×10^{-3}	-2.1	0.0

Table 13. - Summary of results for generally 40 ft packer tests conducted along the path of Chicago's deep tunnels collected from Harza Engineering Company (1975a) (Carlson, 1998a).

Unit	No. of tests	Hydraulic Conductivity Geometric Mean (m/day)	Log K (m/day)	std. dev. (m/day)
Racine	248	3.4×10^{-2}	-1.5	1.1
Manistque	101	3.9×10^{-3}	-2.4	1.2
Joliet	15	3.3×10^{-3}	-2.5	1.0
Kankakee	27	6.6×10^{-3}	-2.2	1.2
Edgewood	79	1.3×10^{-2}	-1.9	1.4
Maquoketa	23	1.6×10^{-3}	-2.8	0.9
Galena	160	4.6×10^{-3}	-2.3	1.1
Platteville	89	5.1×10^{-3}	-2.3	1.0
St. Peter	13	2.0×10^{-2}	-1.7	0.6

Table 14. - Summary of results for generally 15-20 ft packer tests conducted along the path of the Superconductor Super Collider which lies near Auora, Illinois. Results from Kempton and others (1987ab) and Curry and others (1988) were compiled for the below results by stratigraphic unit (Carlson, 1998a).

Unit	No. of tests	Hydraulic Conductivity Geometric Mean (m/day)	Log K (m/day)	std. dev. (m/day)
Joliet-Kankakee	10	2.2×10^{-3}	-2.7	1.0
Joliet	1	1.7×10^{-3}	-2.8	0.0
Kankakee	4	1.5×10^{-3}	-2.8	1.3
Elmwood	7	2.2×10^{-3}	-2.7	1.2
Maquoketa	84	2.2×10^{-3}	-2.7	1.4
Galena	148	1.1×10^{-3}	-3.0	1.0
Platteville	39	1.2×10^{-3}	-2.9	0.9

Table 15. - Confidence of difference between adjacent unit's hydraulic conductivity using the T-test. The data set analyzed is M.M.S.D.'s packer test data.

Unit pair	T-value	Confidence of Difference: >90%	>99%	>99.9%
Lindwurm-Berthelet	1.88	yes	no	no
Berthelet-Thiensville	4.02	yes	yes	yes
Thiensville-Waubakee	12.28	yes	yes	yes
Waubakee-Racine	1.22	no	no	no
Racine-Romeo beds	3.92	yes	yes	yes
Romeo beds-Manistque	4.93	yes	yes	yes
Manistque-Mayville	6.14	yes	yes	yes
Mayville-Maquoketa	1.89	yes	no	no

Table 16. - Confidence of difference between adjacent unit's hydraulic conductivity using the T-test. The data set analyzed is Chicago's deep tunnel project packer test data.

Unit pair	T-value	Confidence of Difference: >90%	>99%	>99.9%
Racine-Manistque	7.00	yes	yes	yes
Manistque-Edgewood	2.65	yes	no	no
Edgewood-Maquoketa	2.86	yes	yes	no
Maquoketa-Galena	1.87	yes	no	no
Galena-Platteville	0.35	no	no	no
Platteville-St. Peter	1.98	yes	no	no

Table 17. - Summary of previous studies that determined hydraulic conductivity of various units by analyzing specific capacity tests.

Source Unit	No.	Hydraulic conductivity Mean (m/day)	Log K (m/day)	Std. Dev. (m/day)
LeRoux (1957)				
St. Peter	4	13.80	1.14	0.50
Franconia-Mt.Simon	11	1.74	0.24	0.37
Walton and Csallany (1962)				
Galena-St.Peter	52	0.11	-0.95	0.56
Glenwood-St. Peter	7	0.26	-0.58	0.20
Ironton-Galesville	13	0.58	-0.24	0.19
Cambrian-Ordovician	150	0.29	-0.54	0.35
Mt. Simon	37	0.13	-0.89	0.18
Mt. Simon	1	0.01	-1.99	0.00
Csallany and Walton (1963)				
Racine Fm/Cook Co.	5	8.51	0.93	1.02
Silurian Dolomite/Cook Co.	162	2.34	0.37	0.84
Silurian Dolomite/DuPage Co.	55	6.17	0.79	0.91
Silurian Dolomite/Kane Co.	14	1.58	0.20	0.78
Silurian Dolomite/Kankakee Co.	21	0.89	-0.05	0.73
Silurian Dolomite/Lake Co.	82	2.69	0.43	0.89
Silurian Dolomite/McHenry Co.	23	1.91	0.28	0.94
Silurian Dolomite/Will Co.	67	2.04	0.31	0.84
Galena-Platteville	29	0.71	-0.15	0.76
Prickett and others (1964)				
Silurian dolomite at:				
Libertyville, Lake Co.	78	6.92	0.84	0.82
Chicago Hts., Cook Co.	133	4.57	0.66	0.72
La Grange, Cook Co.	101	6.31	0.80	0.79
Cline (1965)				
St.Peter-Trempealau	1	0.87	-0.06	0.00
St.Peter-Galesville	1	5.50	0.74	0.00
St.Peter-Eau Clarie	2	0.60	-0.22	0.50
Trempealeau	1	8.32	0.92	0.00
Trempealeau-Franconia	1	0.54	-0.27	0.00
Trempealeau-Galesville	1	1.82	0.26	0.00
Trempealeau-Eau Claire	5	1.48	0.17	0.40
Trempealeau-Mt.Simon	6	1.20	0.08	0.39
Franconia	1	14.79	1.17	0.00
Franconia-Galesville	6	5.13	0.71	0.73
Franconia-Eau Claire	7	2.88	0.46	0.26
Franconia-Mt. Simon	10	2.19	0.34	0.54
Galesville-Mt.Simon	2	1.29	0.11	0.03

Table 17. - Summary of previous studies that determined hydraulic conductivity of various units by analyzing specific capacity tests: -- continued

		Hydraulic conductivity		
Source Unit	No.	Mean (m/day)	Log K (m/day)	Std. Dev. (m/day)
Cline (1965)				
Eau Claire	1	0.87	-0.06	0.00
Eau Claire-Mt.Simon	2	1.78	0.25	0.16
Hoover and Schicht (1967)				
Galena-St. Peter	7	0.14	-0.84	0.36
Glenwood-St. Peter	10	0.35	-0.45	0.23
Cambrian-Ordovician	21	0.35	-0.46	0.19
Hutchinson (1970)				
sand and gravel	7	10.7	1.03	0.45
Silurian dolomite	23	1.35	0.13	0.64
Galena-St.Peter	3	0.02	-1.69	0.41
Galena-Galesville	9	0.10	-1.00	0.72
Galena-Mt.Simon	10	0.08	-1.10	0.37
Gonthier (1975)				
Silurian dolomite	>800	#0.86	N.A.	N.A.
Borman (1976)				
sand and gravel	100	*53.7	range 24 to 120	
Silurian dolomite	50	*3.46	range 0.3 to 40	
Galena-Platteville	90	*3.46	range 0.3 to 40	
Sandstone aquifer	14			
Maquoketa present	N.A.	*0.57	range 0.4 to 0.82	
Maquoketa not present	N.A.	*1.15	range 0.82 to 1.4	
Young and Batton (1980)				
sand and gravel	24	*53.0	range 6.1 to 460	
Silurian dolomite	534	#0.98	range 0.003 to 178	
Thompson (1981)				
Silurian dolomite	5	0.15	-0.81	0.68
Carman (1988)				
sand and gravel	28	26.9	1.43	0.46
rock (Gal.-Platt.)	18	1.17	0.07	1.04
Wehrheim (1989)				
Silurian dolomite	49	0.50	-0.30	0.56
Clite (1992)				
weathered zone	17	2.2	0.35	0.46
Waukesha-Byron	56	1.1	0.03	0.52
Mayville	12	2.2	0.34	0.50
Pearson (1993)				
weathered zone	78	10.7	1.03	0.70
fractured Racine/				

Table 17. - Summary of previous studies that determined hydraulic conductivity of various units by analyzing specific capacity tests: -- continued

Source Unit	No.	Hydraulic conductivity Mean (m/day)	 Log K (m/day)	 Std. Dev. (m/day)
Manistque	89	0.26	0.10	0.56
unfractured Racine/				
Manistque	82	0.0011	-2.96	0.16
Mayville	18	0.389	-0.41	1.04
Schulze-Makuch (1996)				
Thiensville	32	3.98	0.60	0.44
weathered Racine	29	17.4	1.24	0.65
unweathered Racine	16	1.95	0.29	N.A.

median is listed in this report rather than a geometric mean
* geometric center of the range

Table 18. - Carlson's (1998b) hydraulic conductivity values determined for various units by analyzing specific capacity tests.

Unit	No. of tests	Hydraulic Conductivity Geometric Mean (m/day)	Log K (m/day)	std. dev. (m/day)
Outwash	31	19.05	1.28	0.92
New Berlin Till	57	1.05	0.02	0.63
Milwaukee	379	8.91	0.95	0.88
Thiensville	509	12.3	1.09	0.77
Waubakee	97	1.32	0.12	0.90
Racine	1212	1.66	0.22	0.76
Manistque	212	2.57	0.41	0.88
Mayville	192	1.95	0.29	0.69
Maquoketa	66	0.35	-0.45	0.90
Galena/Platteville	258	2.95	0.47	0.93
St. Peter	88	1.10	0.04	1.03

Table 19. - Confidence of difference of hydraulic conductivity between adjacent units determined by analysis of specific capacity data for adjacent units using the T-test method.

Unit pair	T-value	Confidence of Difference: >90%	>99%	>99.9%
Milwaukee-Thiensville	2.51	yes	no	no
Thiensville-Waubakee	11.10	yes	yes	yes
Waubakee-Racine	1.23	no	no	no
Racine-Manistque	3.27	yes	yes	no
Manistque-Mayville	1.51	no	no	no
Mayville-Maquoketa	6.86	yes	yes	yes
Maquoketa-Sinnipee	7.15	yes	yes	yes
Sinnipee-St. Peter	3.61	yes	yes	yes

Table 20. - Previous works that included aquifer tests of various units in or near southeastern Wisconsin model region.

Source Unit	No.	Hydraulic conductivity Mean (m/day)	Log K (m/day)	Std. Dev. (m/day)
Foley and others (1953)				
Sandstone	52	0.93	-0.03	0.27
LeRoux (1957)				
Dresbach-Trempealeau	9	3.31	0.52	0.11
LeRoux (1963)				
Franconian-Mt. Simon	4	2.09	0.32	0.09
Cline (1965)				
Galesville-Mt Simon	4	2.69	0.43	0.07
Hoover and Schicht (1967)				
Sandstone	13	0.49	-0.31	0.23
Hutchinson (1970)				
Sandstone	9	0.38	-0.42	0.11
Illinois State Water Survey (1973)				
Mt. Simon	3	0.042	-1.38	0.54
Gonthier (1975)				
Silurian dolomite	70	# 0.70	N.A.	N.A.
Sandstone <900 ft	N.A.	# 1.0	N.A.	N.A.
Sandstone >900 ft eastern	N.A.	# 0.3	N.A.	N.A.
Sandstone >900 ft western	N.A.	# 0.6	N.A.	N.A.
M.M.S.D. (1981)				
Silurian	4	0.27	-0.57	0.45
Zvilbeman (1983)				
Silurian	1	0.14	-0.85	0.00
Nicholas and others (1987)				
St. Peter	1	0.55	-0.26	0.00
Ironton-Galesville	1	3.05	0.48	0.00
Elmhurst-Mt. Simon	1	0.46	-0.34	0.00
Mt. Simon	1	0.40	-0.40	0.00
Wehrheim (1989)				
Silurian	1	0.22	-0.66	0.00
Rovey (1990)				
Silurian	3	0.51	-0.29	0.73
Schumacher (1990)				
Galena-Platteville	1	2.12	0.32	0.00
St. Peter	1	2.51	0.40	0.00
Jansen (1995)				
Silurian	5	5.25	0.72	0.80

Table 20. - Previous works that included aquifer tests of various units in or near southeastern Wisconsin model region --continued

Source Unit	No.	Hydraulic conductivity Mean (m/day)	 Log K (m/day)	 Std. Dev. (m/day)
Kay and Kraske (1996)				
St. Peter	1	2.52	0.40	0.00
Schulze-Makuch(1996)				
southern Ozaukee Co.:				
weathered zone	22	5.96	0.78	0.40
weathered Lake Church	2	2.33	0.37	0.45
weathered Racine	3	7.17	0.86	0.61
Thiensville	7	41.5	1.62	0.29
Racine	2	0.15	-0.82	0.40
Romeo beds	2	1.81	0.26	0.05
Mayville	26	0.95	-0.02	0.61
M.M.S.D./U.W.M.:				
weathered zone	3	0.35	-0.46	0.50
Thiensville	28	10.2	1.01	0.68
Waubakee/Racine	3	0.30	-0.53	0.22
Racine	4	0.38	-0.42	0.70
Racine/Waukesha	1	0.17	-0.76	0.00
Mayville	23	1.78	0.25	1.12

Table 21. Summary of aquifer test results from Carlson (in progress) and Carlson (1998c) for a variety of units in Ozaukee, Milwaukee, and Waukesha counties that are from analysis of test results in generally unpublished documents of M.M.S.D. or the Wisconsin D.N.R. Note number of observations is larger than the number of tests because some of the tests are multiple-well-aquifer tests: 10 in Pleistocene materials, 5 in Devonian-Silurian and 35 in Silurian.

		Hydraulic conductivity		
Source Unit	No.	Mean (m/day)	Log K (m/day)	Std. Dev. (m/day)
M.M.S.D. data				
sand and gravel	11	129	2.11	1.05
Oak Creek Till	5	0.34	-0.47	0.22
Thiensville	23	2.75	0.44	0.85
weathered Racine	4	1.15	0.06	0.50
Waubakee-Racine	3	0.045	-1.35	0.22
Racine	4	0.033	-1.48	0.25
Mayville	2	0.041	-1.39	0.95
Silurian	24	1.26	0.10	1.06
Mequon data#				
Silurian-Devonian	14	0.31	-0.51	0.80
Silurian	105	0.51	-0.29	0.40
Other data sets				
sand and gravel	43	5.13	0.71	0.49
Silurian	12	1.32	0.12	0.55
Thiensville-Racine	4	10.47	1.02	0.21
Thiensville-Mayville	3	5.89	0.77	0.11
Racine	4	3.02	0.48	0.18
Racine-Manistque	1	2.00	0.30	0.00
Racine-Mayville	17	1.12	0.05	0.76
Manistque-Mayville	14	0.79	-0.10	0.48
Mayville	5	15.85	1.20	0.14

#These results are from 27 multiple-well-aquifer tests plus a few single-well-aquifer tests.

Table 22. - Summary of horizontal anisotropy of hydraulic conductivity results from analysis of multiple-well-aquifer tests conducted throughout southeastern Wisconsin

Jansen (1995)

Northeastern maxima		Northwestern maxima
3	number of tests	2
	geometric mean	
5248	T_{max} (ft^2/day)	12003
123	T_{min} (ft^2/day)	631
3.72	log(T_{max}) (ft^2/day) mean	4.08
0.15	log(T_{max}) (ft^2/day) std.dev.	0.13
2.09	log(T_{min}) (ft^2/day) mean	2.80
0.14	log(T_{min}) (ft^2/day) std.dev.	0.31
42.7	geometric mean anisotropy	19.1
44.7° ± 7.2° E of N	direction mean	47.5° ± 0.7° W of N

Carlson (in progress)

Northeastern maxima		Northwestern maxima
6	number of tests	8
	geometric mean	
955	T_{max} (ft^2/day)	1514
240	T_{min} (ft^2/day)	324
2.98	log(T_{max}) (ft^2/day) mean	3.18
0.45	log(T_{max}) (ft^2/day) std.dev.	0.34
2.38	log(T_{min}) (ft^2/day) mean	2.51
0.30	log(T_{min}) (ft^2/day) std.dev.	0.50
3.98	geometric mean anisotropy	4.67
45.1° ± 16.9° E of N	direction mean	38.6° ± 28.2° W of N

Table 23. - Model results in terms of horizontal hydraulic conductivity and vertical anisotropy of hydraulic conductivity (Kh/Kv) for a variety of models of Pleistocene to Cambrian units in or near southeastern Wisconsin or northeastern Illinois.

Source Unit	horizontal hydraulic conductivity (m/day)	Kh/Kv Anisotropy
Prickett and Lonnquist (1971)		
Platteville	0.21	N.A.
Prairie du Chien- Franconia	0.69	N.A.
Ironton-Galesville	1.98	N.A.
McLeod (1975ab)		
Pleistocene/ Trempealeau Fm	5.3 or 10.6	5300 or 53000
Ironton-Mt. Simon	2.2	N.A.
Young (1976)		
St.Peter	0.21	N.A.
Prairie du Chien- Franconia	0.69	N.A.
Ironton-Galesville	1.98	N.A.
Eau Claire	0.20	N.A.
Mt Simon	0.61	N.A.
Ladwig (1981)		
sand	0.0086	1.0
gravel	8.6	1.0
peat	0.00086	1.0
dolomite	0.86	1.0
Rovey (1983)		
primary direction		
upper dolomite	4.1	1.0
lower dolomite	0.41	1.0
secondary direction		
upper dolomite	2.1	1.0
lower dolomite	0.21	1.0
Emmons (1987)		
Silurian-Devonian	2.41	N.A.
St. Peter- Trempealeu Fm.	0.76 to 2.50	N.A.
Galesville- Mt. Simon	0.94 to 2.52	N.A.
Plomb (1989)		
unconsolidated	1.4	6400
dolomite	N.A.	30.0

Table 23. - Model results in terms of horizontal hydraulic conductivity and vertical anisotropy of hydraulic conductivity (Kh/Kv) for a variety of models of Pleistocene to Cambrian units in or near southeastern Wisconsin or northeastern Illinois -- continued

Source Unit	horizontal hydraulic conductivity (m/day)	Kh/Kv Anisotropy
Webb (1989)		
Silurian dolomite		
upper	4.2	15, 30 or 50
middle	2.6	15, 30 or 50
lower	1.0	15, 30 or 50
Nader (1990)		
unconsolidated	7.9	10.0
Thiensville	8.7	5.1
Racine/Waubakee	0.034	10
Romeo beds	1.7	5.0
Mayville	0.042	0.76
Burch (1991)		
St.Peter	1.22	N.A.
Prairie du Chien	0.12	N.A.
Franconia-St.Law.	0.04	N.A.
Ironton-Galesville	0.41	N.A.
Mt.Simon	1.98	N.A.
Weaver and Bahr (1991)		
Glacial	0.0046	250
Silurian	2.42	10
Maquoketa	0.0026	500
Galena-Platteville		
weathered	2.16	50
unweathered	0.01	500
St. Peter	0.55	20
Prairie du Chien- Trempealeau	0.032	1500
Elkmound- Tunnel City	2.68	50
Cherkauer and Mikulic (1992)		
unconsolidated	0.3	1.0
Milwaukee	0.86	1.0
Thiensville	4.3	1.0
Racine/Waubakee/ Lake Church	0.034	1.0
Romeo beds	1.7	1.0
Mayville	0.43	1.0

Table 23. - Model results in terms of horizontal hydraulic conductivity and vertical anisotropy of hydraulic conductivity (Kh/Kv) for a variety of models of Pleistocene to Cambrian units in or near southeastern Wisconsin or northeastern Illinois -- continued

Source Unit	horizontal hydraulic conductivity (m/day)	Kh/Kv Anisotropy
Clite (1992)		
sand and gravel	110.0	1.0
weathered zone	1.6	1.0
Waukesha-Byron	0.95	1.0
Mayville	2.2	1.0
Mandle and Kontis (1992)		
Silurian-Devonian	0.12	N.A.
St. Peter-Eminence	1.84 to 2.50	N.A.
Ironton-Galesville	1.84 to 2.24	N.A.
Mt. Simon	0.92 to 1.32	N.A.
M.M.S.D. (1992)		
unconsolidated	1.4	6400
Devonian	0.26	100.0
upper Silurian	N.A.	30.0
Mayville	N.A.	1000
Mueller (1992)		
weathered zone/ Devonian	0.24 to 8.7	10.0
Waubakee/Racine	0.034	10.0
Romeo beds	1.7	10.0
Waukesha-Byron	0.017	10.0
Mayville	0.43	10.0
Cannestra (1994) [mean & std. dev. of 8 cross-sections]		
Glacial	0.63 ± 0.37	26 ± 21
Silurian dol.#	0.01 ± 0.00	500 ± 0
Galena-Platteville		
weathered	3.39 ± 0.62	21 ± 8
unweathered	2.19 ± 0.56	114 ± 15
St.Peter-Jordan	0.89 ± 0.38	25 ± 16
St. Lawrence- Tunnel City	1.13 ± 0.31	100 ± 0
Elk Mound	3.24 ± 0.40	36 ± 25
Camp Dresser and McKee (1995)		
Racine	0.045 to 0.2	6.7 or 100
Romeo beds	0.015	6.7
Waukesha	0.00003	100

Table 23. - Model results in terms of horizontal hydraulic conductivity and vertical anisotropy of hydraulic conductivity (Kh/Kv) for a variety of models of Pleistocene to Cambrian units in or near southeastern Wisconsin or northeastern Illinois -- continued

Source Unit	horizontal hydraulic conductivity (m/day)	Kh/Kv Anisotropy
# present in only one of the eight cross-sections		
Mulvey (1995)		
weathered zone	1.30	1.5
Waubakee/Racine	0.0389	1.5
Romeo beds	2.07	1.5
Manistque/Byron	0.0389	1.5
Mayville	1.12	1.5
Conlon (1998)		
Silurian-Devonian	1.00	N.A.
Ancell-Elk Mound	0.46 to 0.91	N.A.
Linnemanstons (in progress)		
glacial till	0.0086	25.0
weathered zone/ New Berlin Till	0.106	29.0
Milwaukee	0.0076	40.0
Thiensville	10.8	10.0
Waubakee/Racine	0.012	1.0
Romeo beds	1.42	1.0
Manistique	0.01	1.0
Mayville	0.108	1.0

Table 23. - Model results in terms of horizontal hydraulic conductivity and vertical anisotropy of hydraulic conductivity (Kh/Kv) for a variety of models of Pleistocene to Cambrian units in or near southeastern Wisconsin or northeastern Illinois – continued.

Source Unit	horizontal hydraulic conductivity (m/day)	Kh/Kv Anisotropy
Carlson (in progress)*		
alluvium	132 to 270	3.8 to 4.7
weathered till	4.24 to 8.61	53.0
lacustrine	2.07 to 2.8	100
Oak Creek Till/ Ozaukee Till	0.0987 to 0.201	120 to 150
New Berlin Till	2.35 to 3.2	63.0
weathered zone	1.29 to 1.60	109 to 608
Lindwurm	0.00695 to 0.0212	15.4 to 55.6
Berthelet	0.362 to 0.412	336 to 369
Thiensville	5.8 to 9.3	262 to 289
Waubakee	0.0302 to 0.0717	66.2 to 102
Racine	0.0421 to 0.0526	27.9 to 70.0
Romeo beds	0.659	681 to 1700
Waukesha	0.032	88.6 to 222
Brandon Bridge	0.0156	43.2 to 108
Franklin	0.0252	69.8 to 175
Byron	0.0108	29.9 to 75.0
Mayville	0.108 to 0.511	1050 to 3110

*range a result of different values for three models

Table 24. - Summary of point results for porosity from the combined data sets of Schulze-Makuch (1996) and Carlson (in progress).

stratigraphic unit	number of observations	mean (%)	standard deviation (%)
Thiensville	6	7.12	3.24
Racine	5	2.27	1.38
Romeo beds	7	3.17	2.54
Mayville	9	2.63	1.47

Table 25. - Porosity for various unconsolidated units in southeastern Wisconsin for only a part of Rodenback's (1988) study area of eastern Wisconsin that lies in southeastern Wisconsin.

Type of sediment or unit	no. of obs.	Percent of water content mean	std. dev.	porosity mean(%)
Ozaukee Till	23	17.50	2.64	32.1
Oak Creek Till	191	17.59	4.19	32.2
New Berlin Till	1	20.50	0.00	35.6
Zenda Till	1	9.90	0.00	21.1
Tiskilwa Till	4	11.65	4.28	23.9
Lacustrine	21	16.29	6.00	30.5
Outwash	4	14.20	5.27	27.7

Table 26. - Porosity for various unconsolidated units in eastern Racine Co. and southern Milwaukee Co. in Simpkins' (1989) study area.

Type of sediment or unit	no. of obs.	Percent of water content mean	std. dev.	porosity mean(%)
Oak Creek Till	1333	18.32	7.46	33.1
New Berlin Till	13	13.25	3.80	26.3
Alluvium	167	13.47	5.74	26.7
Lacustrine	188	17.45	6.57	32.0

Table 27. - Porosity for various unconsolidated units in and around Milwaukee, Wisconsin. Results are from analysis of water content tests conducted by M.M.S.D.

Type of sediment or unit	no. of obs.	Percent of water content mean	std. dev.	porosity mean(%)
M.M.S.D., 1984a				
sediment type:				
esturaine	523	55.0	28.5	59.3
lacustrine	445	20.0	4.3	34.6
glacial till	1140	14.0	4.2	27.1
M.M.S.D., 1984b				
Esturaine	999	57.0	31.0	60.2
lacustrine	627	20.0	5.0	34.6
glacial till	1794	14.0	4.0	27.1
sediment type:				
alluvium	212	23.7	13.2	38.6
outwash	70	14.3	4.2	27.5
lacustrine	1127	18.6	4.5	33.0
esturaine	899	57.1	37.7	60.2
stratigraphic units:				
weathered Ozaukee Till	12	17.5	3.4	31.7
unweathered Ozaukee Till	0	----	----	----
weathered Oak Creek Till	559	14.7	4.4	28.0
unweathered Oak Creek Till	1189	13.0	3.6	25.6
weathered New Berlin Till	0	----	----	----
unweathered New Berlin Till	37	12.2	4.3	24.4

Table 28. - Porosity values as determined from core-volume-displacement method for six major studies in southeastern Wisconsin.

Type of sediment or unit	no. of obs.	porosity (%) mean	porosity (%) std. dev.
(M.M.S.D., 1981, 1984a,b, 1989)			
Lindwurm	6	8.75	3.00
Berthelet	2	4.15	5.44
Thiensville	6	11.83	7.19
Waubakee	6	4.60	6.79
Racine	12	4.68	2.48
Romeo beds	1	8.20	0.00
Waukesha	1	5.30	0.00
Franklin	1	3.40	0.00
Palispis (1985)			
Waubakee	14	13.28	1.35
Racine	30	6.34	1.06
Schulze-Makuch (1996)			
Thiensville	20	11.78	4.70
Racine	4	6.15	4.56
Romeo beds	9	5.07	3.46
Mayville	8	3.46	2.19
composite results			
Lindwurm	6	8.75	3.00
Berthelet	2	4.15	5.44
Thiensville	26	11.79	5.21
Waubakee	20	10.68	5.48
Racine	46	6.20	2.30
Romeo beds	10	5.38	3.41
Waukesha	1	5.30	0.00
Franklin	1	3.40	0.00
Mayville	8	3.46	2.19

Table 29. - Porosity values as determined from core-volume displacement method for Chicago's deep tunnel project (Harza Engineering Company, 1975a).

Type of sediment or unit	no. of obs.	porosity (%) mean	porosity (%) std. dev.
Racine	200	10.74	4.37
Romeo beds	35	6.32	4.19
Joliet			
Markgraf	62	7.74	4.05
Brandon Bridge	11	6.98	4.47
Kankakee	69	5.18	2.16
Edgewood	51	6.40	3.17
Maquoketa	36	17.28	8.31
Brainard	14	20.96	8.41
Ft. Atkinson	8	10.25	6.10
Scales	14	17.69	7.13
Galena	167	6.91	4.21
Platteville	174	5.81	3.85
St. Peter	13	19.41	4.06
Prairie du Chien	6	7.83	4.33
Potosi	8	6.94	3.96
Franconia	11	13.95	5.21
Ironton	2	8.35	1.95
Eau Claire	2	13.90	8.90

Table 30. - Porosity for a variety of studies completed in St. Peter Fm. down to Mt. Simon Fm. throughout southern Wisconsin and northern Illinois.

Type of sediment or unit	no. of obs.	porosity (%) mean	std. dev.
Emrich (1966)			
Galesville			
Herscher, Illinois	81	19.20	N.A.
Garfeild, Illinois	~50	21.70	N.A.
Ancona, Illinois	~25	22.50	N.A.
Potiac, Illinois	~25	20.20	N.A.
Mahomet, Illinois	~35	17.80	N.A.
Cutler (1979)			
Platteville	1	4.30	0.00
St. Peter	15	20.31	3.32
Jordan	2	16.00	4.53
Pujol-Rius (1980)			
St. Peter	64	22.70	3.30
Swingen (1981)			
St. Peter	8	13.28	2.11
Jachim dolomite	16	29.28	
Vaticon (1981)			
Mt. Simon	36	18.03	1.96
Spoerl (1984)			
St. Peter	18	23.76	1.57

Table 43. - Result of determining the confidence of difference for shale/clay content for the various pairs of adjacent units listed in Table 40. This WGNHS natural gamma data is from borings in Kenosha, Milwaukee, Racine and Washington Counties, all of which are in the southeastern Wisconsin model region.

		Confidence of Difference:		
Unit pair	T-value	>90%	>99%	>99.9%
Silurian-Maquoketa	12.99	yes	yes	yes
Maquoketa-Sinnipee	15.26	yes	yes	yes
Sinnipee-Glenwood	7.38	yes	yes	yes
Glenwood-St. Peter	6.84	yes	yes	yes
St. Peter-Jordan	0.07	no	no	no
Jordan-St. Lawrence	0.25	no	no	no
St. Lawrence-Lone Rock	9.16	yes	yes	yes
Lone Rock-Mazomanie	0.75	no	no	no
Mazomanie-Wonewoc	0.76	no	no	no
Wonewoc-Eau Claire	8.99	yes	yes	yes
Eau Claire-Mt. Simon	18.19	yes	yes	yes

Table 31. - Bulk porosity determined in Carlson (in progress) from the examination of M.M.S.D. neutron logs.

Type of sediment or unit	no. of obs.	porosity (%) mean	porosity (%) std. dev.
unconsolidated:			
alluvium	33	19.16	2.31
lacustrine	64	19.78	2.52
esturaine	0	-----	-----
outwash	23	17.25	1.02
Oak Creek Till	36	22.48	1.77
New Berlin Till	11	20.99	2.80
Silurian dolomite:			
Racine	473	4.89	0.73
Romeo beds	41	3.93	0.59
Waukesha	163	3.93	0.57
Brandon Bridge	51	3.58	0.41
Franklin	103	5.68	1.13
Byron	35	3.83	0.60
Mayville	330	3.98	0.49
Ordovician rock:			
Maquoketa Group			
Brainard	50	8.57	2.91
Fort Atkinson	65	8.52	2.00
Scales	155	13.94	3.89
Sinnipee Group			
Galena	45	2.68	1.61
Decorah	33	3.34	0.78
Platteville	57	2.57	1.63
Ancell Group			
St. Peter	13	6.75	1.83

Table 32. - Bulk porosity determined in Carlson (in progress) from the examination of M.M.S.D. density logs. The base reference for material density is that of limestone for Silurian units and Sinnipee units. For the Maquoketa Group base density used was that of limestone for Ft. Atkinson and shale for Brainard and Scales.

		porosity (%)	
Type of sediment or unit	no. of obs.	mean	std. dev.
Silurian dolomite:			
Racine	657	5.88	2.91
Romeo beds	48	8.45	1.86
Waukesha	181	7.20	2.39
Brandon Bridge	69	5.99	2.17
Franklin	115	9.43	4.12
Byron	41	6.93	1.94
Mayville	492	7.53	2.95
Ordovician rock:			
Maquoketa Group			
Brainard	55	0.08	3.55
Fort Atkinson	71	3.75	3.39
Scales	155	-0.29	2.57
Sinnipee Group			
Galena	39	5.01	1.67
Decorah	33	7.02	1.37
Platteville	55	4.93	3.29

Table 33. - Bulk porosity determined in Carlson (1998d) from the examination of Chicago deep tunnel (sonic logs).

Type of sediment or unit	no. of obs.	porosity (%) mean	std. dev.
Racine	221	9.48	3.06
Joliet			
Romeo beds	43	8.14	1.55
Markgraf	117	9.83	2.47
Brandon Bridge	14	10.07	2.01
Kankakee	177	8.31	2.00
Edgewood	136	9.99	2.51
Maquoketa			
Neda	13	23.62	9.74
Brainard	356	25.00	3.92
Fort Atkinson	69	15.95	5.32
Scales	368	32.40	3.29
Galena			
Wise Lake	750	8.73	2.89
Guttenberg	20	10.43	2.44
Platteville			
Naschusa	130	7.85	1.57
Grand Detour	118	7.16	1.09
Mifflin	73	7.38	1.08
Pecatonica	156	7.88	1.32
Ancell			
Glenwood	15	8.33	0.92
St. Peter	90	20.19	4.34
Prairie du Chien	66	12.33	5.82
Potosi	99	8.85	2.63
Franconia	63	15.68	3.12
Ironton	60	15.40	3.60
Galesville	25	23.28	2.54
Eau Claire	7	13.00	5.98

Table 34. - Confidence of the difference of porosity for adjacent units for the analysis of neutron logs in Milwaukee as listed in Table 31. Statistical analysis is completed by the use of a T-test.

		Confidence of Difference:		
Unit pair	T-value	>90%	>99%	>99.9%
Racine-Romeo beds	8.08	yes	yes	yes
Romeo beds-Waukesha	0.00	no	no	no
Waukesha-Brandon Bridge	4.01	yes	yes	yes
Brandon Bridge-Franklin	12.66	yes	yes	yes
Franklin-Byron	9.40	yes	yes	yes
Byron-Mayville	1.76	yes	no	no
Mayville-Brainard	26.16	yes	yes	yes
Brainard-Ft. Atkinson	0.11	no	no	no
Ft. Atkinson-Scales	10.53	yes	yes	yes
Scales-Galena	18.65	yes	yes	yes
Galena-Decorah	2.11	yes	no	no
Decorah-Platteville	2.49	yes	yes	no
Platteville-St. Peter	7.77	yes	yes	yes

Table 35. - Confidence of the difference of porosity for adjacent units for the analysis of sonic logs in Chicago as listed in Table 33. Statistical analysis is completed by the use of a T-test.

Unit pair	T-value	Confidence of Difference: >90%	>99%	>99.9%
Racine-Romeo beds	2.76	yes	yes	no
Romeo beds-Markgraf	4.12	yes	yes	yes
Markgraf-Brandon Bridge	0.14	no	no	no
Brandon Bridge-Kankakee	3.04	yes	yes	yes
Kankakee-Edgewood	6.55	yes	yes	yes
Edgewood-Neda	18.61	yes	yes	yes
Neda-Brainard	1.11	no	no	no
Brainard-Ft. Atkinson	16.33	yes	yes	yes
Ft. Atkinson-Scales	33.76	yes	yes	yes
Scales-Wise Lake	122.24	yes	yes	yes
Wise Lake-Guttenberg	2.54	yes	no	no
Guttenberg-Naschusa	6.11	yes	yes	yes
Naschusa-Grand Detour	3.95	yes	yes	yes
Grand Detour-Mifflin	1.35	no	no	no
Mifflin-Pecatonica	2.79	yes	yes	no
Pecatonica-Glenwood	1.24	no	no	no
Glenwood-St. Peter	10.09	yes	yes	yes
St.Peter-Prairie du Chien	9.54	yes	yes	yes
Prairie du Chien-Potosi	5.16	yes	yes	yes
Potosi-Franconia	14.78	yes	yes	yes
Franconia-Ironton	0.45	no	no	no
Ironton-Galesville	9.66	yes	yes	yes
Galesville-Eau Claire	6.22	yes	yes	yes

Table 36. - Average recharge rate for previous ground water models used for studies in or near southeastern Wisconsin.

Source	recharge rate (cm/yr)	location
Ladwig (1981)		
glacial till	0.54	Cedarburg Bog
peat	0.06	Ozaukee Co., WI
Rovey (1983)	1.4	Mequon, WI
Emmons (1987)	1.7	northeastern WI
Young and others (1988)		
steady state		
Silurian-Devonian	0.05	Chicago-Madison- Milwaukee
St. Peter-Jordan	0.61	
Ironton-Galesville	0.15	
Mt. Simon	0.08	
Young and others (1988)		
unsteady state		
Silurian-Devonian	0.20	Chicago-Madison- Milwaukee
St. Peter-Jordan	1.14	
Ironton-Galesville	0.20	
Mt. Simon	0.08	
Young and others (1988)		
Silurian-Devonian	0.07	Chicago-Milwaukee
Maquoketa-Sinnipee	0.46	
St.Peter-Jordan	1.19	
Plomb (1989)	2.5	Menomonee Valley Milwaukee, WI
Webb (1989)	5.1	Kewaunee Co. to Port Washington, WI
Nader (1990)	6.3	eastern Mequon, WI
Burch (1991)		
Maquoketa shale missing		northeastern Illinois/southeastern Wisconsin
in Wisconsin	1.9	
in Illinois	1.6	
Maquoketa shale present	0.11	

Table 36. - Average recharge rate for previous ground water models used for studies in or near southeastern Wisconsin -- continued

Source	recharge rate (cm/yr)	location
Cherkauer and Mikulic (1992)	1.9	Kenosha, Milwaukee, Ozaukee & Racine Co., WI
Clite (1992)	7.1	Sussex, WI
Mueller (1992)	5.1	Kenosha, Milwaukee,Ozaukee & Racine Co., WI
M.M.S.D. (1992)	5.1	east side of Milwaukee WI
Mulvey (1995)	5.4	Kewaunee Co. to Sheboygan Co.
Conlon (1998)	1.8	northeastern Wisconsin
Carlson (in progress)		
model AA'	1.2	east side of Milwaukee WI
model BB'	1.0	east side of Milwaukee WI
model CC'	4.6	Wauwatosa, Wi

Table 37. - Average baseflow "recharge rate" for watersheds that are at least partially in the southeastern Wisconsin groundwater model study area: and have at least 10 years of gaging records for Wisconsin watersheds and 5 years for Illinois watersheds.

Watershed	Years of Record	Recharge Rate (cm/yr) mean	std dev
Walton (1965)			
Crow Creek (Washburn)	5	7.72	N.A.
Des Plaines River (Gurnee)	5	5.65	N.A.
Des Plaines River (Des Plaines)	5	9.93	N.A.
Des Plaines River (Riverside)	5	8.14	N.A.
Du Page River (Troy)	5	13.23	N.A.
Hickory Creek (Lake Bloomington)	5	10.34	N.A.
Hickory Creek (Joliet)	5	8.00	N.A.
Iroquois River (Chebanse)	5	10.21	N.A.
Iroquois River (Iroquois)	5	10.21	N.A.
Kankakee River (Momence)	5	19.24	N.A.
Kankakee River (Wilmington)	5	13.86	N.A.
Killbuck Creek (Monroe)	5	6.34	N.A.
Kiswaukee River (Perryville)	5	10.34	N.A.
Kiswaukee River (Belvidere)	5	9.79	N.A.
North Fork Vermillion River	5	5.96	N.A.
Mackinaw River (Congerville)	5	8.69	N.A.
Mazon River (Coal City)	5	4.62	N.A.
Money Creek (Lake Bloomington)	5	10.07	N.A.
Salt Creek (Western Springs)	5	11.31	N.A.
South Branch Kiswaukee River			
near Firdale	5	7.79	N.A.
at DeKalb	5	8.48	N.A.
Spring Creek (Joliet)	5	13.52	N.A.
Vermillion River (Pontiac)	5	4.83	N.A.
Vermillion River (Lowell)	5	6.83	N.A.
Carlson (in progress)			
Kinnickinnic River (Milwaukee)	20	10.93	1.49
Menomonee River (Men. Falls)	19	11.58	3.76
Menomonee River (Wauwatosa)	36	9.12	3.60
Milwaukee River (Waubeka)	13	11.53	4.58
Milwaukee River (Cedarburg)	16	13.35	3.53
Milwaukee River (Milwaukee)	82#	9.92	4.18
Oak Creek (Oak Creek)	34	5.74	2.41
Root River (Franklin)	34	7.61	3.25
Underwood Creek (Wauwatosa)	21	8.46	2.43

Table 37. - Average baseflow "recharge rate" for watersheds that are at least partially in the southeastern Wisconsin groundwater model study area: and have at least 10 years of gaging records for Wisconsin watersheds and 5 years for Illinois watersheds -- continued

Watershed	Years of Record	Recharge Rate (cm/yr) mean	std dev
Carlson (1998e)			
Bark River (Rome)	16	14.45	4.87
Cedar Creek (Cedarburg)#	58	10.05	5.17
Des Plaines River (Russel Ill)	29	6.83	3.66
Fox River (Waukesha)	33	15.87	6.04
Fox River (Wilmot)#	57	11.37	5.15
Mukwonago River (Mukwonago)	24	11.07	3.92
Pike River (Racine)	26	9.13	2.45
Rock River (Watertown)#	59	8.17	5.74
Rock River (Afton)#	82	12.22	6.22
Root River (Racine)	34	6.15	2.97
Turtle Creek (Clinton)#	57	12.75	5.50

records that extend back to 1940s or earlier

Table 38. - Summary of analysis to determine Shale/clay content for various units from Lindwurm Member of the Milwaukee Fm. to St.Peter Fm. in the Ancell Group for M.M.S.D. natural gamma logs.

		Percentage of shale content	
Stratigraphic unit	no. of obs.	mean	std. dev.
Lindwurm	19	52.1	22.4
Berthelet	11	39.4	12.2
Thiensville	28	17.5	10.9
Waubakee	44	10.5	3.6
weathered Racine	105	19.2	9.6
unweathered Racine	618	17.7	10.0
Romeo beds	66	3.4	3.3
Waukesha	203	6.1	2.7
Brandon Bridge	72	12.7	5.5
Franklin	131	9.0	4.2
Byron	39	6.5	2.9
Mayville	505	7.4	7.6
Maquoketa:			
Brainard	67	37.3	18.7
Ft. Atkinson	90	30.5	13.9
Scales	196	57.2	20.7
Sinnipee:			
Galena	58	10.3	4.2
Decorah	52	8.6	4.6
Platteville	78	15.1	10.8
Ancell:			
St. Peter	11	7.4	11.3

Table 39. - Summary of analysis to determine Shale/clay content for various units from Racine Fm. to Eau Claire Fm. for Chicago deep tunnel natural gamma logs (Carlson, 1998f).

Stratigraphic unit	no. of obs.	Percentage of shale content mean	std. dev.
Racine	1339	8.69	11.17
Romeo beds	129	8.09	5.81
Markgraf	309	15.95	7.41
Kankakee	430	13.35	6.81
Edgewood	553	23.30	14.30
Maquoketa:			
Brainard	262	59.74	12.90
Ft. Atkinson	105	37.30	15.18
Scales	444	73.43	13.27
Galena:			
Wise Lake	870	7.45	4.58
Guttenberg	21	6.63	4.11
Platteville:			
Naschusa	164	5.25	2.81
Grand Detour	138	8.36	4.63
Mifflin	93	12.77	5.63
Pecatonica	157	6.52	3.78
Ancell			
Glenwood	16	13.02	5.50
St. Peter	339	5.88	5.14
Prairie du Chien	174	13.26	7.33
Potosi	233	9.61	7.14
Franconia	141	62.11	25.91
Ironton	104	15.65	7.95
Galesville	36	9.27	6.03
Eau Claire	6	23.02	5.29

Table 40. - Summary of analysis to determine Shale/clay content for various units from Racine Fm. to Mount Simon Fm. for Wisconsin Geological and Natural History Survey logs natural gamma logs (Carlson, 1998f).

		Percentage of shale content	
Stratigraphic unit	no. of obs.	mean	std. dev.
Silurian	92	26.96	11.72
Maquoketa	79	55.21	16.29
Sinnipee	129	21.20	14.90
Glenwood	9	64.07	26.52
St. Peter	56	15.98	16.76
Jordan	2	14.80	10.75
St. Lawrence	13	18.94	15.17
Lone Rock	5	34.00	34.02
Mazomanie	2	3.95	1.48
Wonewoc	33	16.45	16.00
Eau Claire	54	67.48	29.22
Mt. Simon	227	15.05	15.40

Note the stratigraphy noted is that of WGNHS, where the following is true
Silurian is Racine through Mayville
Maquoketa is Brainard through Scales
Sinnipee is Galena, Decorah and Platteville
Eminence & Potosi & Franconia are defined as Trempealeau and Tunnel City
Wonewoc is Ironton and Galesville

Table 41. - Results of determining the confidence of difference for shale/clay content for the various pairs of adjacent units listed in Table 38. This M.M.S.D. natural gamma data is from borings in Milwaukee, Wisconsin.

Unit pair	T-value	Confidence of Difference: >90%	>99%	>99.9%
Lindwurm-Berthelet	1.60	no	no	no
Berthelet-Thiensville	5.11	yes	yes	yes
Thiensville-Waubakee	3.83	yes	yes	yes
Waubakee-Racine	4.69	yes	yes	yes
Racine-Romeo beds	11.45	yes	yes	yes
Romeo beds-Waukesha	6.60	yes	yes	yes
Waukesha-Brandon Bridge	13.09	yes	yes	yes
Brandon Bridge-Franklin	5.18	yes	yes	yes
Franklin-Byron	3.42	yes	yes	yes
Byron-Mayville	0.72	no	no	no
Mayville-Brainard	23.83	yes	yes	yes
Brainard-Ft. Atkinson	2.58	yes	no	no
Ft. Atkinson-Scales	11.04	yes	yes	yes
Scales-Galena	16.94	yes	yes	yes
Galena-Decorah	1.99	yes	no	no
Decorah-Platteville	4.03	yes	yes	yes
Platteville-St. Peter	2.09	yes	no	no

Table 42. - Result of determining the confidence of difference for shale/clay content for the various pairs of adjacent units listed in Table 39. This Chicago deep tunnel natural gamma data is from borings in Chicago, Illinois

		Confidence of Difference:		
Unit pair	T-value	>90%	>99%	>99.9%
Racine-Romeo beds	0.60	no	no	no
Romeo beds-Markgraf	10.69	yes	yes	yes
Markgraf-Kankakee	4.92	yes	yes	yes
Kankakee-Edgewood	13.27	yes	yes	yes
Edgewood-Brainard	39.94	yes	yes	yes
Brainard-Ft. Atkinson	14.20	yes	yes	yes
Ft. Atkinson-Scales	24.24	yes	yes	yes
Scales-Wise Lake	131.86	yes	yes	yes
Wise Lake-Guttenberg	0.79	no	no	no
Guttenberg-Nachusa	1.94	yes	no	no
Nachusa-Grand Detour	7.13	yes	yes	yes
Grand Detour-Mifflin	6.44	yes	yes	yes
Mifflin-Pecatonica	10.40	yes	yes	yes
Pecatonica-Glenwood	6.04	yes	yes	yes
Glenwood-St. Peter SD	5.23	yes	yes	yes
St.Peter-Prairie du Chien	13.19	yes	yes	yes
Prairie du Chien-Potosi	5.02	yes	yes	yes
Potosi-Franconia SD	29.01	yes	yes	yes
Franconia SD-Ironton SD	17.53	yes	yes	yes
Ironton SD-Galesville SD	4.31	yes	yes	yes
Galesville SD-Eau Claire	4.72	yes	yes	yes

Table 43. - Result of determining the confidence of difference for shale/clay content for the various pairs of adjacent units listed in Table 40. This WGNHS natural gamma data is from borings in Kenosha, Milwaukee, Racine and Washington Counties, all of which are in the southeastern Wisconsin model region.

		Confidence of Difference:		
Unit pair	T-value	>90%	>99%	>99.9%
Silurian-Maquoketa	12.99	yes	yes	yes
Maquoketa-Sinnipee	15.26	yes	yes	yes
Sinnipee-Glenwood	7.38	yes	yes	yes
Glenwood-St. Peter	6.84	yes	yes	yes
St. Peter-Jordan	0.07	no	no	no
Jordan-St. Lawrence	0.25	no	no	no
St. Lawrence-Lone Rock	9.16	yes	yes	yes
Lone Rock-Mazomanie	0.75	no	no	no
Mazomanie-Wonewoc	0.76	no	no	no
Wonewoc-Eau Claire	8.99	yes	yes	yes
Eau Claire-Mt. Simon	18.19	yes	yes	yes

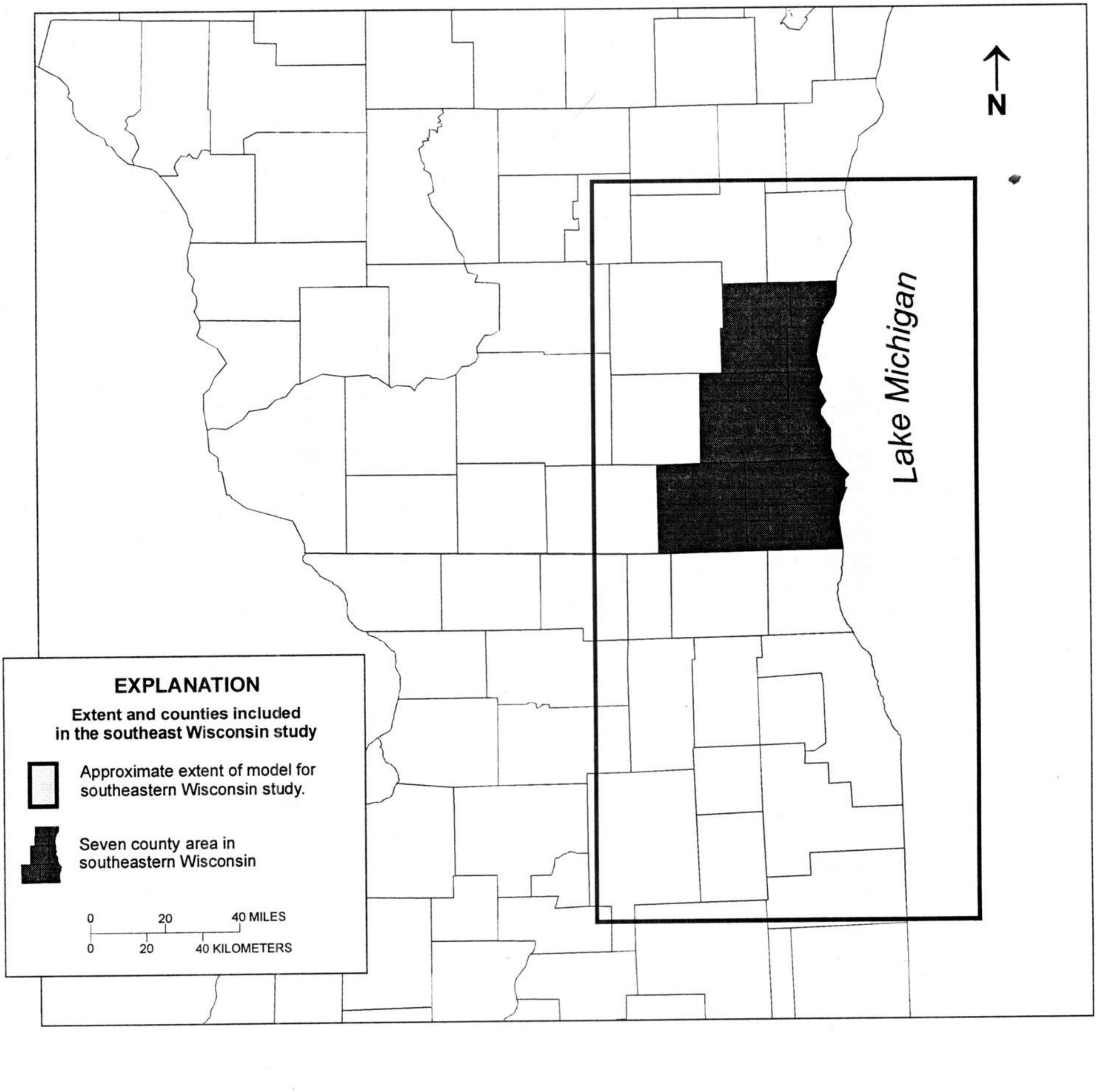


Figure 1. Location of southeastern Wisconsin study area which includes the following counties: Kenosha, Milwaukee, Ozaukee, Walworth, Washington and Waukesha.

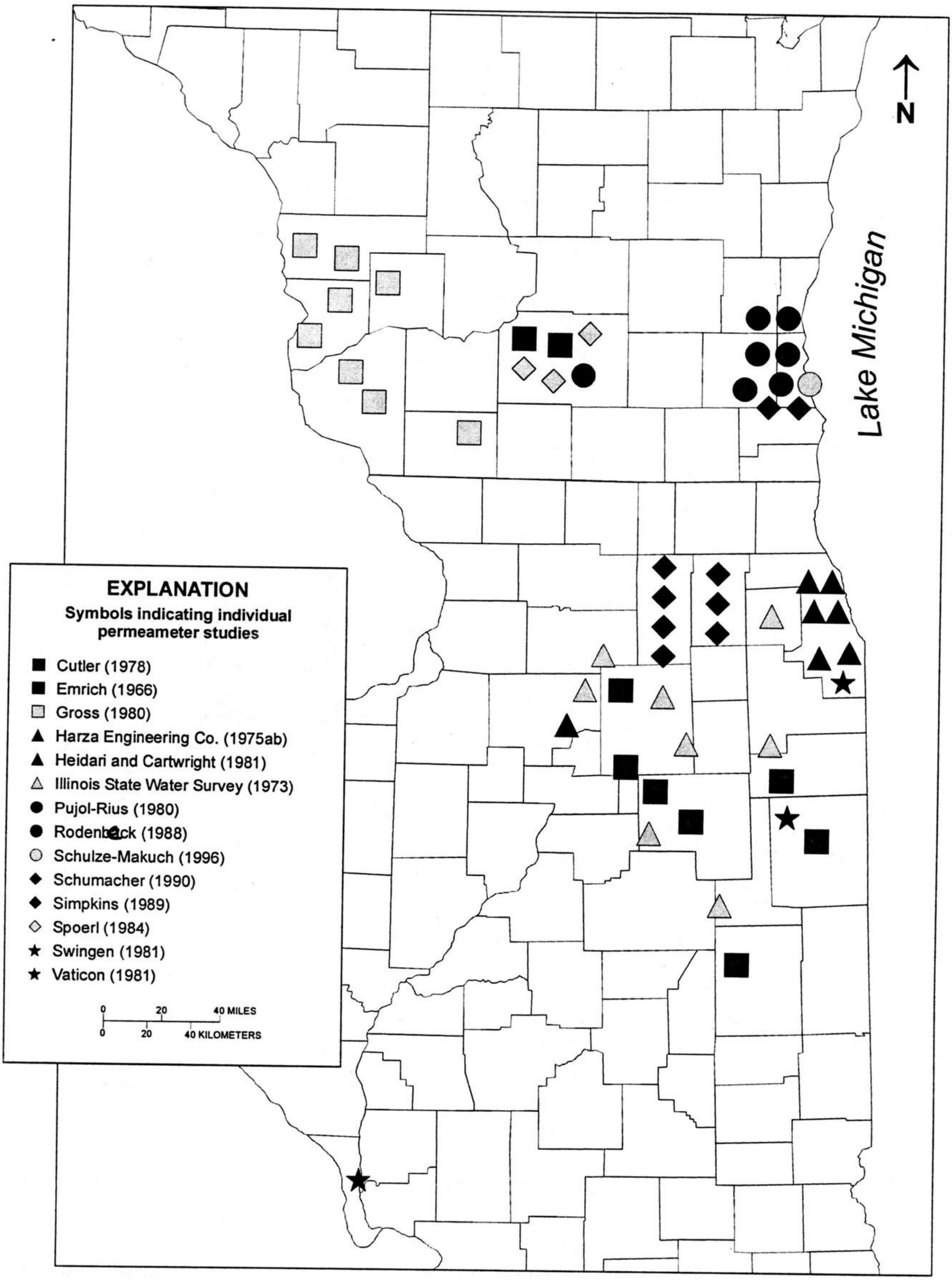
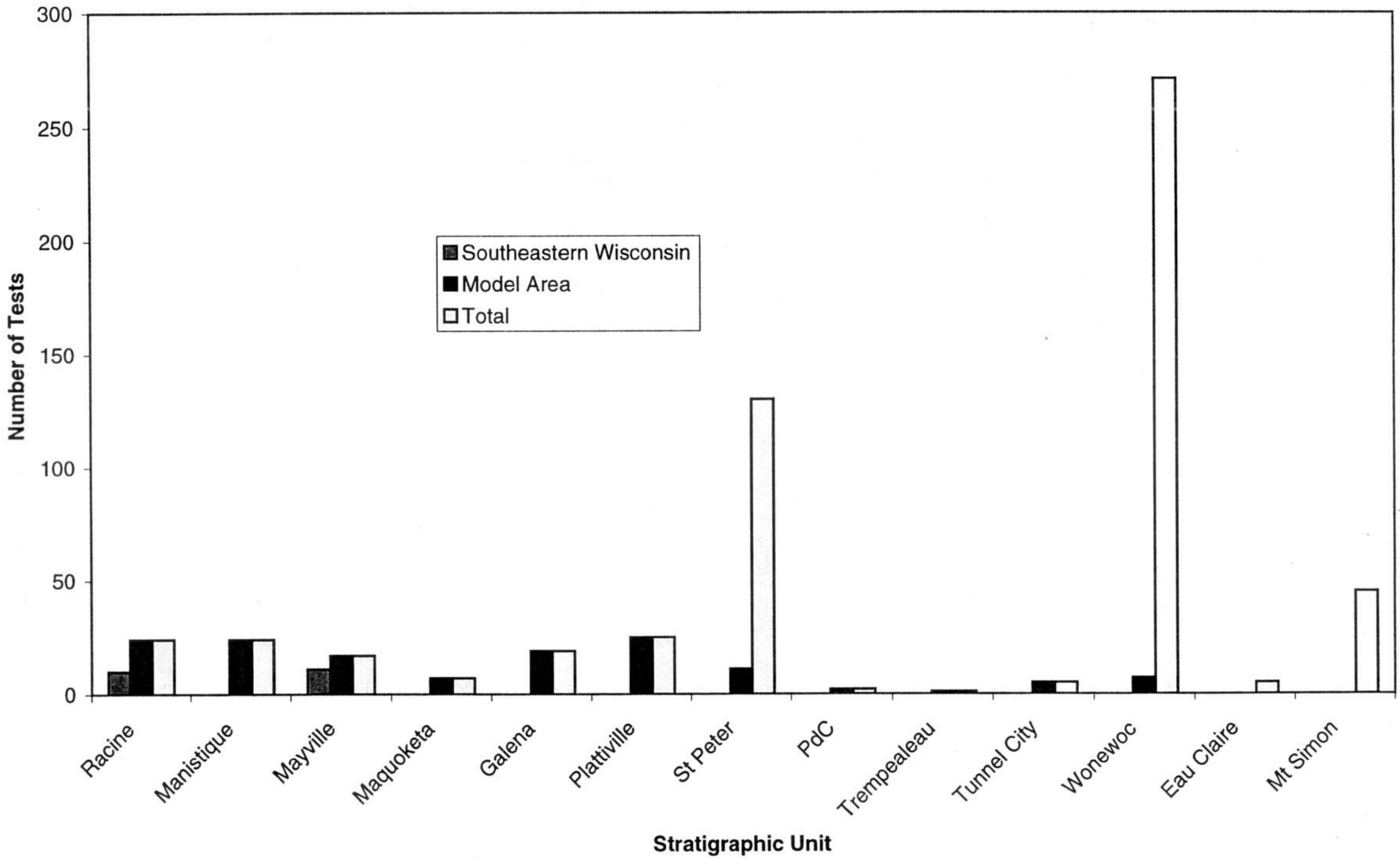


Figure 2. Location of permeameter studies throughout southern Wisconsin and northern Illinois in or near the southeastern Wisconsin study area.

Figure 3. -- Number of permeameter tests in southeastern Wisconsin and the model area.



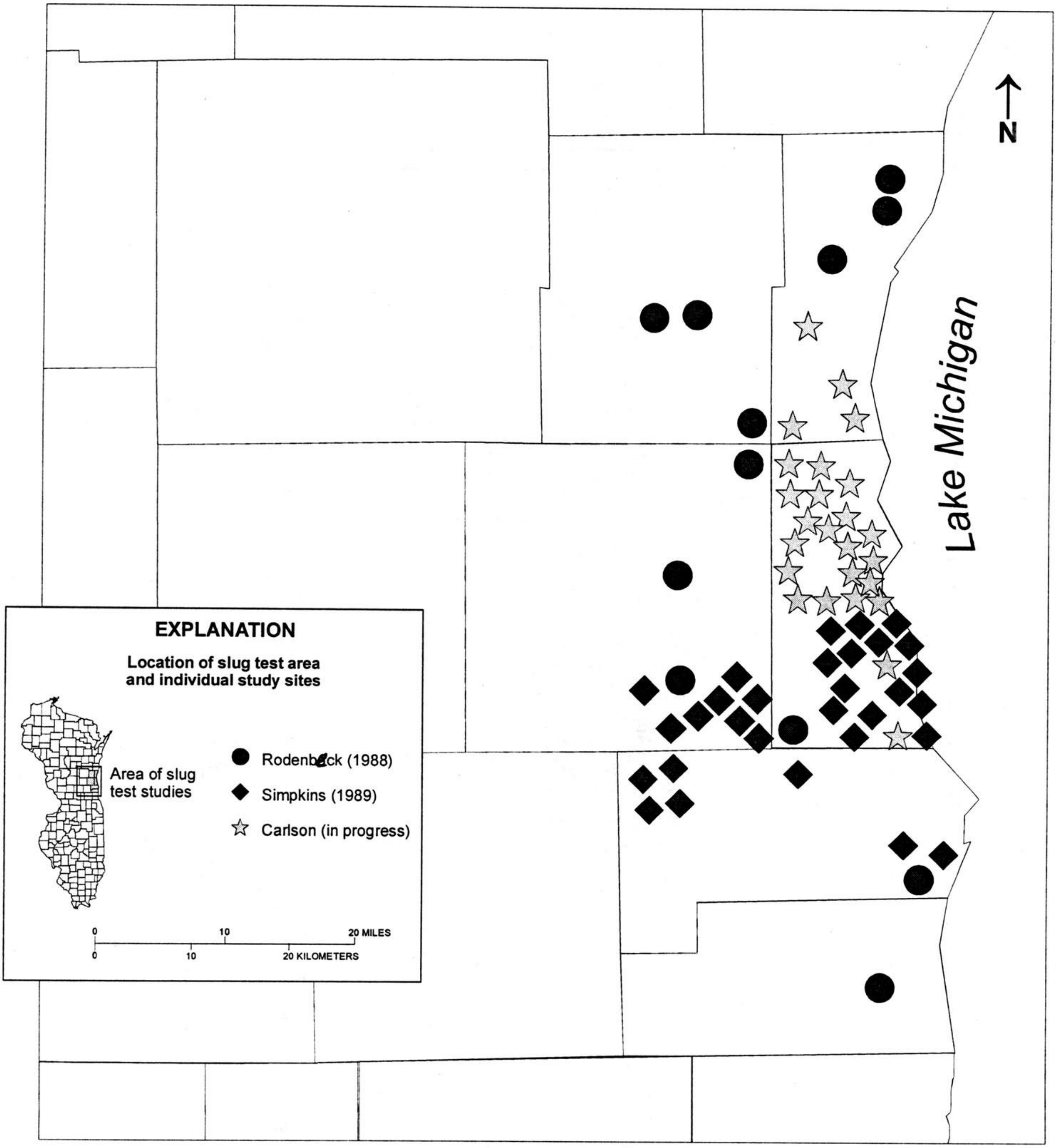


Figure 4. Location of slug test studies throughout southeastern Wisconsin.

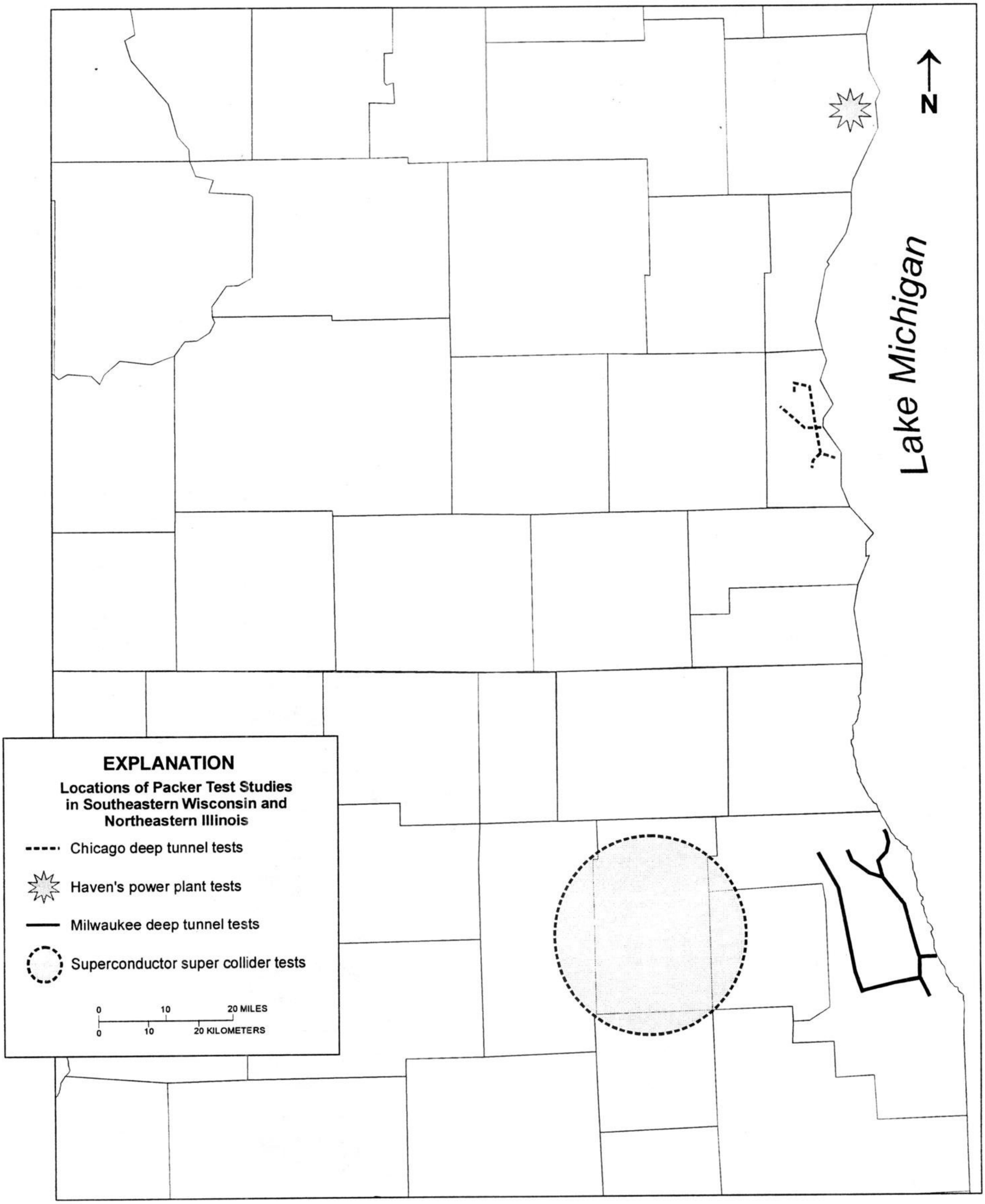
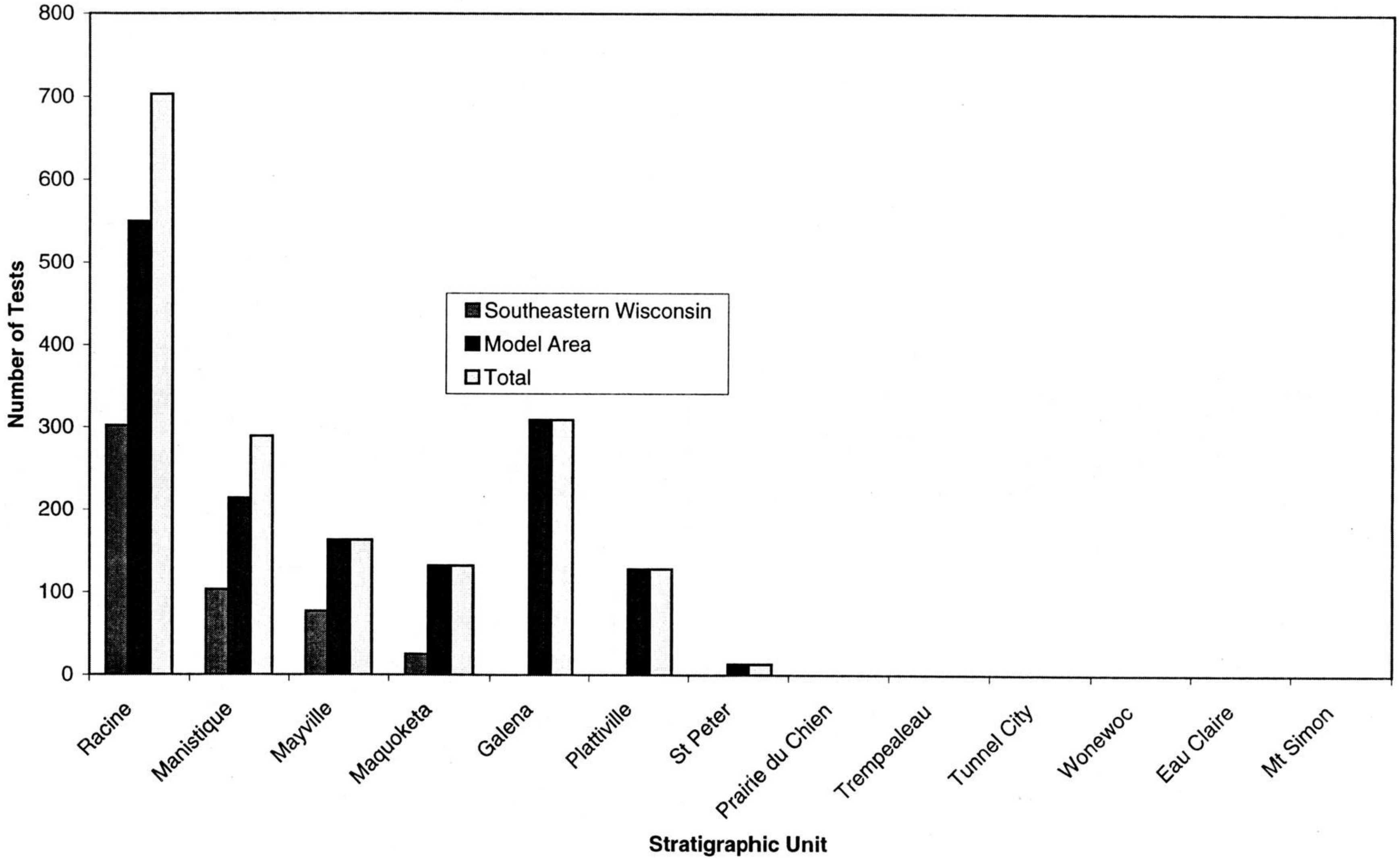


Figure 5. Location of packer (pressure) test studies throughout southeastern Wisconsin and northeastern Illinois.

Figure 6. -- Number of packer tests in southeastern Wisconsin and the model area.



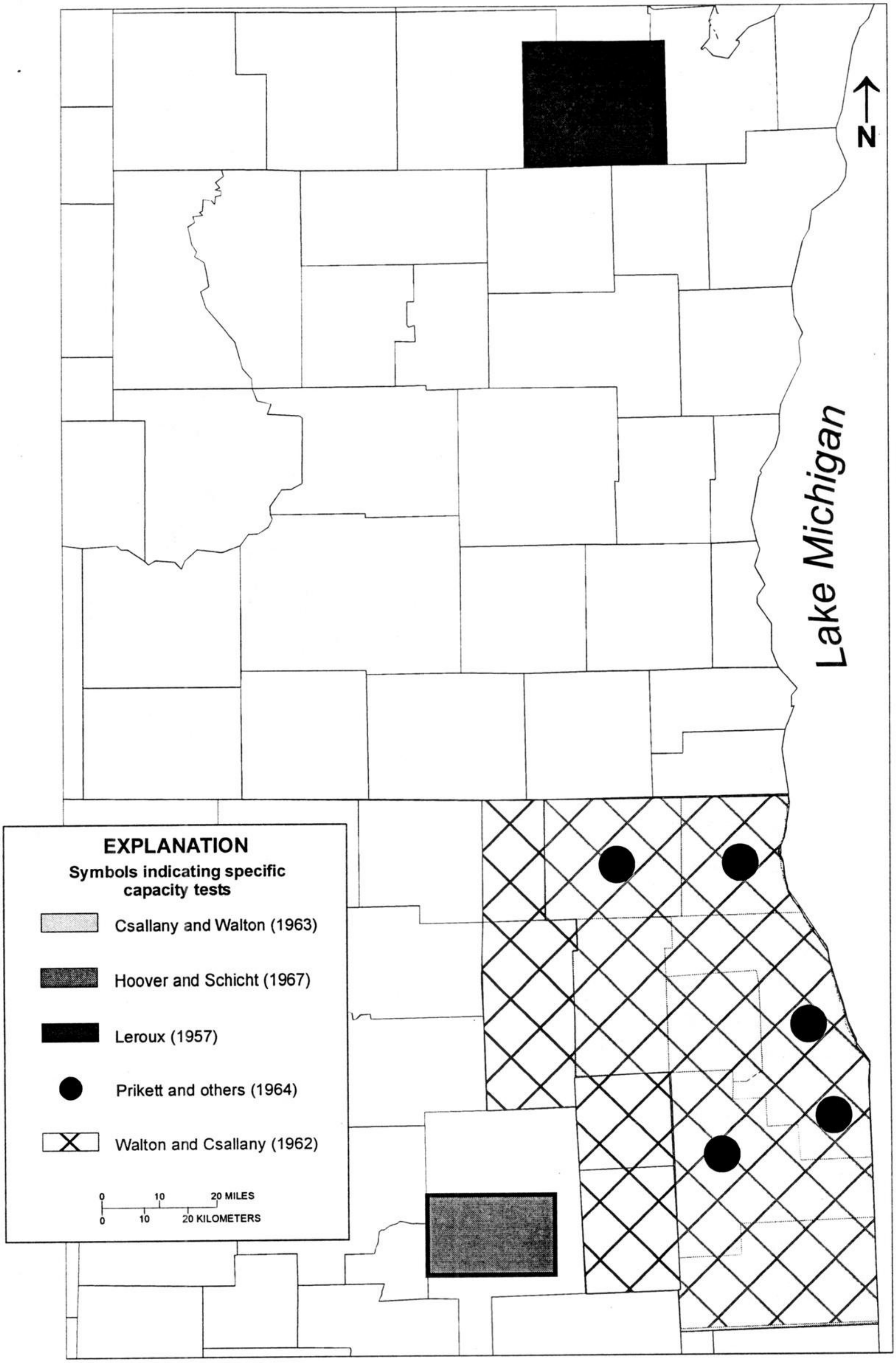


Figure 7a. Location of specific capacity test studies for the years between 1950-1969, in southern Wisconsin and northern Illinois.

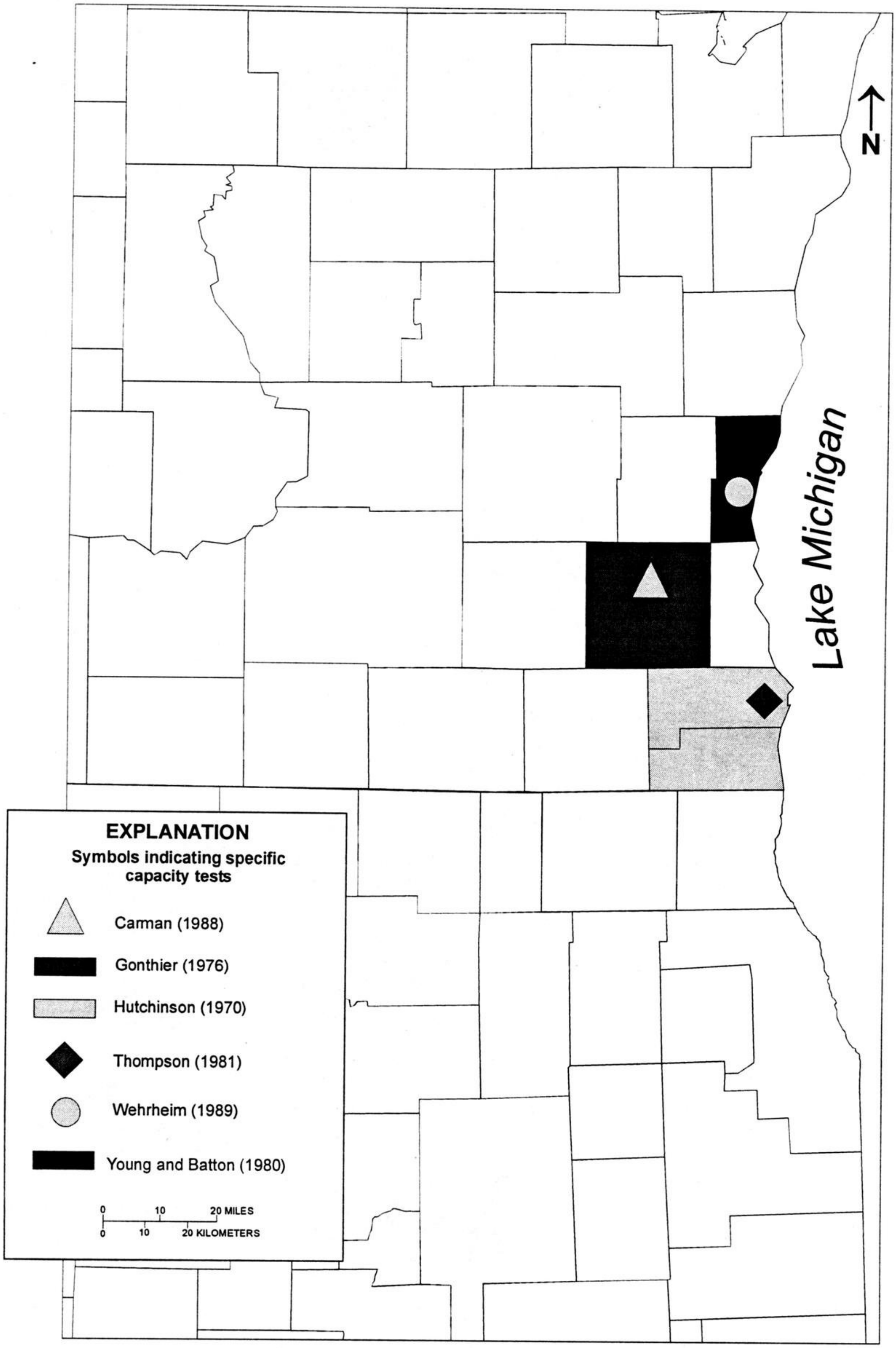


Figure 7b. Location of specific capacity test studies for the years between 1970-1989, in southern Wisconsin and northern Illinois.

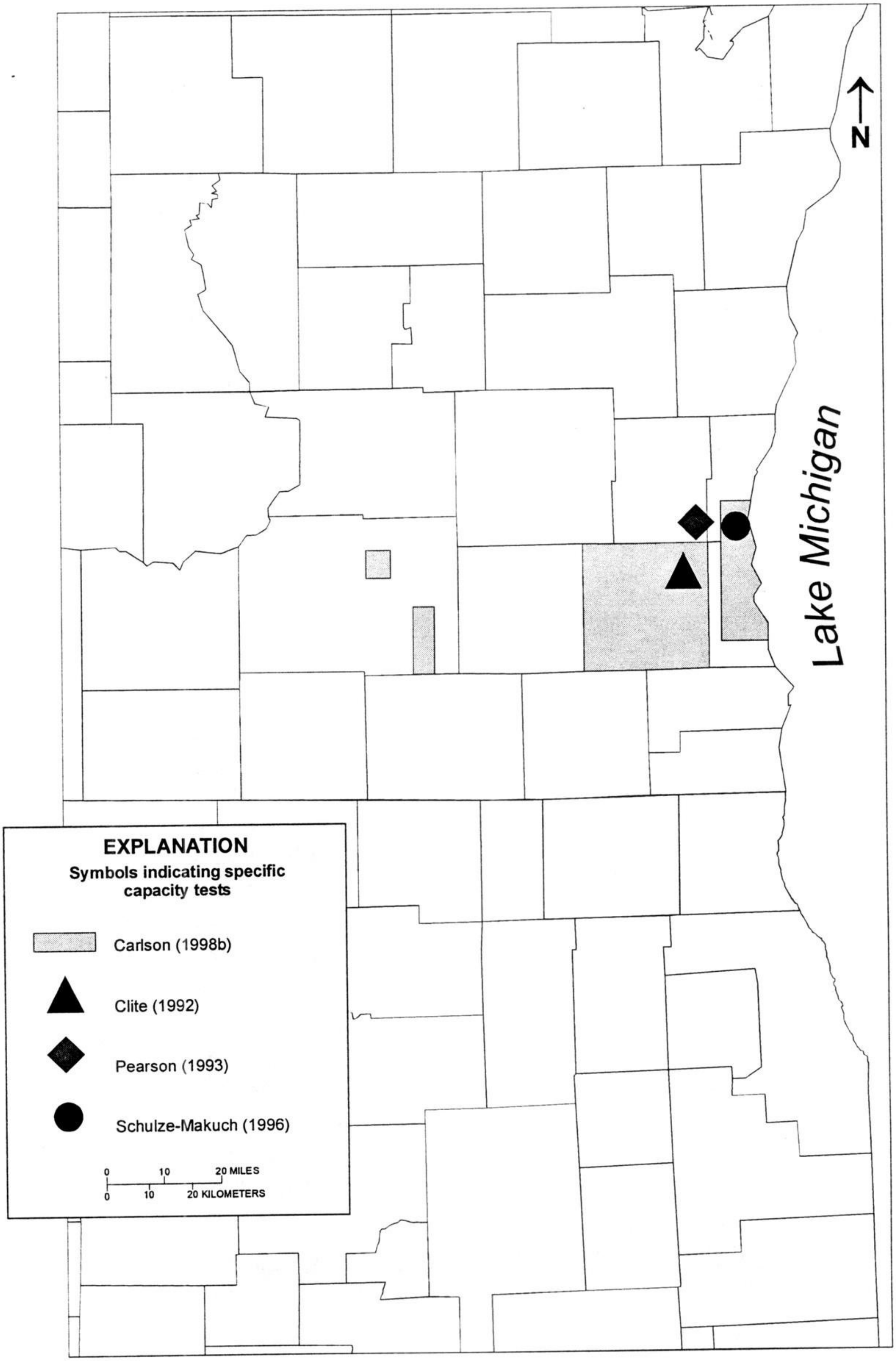
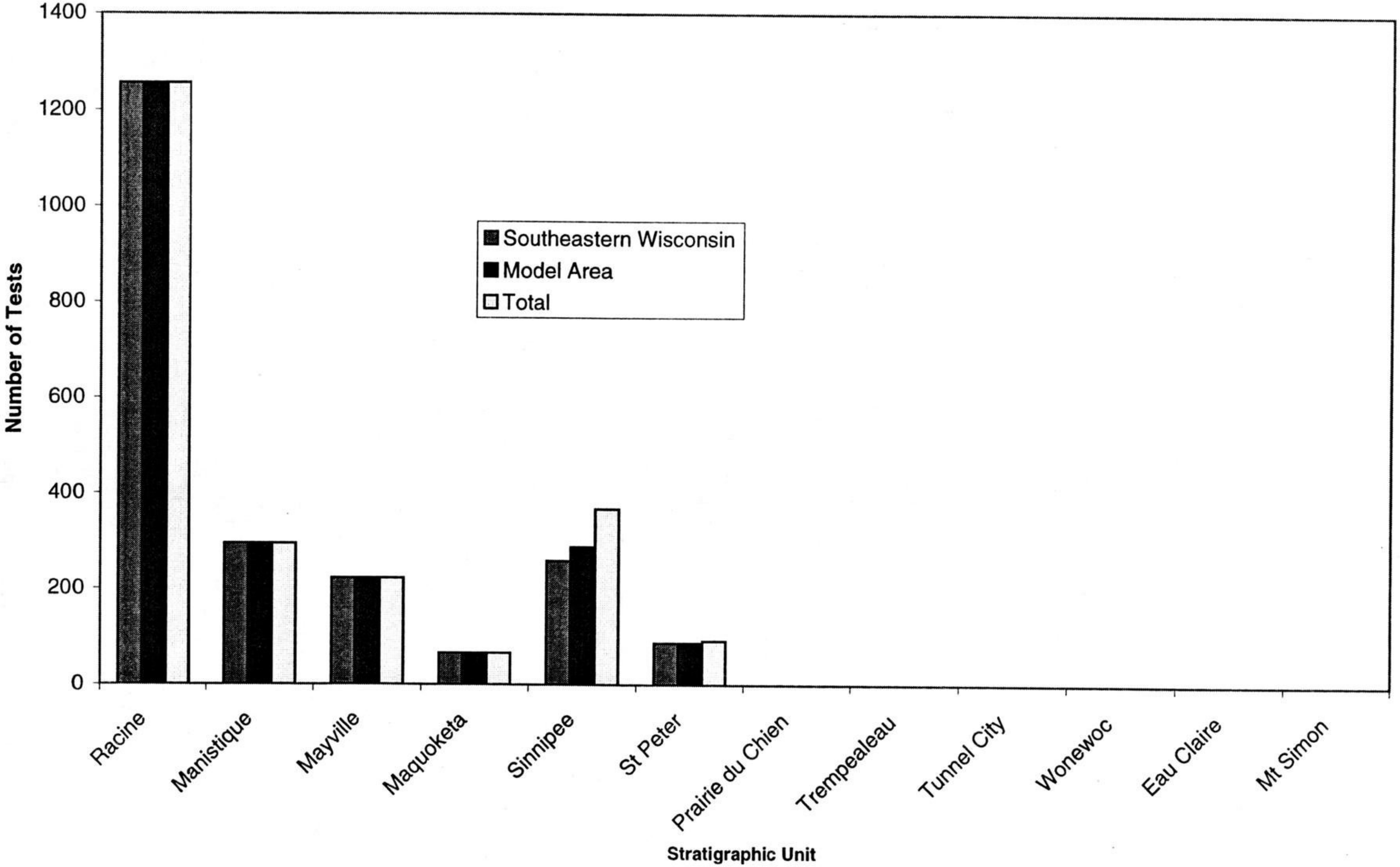


Figure 7c. Location of specific capacity test studies for the years between 1990-1999, in southern Wisconsin and northern Illinois.

Figure 8. -- Number of specific capacity tests in southeastern Wisconsin and the model area.



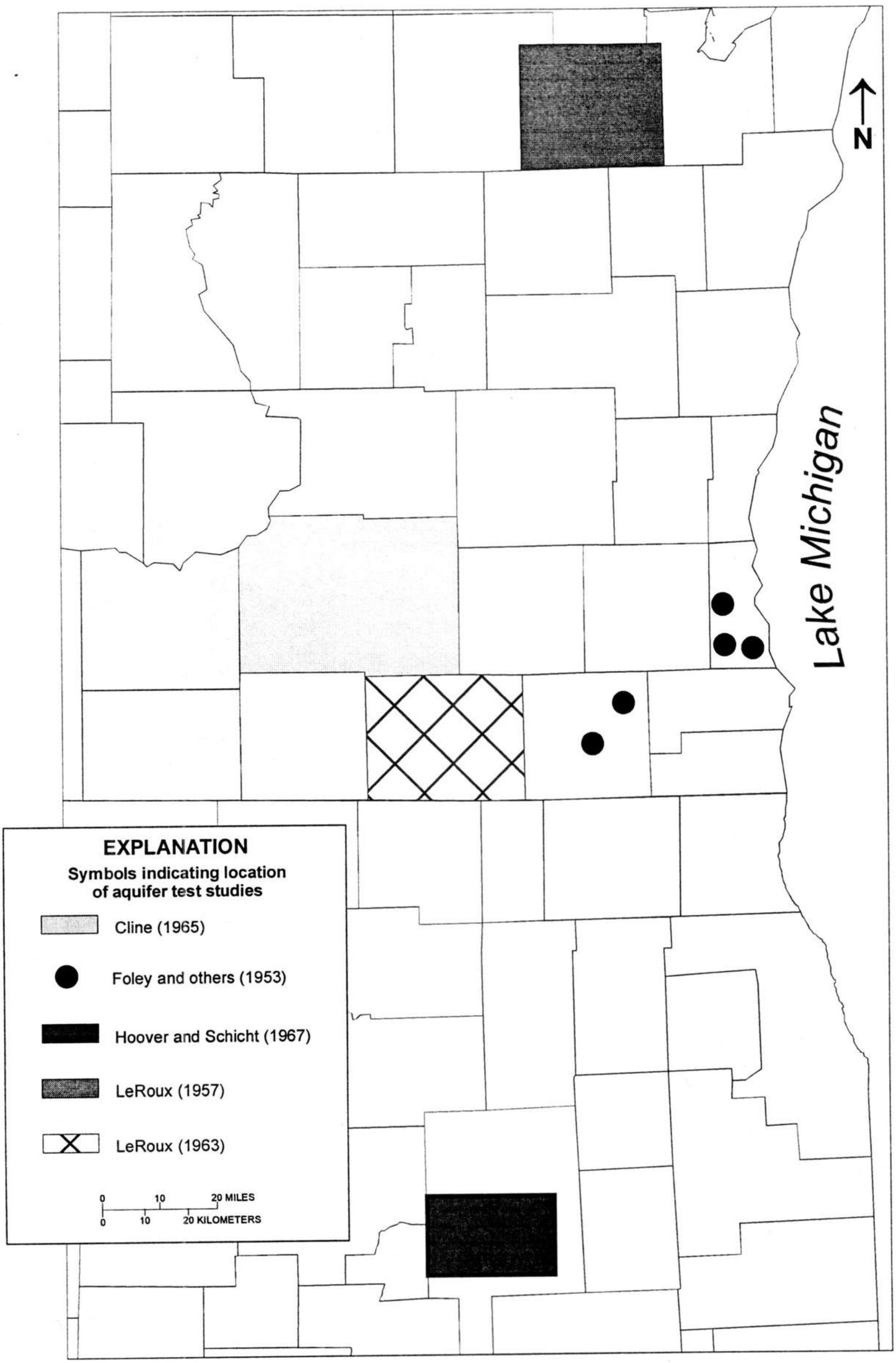


Figure 9a. Location of aquifer test studies for the years between 1950-1969, in southeastern Wisconsin and northern Illinois.

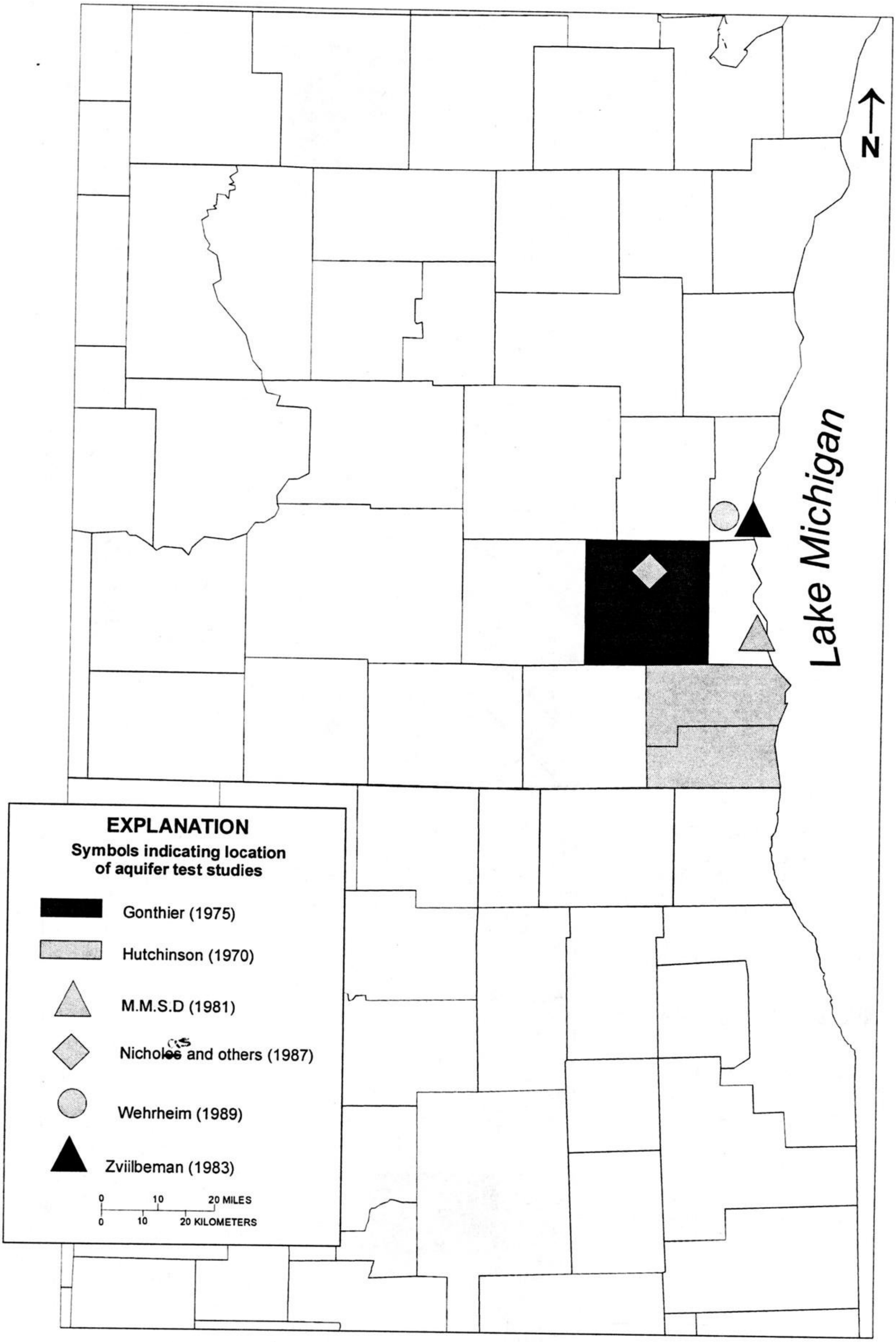


Figure 9b. Location of aquifer test studies for the years between 1970-1989, in southeastern Wisconsin and northern Illinois.

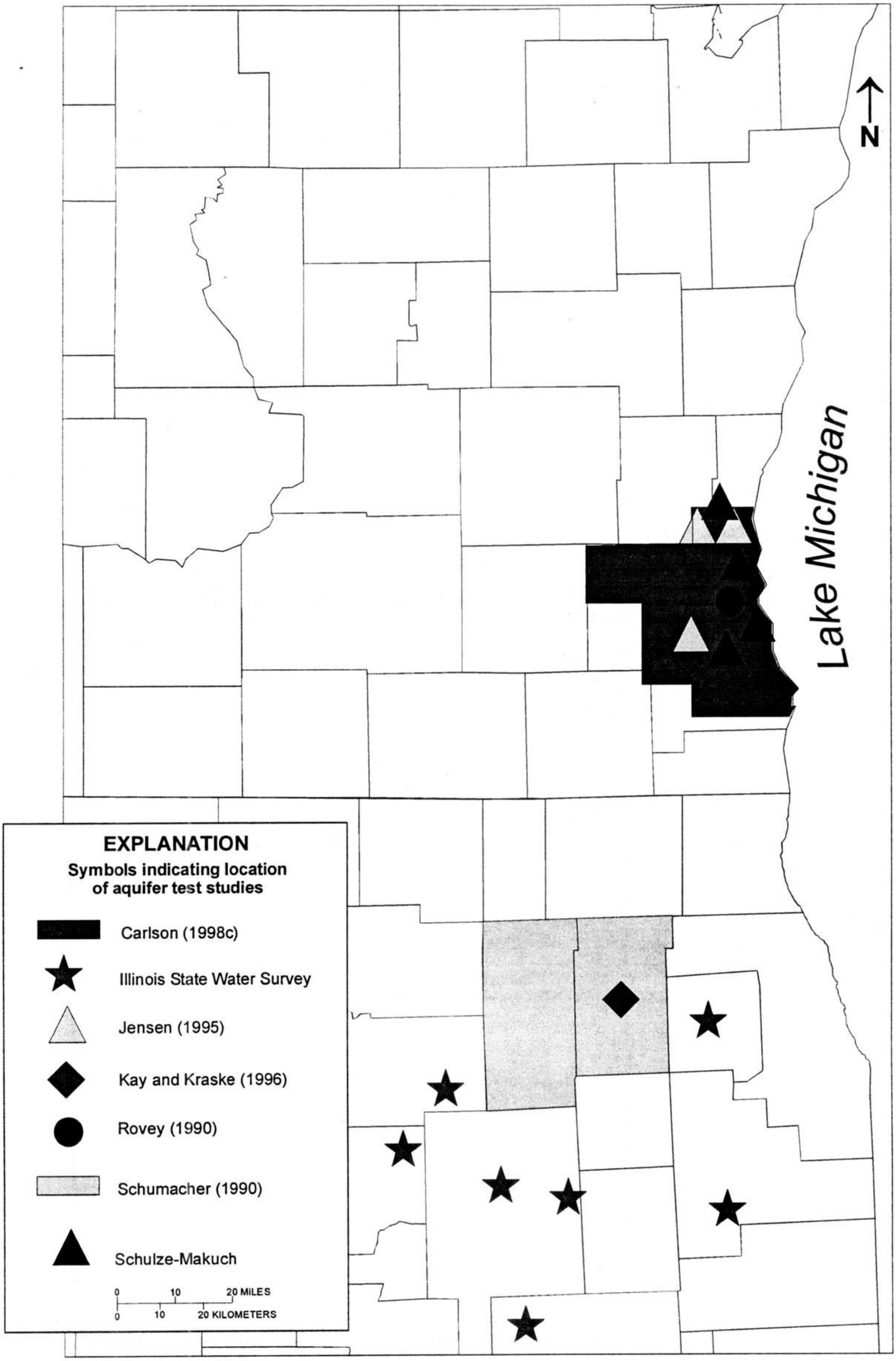


Figure 9c. Location of aquifer test studies for the years between 1990-1999, in southeastern Wisconsin and northern Illinois.

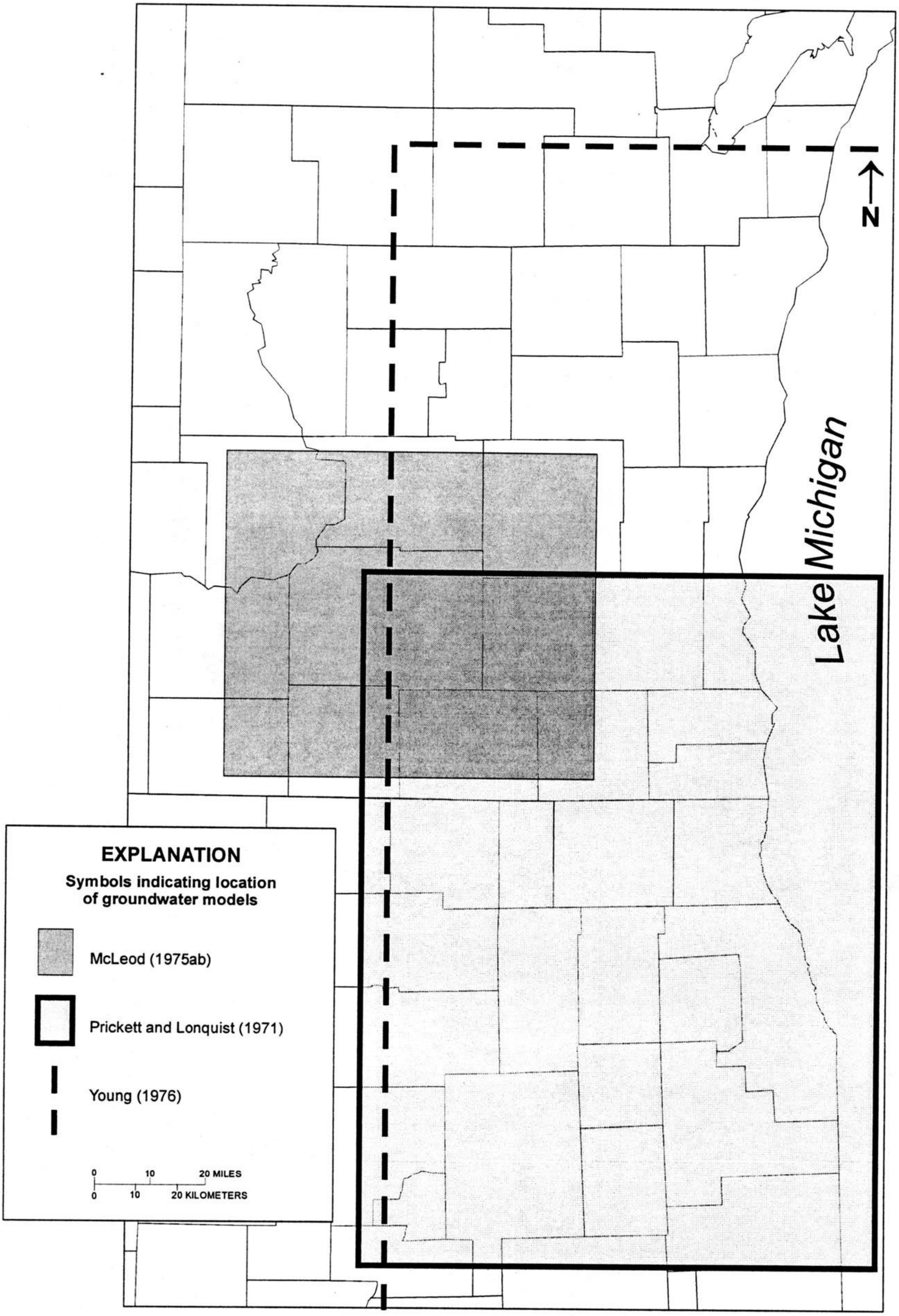


Figure 10a. Location of groundwater model studies for the years between 1970-1979, that are in or near southeastern Wisconsin and northern Illinois.

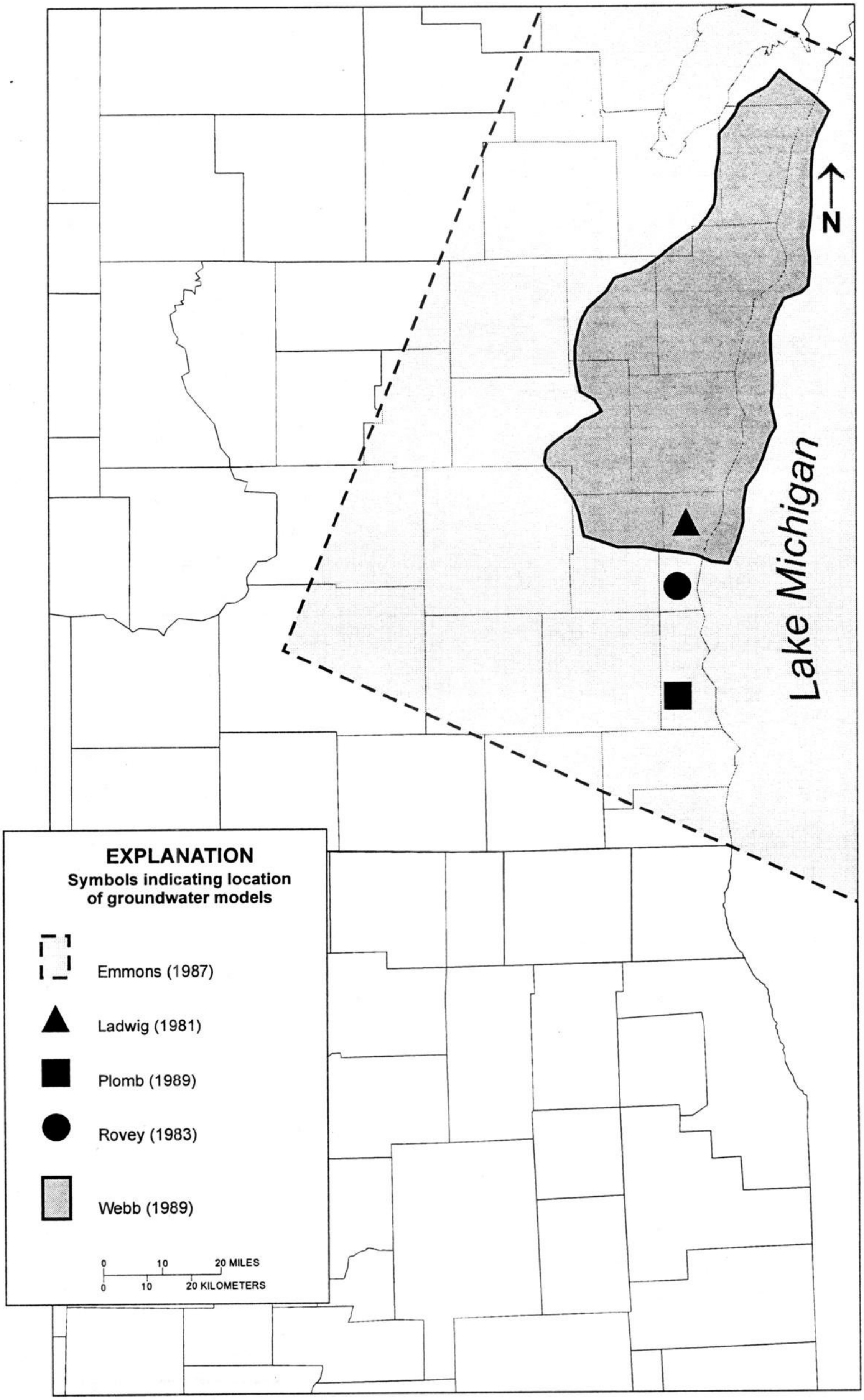


Figure 10b. Location of groundwater model studies for the years between 1980-1989, that are in or near southeastern Wisconsin and northern Illinois.

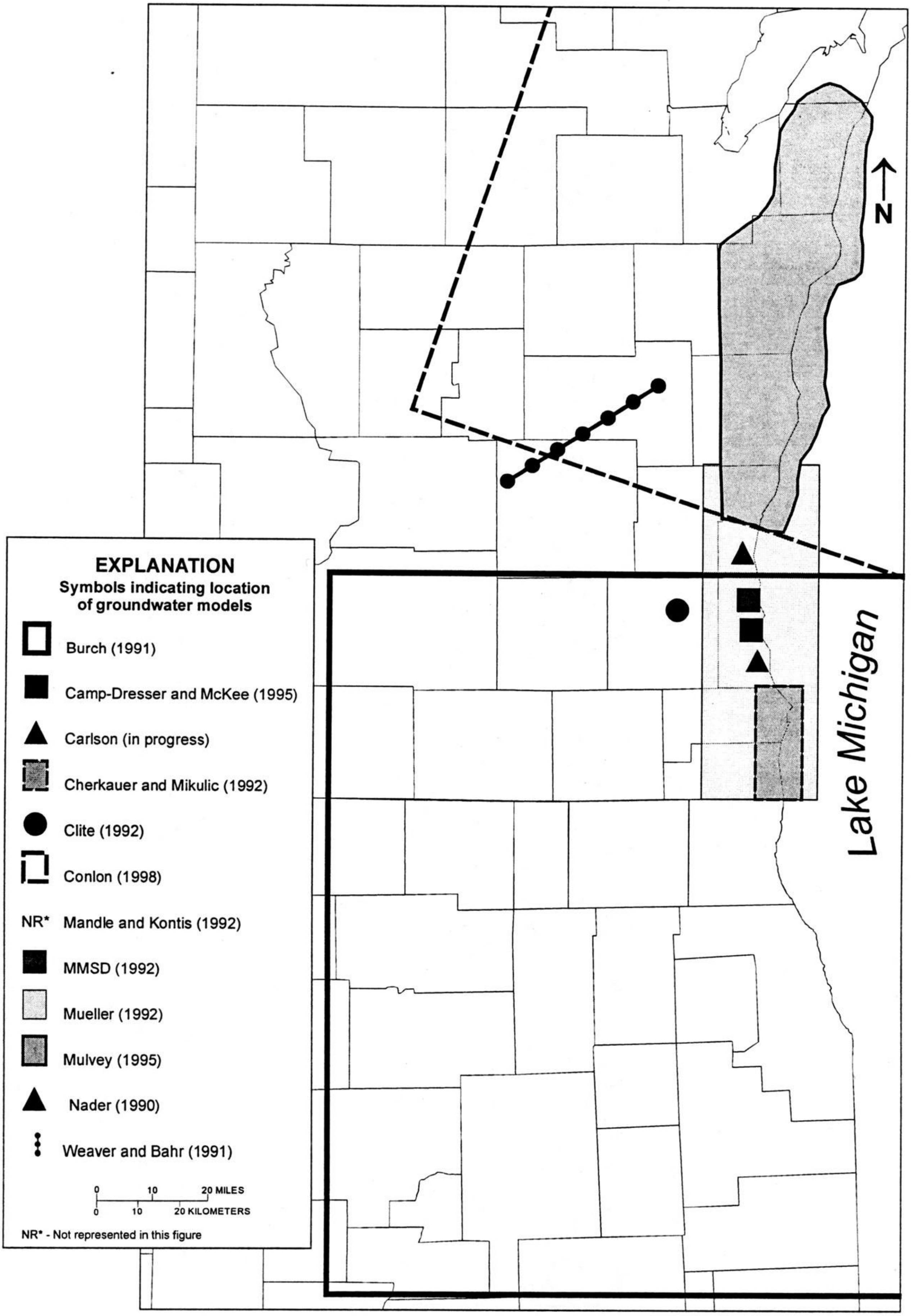
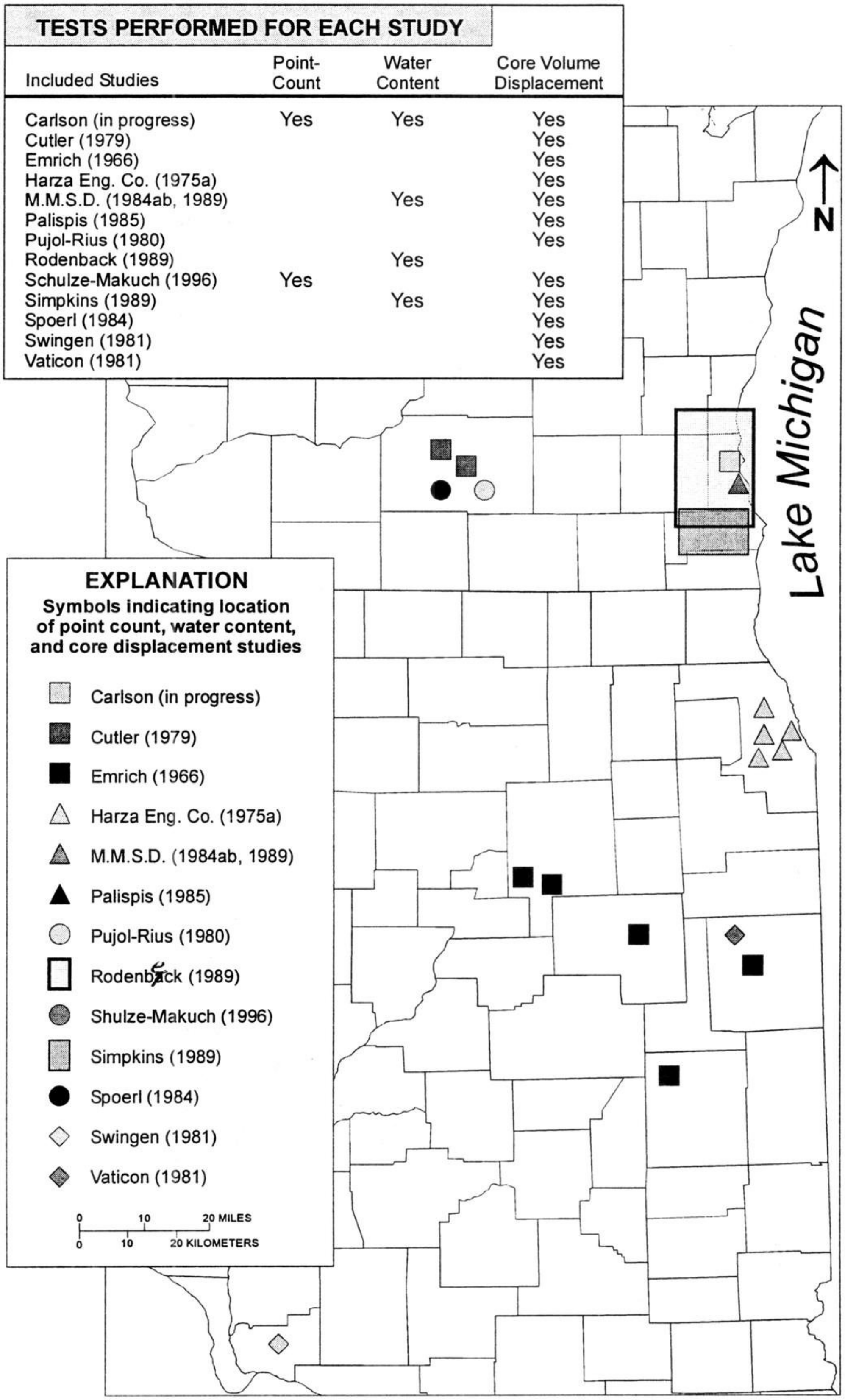


Figure 10c. Location of groundwater model studies for the years between 1990-1999, that are in or near southeastern Wisconsin and northern Illinois.



Included Studies	Point-Count	Water Content	Core Volume Displacement
Carlson (in progress)	Yes	Yes	Yes
Cutler (1979)			Yes
Emrich (1966)			Yes
Harza Eng. Co. (1975a)			Yes
M.M.S.D. (1984ab, 1989)		Yes	Yes
Palispis (1985)			Yes
Pujol-Rius (1980)			Yes
Rodenback (1989)		Yes	
Schulze-Makuch (1996)	Yes		Yes
Simpkins (1989)		Yes	Yes
Spoerl (1984)			Yes
Swingen (1981)			Yes
Vaticon (1981)			Yes

Figure 11. Location of point-count, water content and core volume displacement studies that lie either within or near southeastern Wisconsin or northeastern Illinois

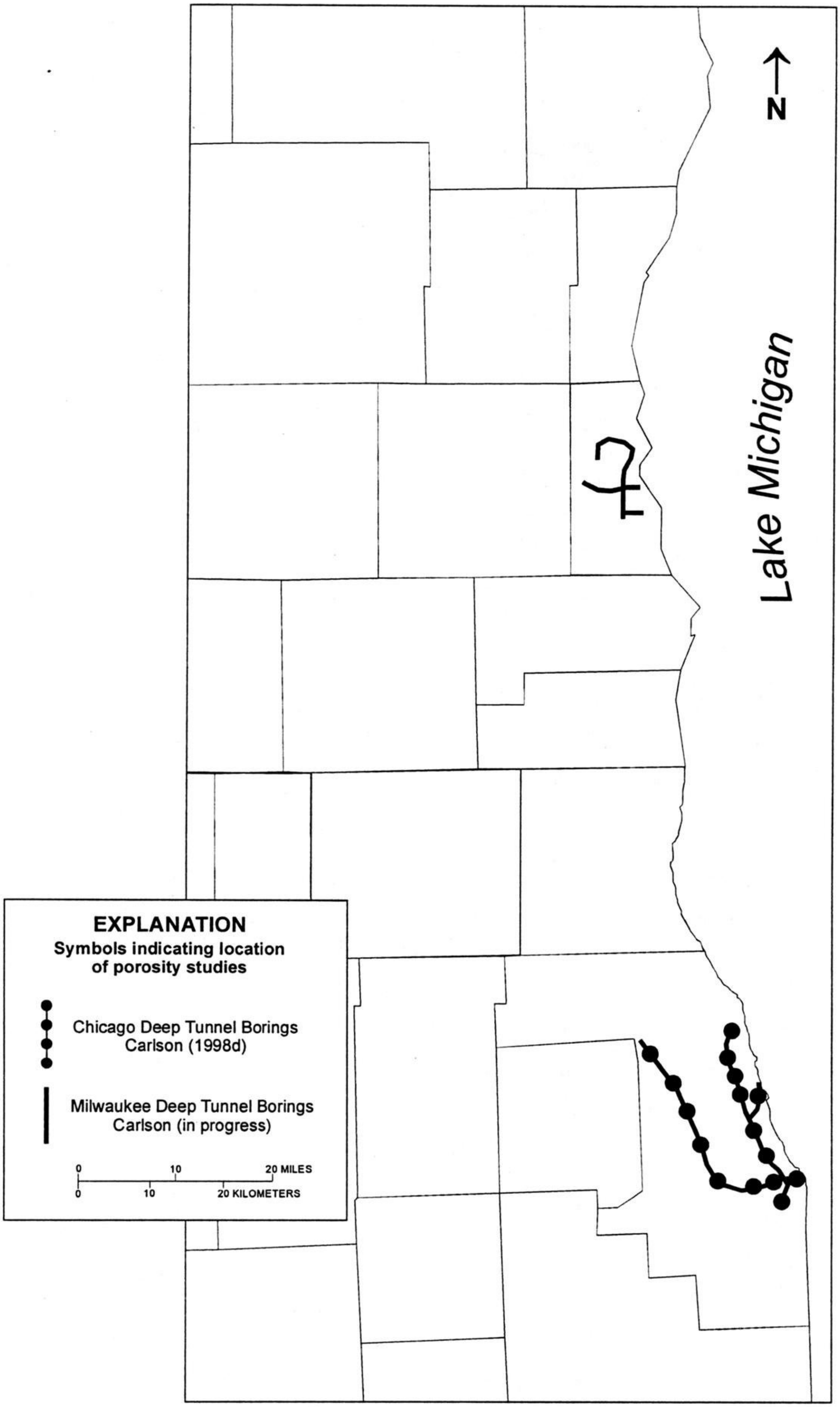


Figure 12. Location of porosity studies that are a result of analyzing geophysical logs throughout southeastern Wisconsin and northeastern Illinois.

Figure 13. -- Number of porosity values from core volume displacement tests in southeastern Wisconsin and the model area.

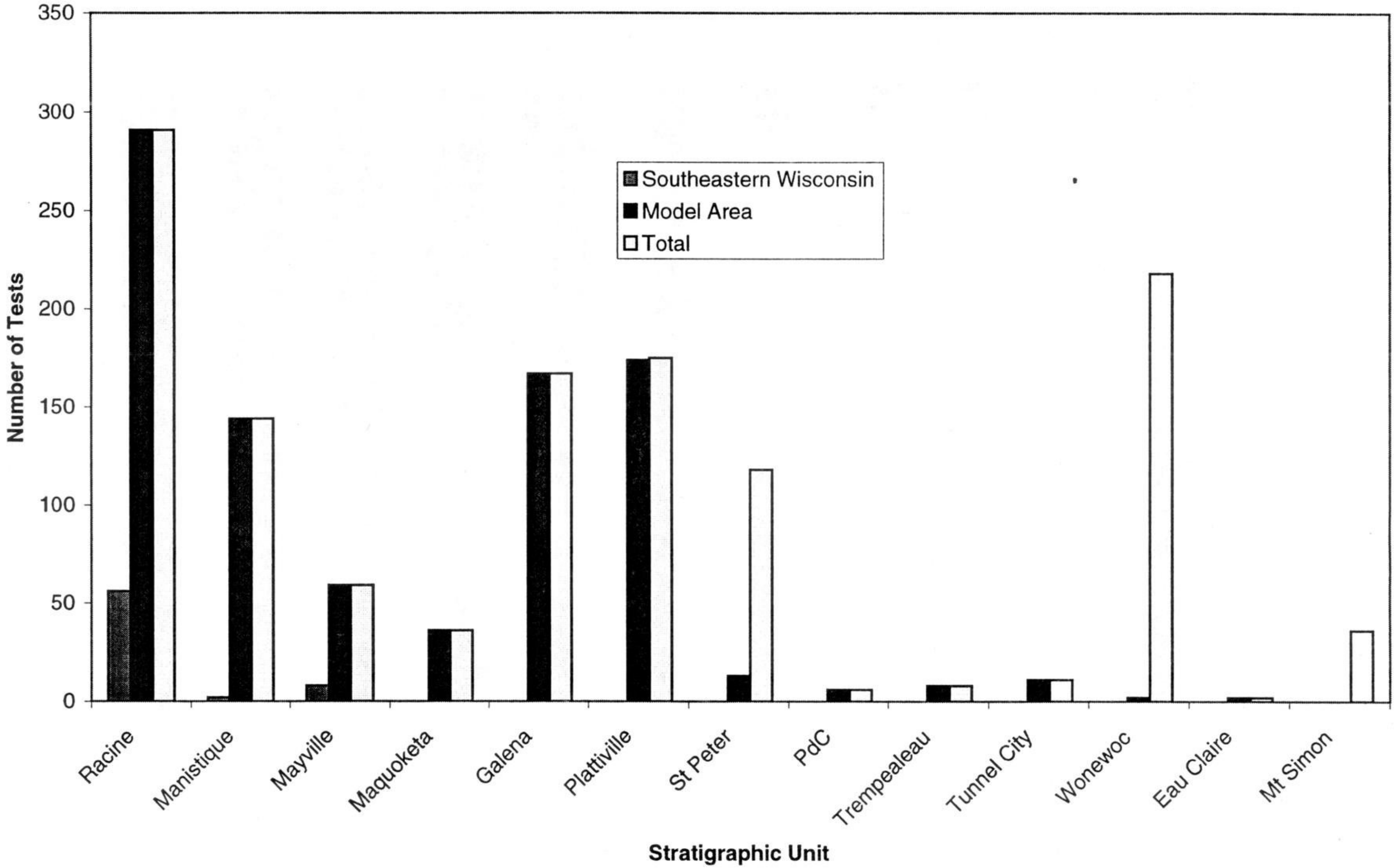
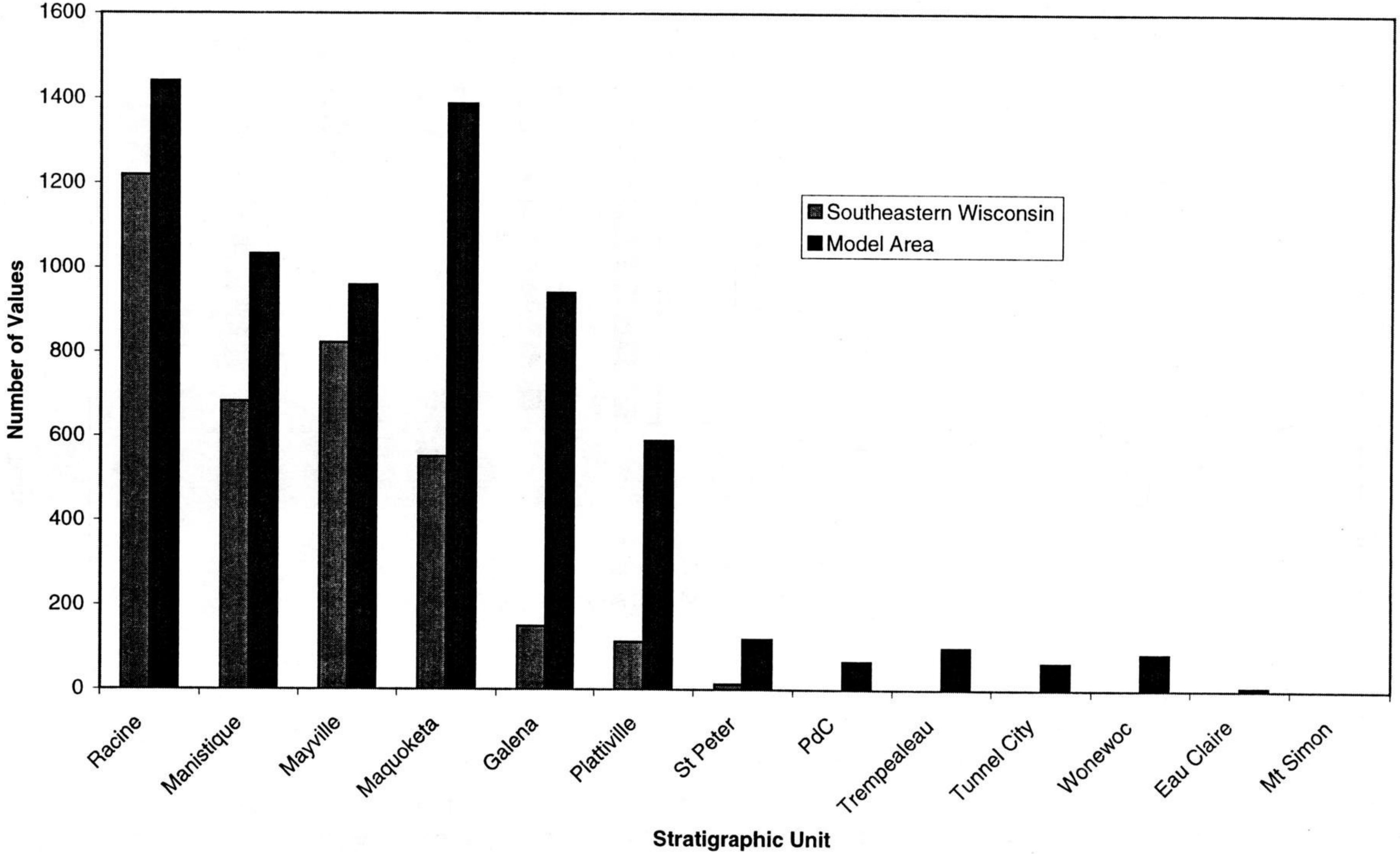


Figure 14. --Number of porosity values from geophysical logs in southeastern Wisconsin and the model area.



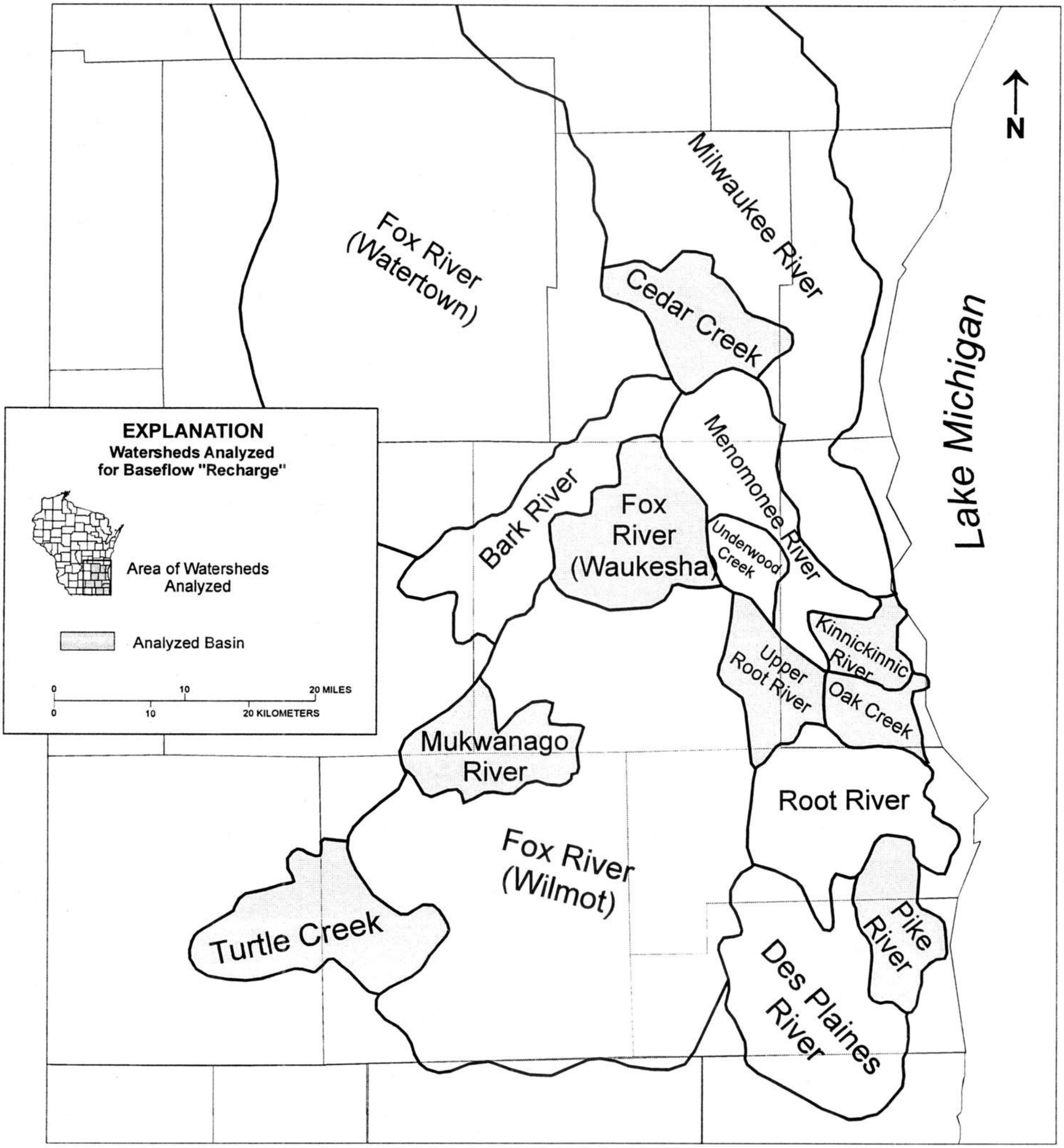


Figure 15. Location of watersheds analyzed for baseflow "recharge" that are either fully or partly in southeastern Wisconsin.

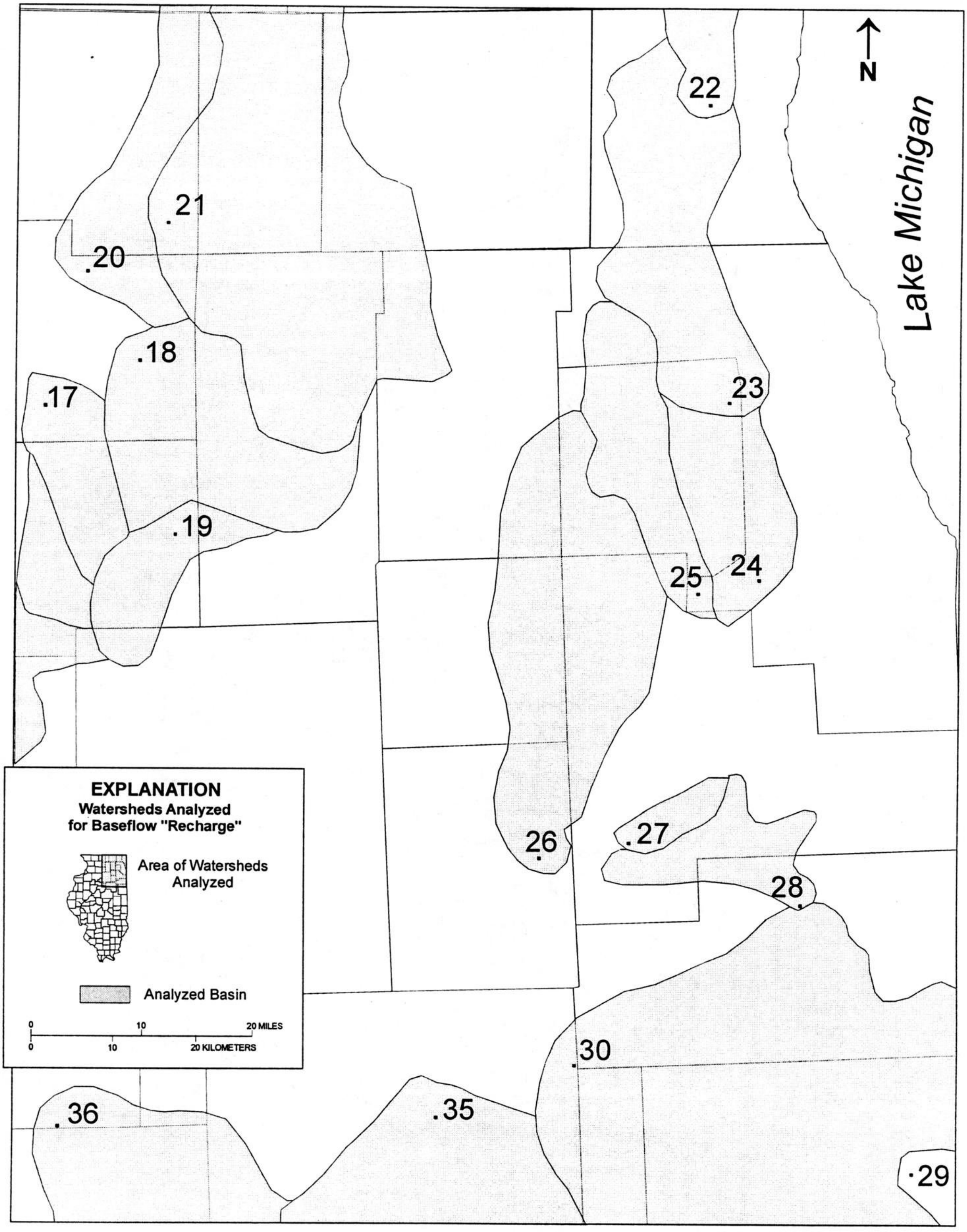


Figure 16. Location of watersheds analyzed for baseflow "recharge" that are either fully or partly in southeastern Wisconsin.

Appendix

While completing this study it was apparent that existing sources geologic/hydrologic information were using a variety of stratigraphic nomenclatures. So considering this variety of nomenclature the following tables that relate various common nomenclatures to each other are included in this study.

Table A1. -- Conventional Wisconsin stratigraphy versus M.M.S.D. in-house stratigraphy. Information for Devonian and Silurian units is from Carlson (in progress).

M.M.S.D. (M.M.S.D., 1984ab)			Conventional (Rovey, 1990)	
Formation	**Unit**	**Descriptive Subunit**	**Formation**	**Member**
Devonian:				
Milwaukee	Milwaukee 1		Milwaukee	Lindwurm
Milwaukee	Milwaukee 2		Milwaukee	Lindwurm
Milwaukee	Milwaukee 3		Milwaukee	Lindwurm
Milwaukee	Milwaukee 4		Milwaukee	Berthelet
Thiensville			Thiensville	
Silurian:				
Waubakee			Waubakee	
Racine			Racine	
Waukesha	Waukesha 1	dwcn	Racine	#cherty Racine
Waukesha	Waukesha 1	vws	Racine	#Romeo beds
Waukesha	Waukesha 1	dwcn	Manistque	Waukesha
Waukesha	Waukesha 2	vws	Manistque	Waukesha
Waukesha	Waukesha 2	ygwsp	Manistque	Brandon Bridge
Waukesha	Waukesha 3		Manistque	Franklin
Waukesha	Waukesha 3		Byron	
Mayville			Mayville	

M.M.S.D. (M.M.S.D., 1984ab)		Conventional (Young and Batton, 1980; and Ostrom and others, 1970)	
Group/Series	**Formation**	**Group/Series**	**Formation**
Ordovician:			
Maquoketa	Brainard	Maquoketa	
Maquoketa	Ft. Atkinson	Maquoketa	
Maquoketa	Scales	Maquoketa	
Sinnipee	Galena	Sinnipee	Galena
Sinnipee	Decorah	Sinnipee	Decorah
Sinnipee	Platteville	Sinnipee	Platteville
Ancell	St. Peter	Ancell	Glenwood
Ancell	St. Peter	Ancell	St. Peter

dwcn means dense with chert nodules
vws means vuggy with styolites
ygwsp means yellow-gray with shaly partings
informal units

Table A2. -- Conventional Illinois stratigraphy versus Chicago Deep Tunnel project stratigraphy

Chicago Deep Tunnel (Harza Engineering, 1975a)			Conventional (Kempton and others, 1987a, Schumacher 1990)	
Group/Series	**Formation**	**Member**	**Group/Series**	**Formation**
Silurian:				
Niagrian	Racine		Niagrian	Racine
Niagrian	Joliet	Romeo	Niagrian	Joliet
Niagrian	Joliet	Markgraf	Niagrian	Joliet
Niagrian	Joliet	Brandon Bridge	Niagrian	Joliet
Alexandrian	Kankakee		Alexandrian	Kankakee
Alexandrian	Edgewood		Alexandrian	Elmwood
Alexandrian	Edgewood		Alexandrian	Wihlemi
Ordovician:				
Maquoketa	Neda		Maquoketa	Neda
Maquoketa	Brainard		Maquoketa	Brainard
Maquoketa	Ft. Atkinson		Maquoketa	Ft. Atkinson
Galena	Wise Lake/Dunleith		Galena	Wise Lake
Galena	Wise Lake/Dunleith		Galena	Dunleith
Galena	Guttenberg		Galena	Guttenberg
Platteville	Naschusa		Platteville	
Platteville	Grand Detour		Platteville	
Platteville	Mifflin		Platteville	
Platteville	Pecatonica		Platteville	
Ancell	Glenwood		Ancell	Glenwood
Ancell	St. Peter SD		Ancell	St. Peter SD
Prairie du Chien:			Prairie du Chien	
	Oneota			
	unter			
Cambrian:				
Croixan	Eminence		Croixan	Eminence
Croixan	Potosi		Croixan	Potosi
Croixan	Franconia		Croixan	Franconia
Croixan	Ironton		Croixan	Ironton
Croixan	Galesville		Croixan	Galesville
Croixan	Eau Claire		Croixan	Eau Claire
Croixan	Mt. Simon		Croixan	Mt. Simon

Table A3. -- Conventional Wisconsin stratigraphy versus conventional Illinois stratigraphy.

Wisconsin (Ostrom and others, 1970; Young and Batton, 1980; and Rovey, 1990)		**Illinois (Kempton and others, 1987a & Schumacher, 1990)**	
Group	**Formation**	**Group**	**Formation**
Silurian:			
Niagrian	Racine	Niagrian	Racine
Niagrian	Mansitque	Niagrian	Joliet
Niagrian	Mansitque	Niagrian	Kankakee
Alexandrian	Byron	Alexandrian	Kankakee
Alexandrian	Mayville	Alexandrian	Elmwood
Alexandrian	Mayville	Alexandrian	Wihelmi
Ordovician:			
Maquoketa		Maquoketa	
Sinnipee	Galena	Galena	
Sinnipee	Decorah	Galena	
Sinnipee	Platteville	Platteville	
Ancell	Glenwood	Ancell	Glenwood
Ancell	St. Peter	Ancell	St. Peter
Prairie du Chien:		Prairie du Chien	
	Shakopee	Oneota	
	Oneota	Gunter	
Cambrian:			
Trempealeau	Jordan	Croixan	Eminence
Trempealeau	St. Lawrence	Croixan	Potosi
Tunnel City	Mazomanie/Lone	Rock Croixan	Franconia
Elk Mound	Wonewoc	Croixan	Ironton
Elk Mound	Wonewoc	Croixan	Galesville
Elk Mound	Eau Claire	Croixan	Eau Claire
Elk Mound	Mt. Simon	Croixan	Mt. Simon