ELECTRIC ANALOG MODEL STUDY OF THE HYDROLOGY OF THE SAGINAW FORMATION IN THE LANSING, MICHIGAN AREA

Thesis for the Degree of M. S.

MICHIGAN STATE UNIVERSITY

MERLIN L. WHEELER

1967

ABSTRACT

ELECTRIC ANALOG MODEL STUDY OF THE HYDROLOGY OF THE SAGINAW FORMATION IN THE LANSING, MICHIGAN AREA

by Merlin L. Wheeler

The Saginaw Formation, a bedrock artesian aquifer, is the primary source of water for domestic and industrial use in the Lansing, Michigan area. Ground water withdrawal by the many centralized supply systems has resulted in a large cone of depression which is expanding rapidly. Community or city planning, desirable for many reasons, must include an analysis of the present and future ground water resources. Previous investigations, employing various types of theoretical analyses, have been hampered by the great complexity of the aquifer. The idealized assumptions made in these analyses have invalidated the results, and theoretical analysis without these assumptions is extremely difficult.

To facilitate an analytical approach to the problem, an electric analog model was constructed. The initial design of the model utilized data presently available. The model was then modified until the analog simulation of the decline in the piezometric surface for several

periods agreed closely with the actual declines. The model is now considered to be an accurate analog of the aquifer.

Analysis of the model has revealed several significant facts about the hydrology of the aquifer. The single most important source of recharge is from the leakage of water through the upper confining beds. Further, this leakage has significantly lowered the water levels in the saturated glacial material above the confining beds. The variation in the leakage rate throughout the area has been specified. The uniformity of the leakage rate results in a reduction of the horizontal movement of water through the aquifer. This means that the transmissibility of the aquifer is not as significant a factor as it was once considered to be. The artesian storage coefficient was found to have no effect upon the long term drawdowns in the aquifer. In areas where the aquifer has begun to dewater, the water table storage coefficient has only a minor effect. Recharge to the aquifer from the rivers flowing through the area has been determined, and was found to reach a maximum after the piezometric surface dropped below the bottom of the river channel.

The electric analog model will be useful in the planning of future water resource development.

ELECTRIC ANALOG MODEL STUDY OF THE HYDROLOGY

OF THE SAGINAW FORMATION IN THE

LANSING, MICHIGAN AREA

By

Merlin L. Wheeler

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Geology

1967

ACKNOWLEDGMENTS

I would like to express my appreciation to everyone who has assited me in this study. I am indebted to Ken Vanlier, of the United States Geological Survey in Lansing, who suggested the project to me, and provided a great deal of extremely valuable criticism and encouragement as it proceeded. I would like to thank the United States Geological Survey in Lansing, which provided me with most of the data used in the study; also the municipal supply systems in the area, the Lansing Board of Water and Light, the City of East Lansing, Michigan State University, and the local townships, which were very cooperative in providing me with pumping information.

Dr. William Hinze, my academic advisor, was very helpful throughout the study, and provided the equipment needed for the construction and analysis of the analog model, through the use of funds from the Water Resources Institute.

In addition, I would like to thank all of the other people, too numerous to mention, who have helped me in so many ways.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

The Saginaw Formation is the primary source of water for domestic and industrial use in the Lansing, Michigan area. Nearly all of the high-yield wells (greater than 200 gpm) tapping this bedrock aquifer are owned by municipal supply systems: The Lansing Board of Water and Light, the City of East Lansing, Michigan State University, and Lansing, Delta, Delhi, and Meridian Townships. The remaining high-yield wells are privately or commercially owned, and for the most part are located outside the present metropolitan area. Low-yield domestic wells are found in the many areas not presently served by a centralized water supply system. The average withdrawal of ground water from the aquifer in 1964 was in excess of 25 million gallons per day.

The untreated water from the aquifer is quite consistent in chemical quality. The iron content, generally high, averages about 0.2 ppm, and the total carbonate hardness averages about 350 ppm. Other ions are present: chlorides, sulphates, etc., but none in any significant quantity. The water temperature is generally around 50° F.

Domestic softening systems can lower the hardness, but in most cases will not affect the iron content. This has been a major reason for the expansion of municipal systems, which with superior treatment facilities can produce water of a much higher quality.

The Saginaw Formation varies radically in thickness and composition throughout the area, being composed mostly of interbedded sandstone and shale. The sandstone is quite consistent in permeability, about 100 gpd/ft^2. The shale is relatively impermeable, therefore the transmissibility of the aquifer is primarily a function of the total thickness of sandstone. The bedrock is overlain by a mantle of Pleistocene glacial material, varying from outwash sands and gravels to thick beds of clay. In most areas the sandstone beds are overlain by shale or clay, or both. These confining beds of shale and clay make the Saginaw Formation an artesian aquifer. That is, the water level in a well penetrating the aquifer will generally be above the bottom of the confining beds. The piezometric surface of an artesian aquifer is the imaginary surface defined by the elevation of the water levels in wells tapping the aquifer. The Saginaw Formation is in reality a leaky-artesian aquifer, because the confining beds are permeable enough to allow a significant flow of water between the aquifer and the overlying material. This movement occurs whenever there is a difference in elevation between the piezometric surface and the free water surface in the glacial material.

The population of the Lansing, Michigan area is growing at an increasing rate, and the resultant demand for high quality water even faster. Community or city planning, desirable for several reasons, must include an analysis of the present and future water supplies, both ground and surface water. To insure the most efficient and economical use of water resources, a thorough understanding of all hydrologic systems in the area is necessary. The Saginaw Formation is one of these systems, and because of its size and complexity is perhaps one of the most difficult to understand.

HISTORY OF INVESTIGATION

The Saginaw Formation has long been the subject of intensive investigation in the Lansing area by Michigan State University, the Michigan Geological Survey, and the United States Geological Survey. In 1945, W. T. Stuart, then of the United States Geological Survey in Lansing, authored Ground Water Resources of the Lansing, Michigan Area (Stuart, 1945). This report utilized data collected over a period of many years. The study involved water level measurements, pumping tests, and other field investigations. The report served as a basis for further work, both in regard to the physical parameters of the aquifer and the general concept of the hydrologic processes in the area.

The bulk of Stuart's work was aimed at determining the physical parameters of the aquifer (its transmissibility and storage coefficient), and the determination of the changes in the hydrologic conditions that had occurred up to that time. To do so, he compiled a great deal of data on water levels for both 1945 and previous years. Extensive pumping tests were performed, using many of the large diameter, deep Lansing wells. Records were compiled of ground water usage by the Lansing Municipal System, as well as by East Lansing, Michigan State University, and by the various industrial and commercial establishments in the area.

Stuart's report views the aquifer as a leaky-artesian system, with a transmissibility ranging from 3000 to 50,000 gpd/ft. The storage coefficient varied from 10^{-3} to 10^{-4}, realistic values for an artesian aquifer. The study indicated that the aquifer was in equilibrium during the period from 1930 to 1935. Pumping rates remained essentially constant, as did the position of the piezometric surface. Stuart felt that the aquifer was not in equilibrium in 1945, and that a continuation of pumpage at the 1945 rate would cause a continued decline in the piezometric surface.

For an aquifer to be in equilibrium, it must be recharged at the same rate as water is discharged from it. Stuart listed three main sources of recharge to the aquifer; first, the hydrologic connection between the sandstone and the surface water bodies, especially the rivers and streams in the area; second, the direct recharge where the sandstone is at or very near the ground surface; and third, the leakage into the sandstone from the saturated glacial material above the confining beds. However, Stuart was unable to quantify the total capabilities of recharge. He was able to determine the recharge rate in 1935, knowing that equilibrium conditions existed, but beyond this, analysis was very difficult.

The dangers of developing the aquifer beyond its safe yield were pointed out. The Saginaw Formation is underlain by the Michigan Formation which is composed predominately of shale, gypsum and limestone. This formation produces water which is high in sulphates and chlorides. If the water levels in the Saginaw are excessively low, water from the Michigan will begin to enter the aquifer, contaminating it.

Later investigation in the area took primarily a reportative attitude. Two theses (Firouzian, 1962; Mencenberg, 1963) examined the aquifer in the light of further study, and reported the then existent hydrologic conditions. Neither report goes into any great detail on the recharge capabilities of the aquifer.

All of the reports to the present have approached the problem on a theoretical level. Pumping tests were analyzed by theoretical techniques, involving certain ideal assumptions. Flow net analyses were performed, again using ideal assumptions. The hydrology in this area is, however, very far from idealized, and any attempt at predicting future hydrologic conditions must take into account all of the important aquifer and recharge characteristics.

The complexity of the hydrologic conditions in the area invited some type of analytical approach. It was decided that an electric analog model would be the best method of investigation. This decision was prompted by several things. First, the size and complexity of the aquifer discouraged any form of mathematical approach, even with the utilization of electronic computers. Second, an electric analog model could be built for comparatively low cost, and further, could very easily be modified to simulate any hydrologic condition, past, present, or future. Third, once the model was built and verified using historical data, it could be used as a predictive agent, determining future safe yields, recharge capabilities, drawdown distributions, and other parameters of the water resource system.

THEORY OF ELECTRIC ANALOG MODELING

An electric analog model consists of an array of resistors and capacitors, interconnected in a particular manner. The resistors simulate the transmissibility or permeability of an aquifer, and the capacitors simulate the storage capacity of the aquifer. It is necessary to demonstrate the analogy between this electrical network and the aquifer, and to develop methods for building a specific model, given a particular aquifer (Walton and Prickett, 1963).

The equation governing the two-dimensional flow of water in an infinite isotropic aquifer is:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = \frac{S}{T}\frac{\partial h}{\partial t} \qquad (1)$$

where:

h = hydraulic head at some point within the aquifer

x,y = perpendicular horizontal axes within the aquifer

S = storage coefficient of the aquifer

T = transmissibility of the aquifer

t = time in appropriate units.

Let some finite distance $\Delta x = \partial x$, and $\Delta y = \partial y$. Envision a grid system placed within the aquifer, as depicted in Figure 1, with spacing Δx and Δy, where Δx and Δy are small in relation to the aquifer size.

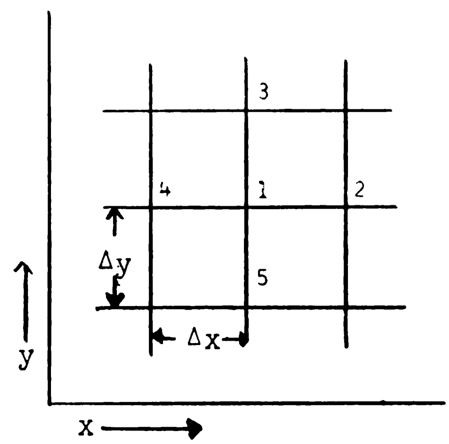


Figure 1.--Aquifer Grid

Now, $\frac{\partial h}{\partial x}$ is the change in head with distance in the x-direction. Using the points numbered in Figure 1, $\frac{\partial h}{\partial x}$ may be approximated by:

$$\left(\frac{\partial h}{\partial x}\right)_1 \cong \frac{h_1 - h_4}{\Delta x} \quad ; \quad \left(\frac{\partial h}{\partial x}\right)_2 \cong \frac{h_2 - h_1}{\Delta x} \tag{2}$$

The change in $\frac{\partial h}{\partial x}$ with distance in the x-direction, $\frac{\partial^2 h}{\partial x^2}$ is then approximated by

$$\frac{\partial^2 h}{\partial x^2} \cong \frac{\left(\frac{\partial h}{\partial x}\right)_2 - \left(\frac{\partial h}{\partial x}\right)_1}{\Delta x} \cong \frac{\frac{h_2 - h_1}{\Delta x} - \frac{h_1 - h_4}{\Delta x}}{\Delta x}$$

or

$$\frac{\partial^2 h}{\partial x^2} \cong \frac{h_2 + h_4 - 2h_1}{(\Delta x)^2} \tag{3}$$

In a similar manner,

$$\frac{\partial^2 h}{\partial y^2} \cong \frac{h_5 + h_3 - 2h_1}{(\Delta y)^2} \tag{4}$$

The area within any small rectangle of the grid is given by $(\Delta x)(\Delta y)$. With $\Delta x = \Delta y$, the area, a^2 is $(\Delta x)^2$. Then,

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} \simeq \frac{h_2 + h_3 + h_4 + h_5 - 4h_1}{(\Delta x)^2} \cong \frac{S}{T} \frac{\partial h}{\partial t} . \tag{5}$$

Rearranging terms, and substituting a^2 for $(\Delta x)^2$, we obtain:

$$T(h_2 + h_3 + h_4 + h_5 - 4h_1) \cong a^2 S \frac{\partial h}{\partial t} . \tag{6}$$

We construct an electrical network of resistors such that the resistors connect a series of junction, or nodes, as shown in Figure 2, page 11. A capacitor is connected from each node to a common ground. From Kirchoff's Laws for the flow of current through such a network:

$$I_2 + I_3 + I_4 + I_5 = C \frac{\partial V_1}{\partial t} . \tag{7}$$

Applying Ohm's Law,

$$I = \frac{V}{R};$$

$$\frac{V_2 - V_1}{R_2} + \frac{V_3 - V_1}{R_3} + \frac{V_4 - V_1}{R_4} + \frac{V_5 - V_1}{R_5} = C \frac{\partial V}{\partial t} \tag{8}$$

where:

I = current flowing through a particular resistor;

V = voltage at some node;

R = resistance of the resistor connecting two nodes;

C = capacitance of the capacitor connected to a node;

t = time in appropriate units.

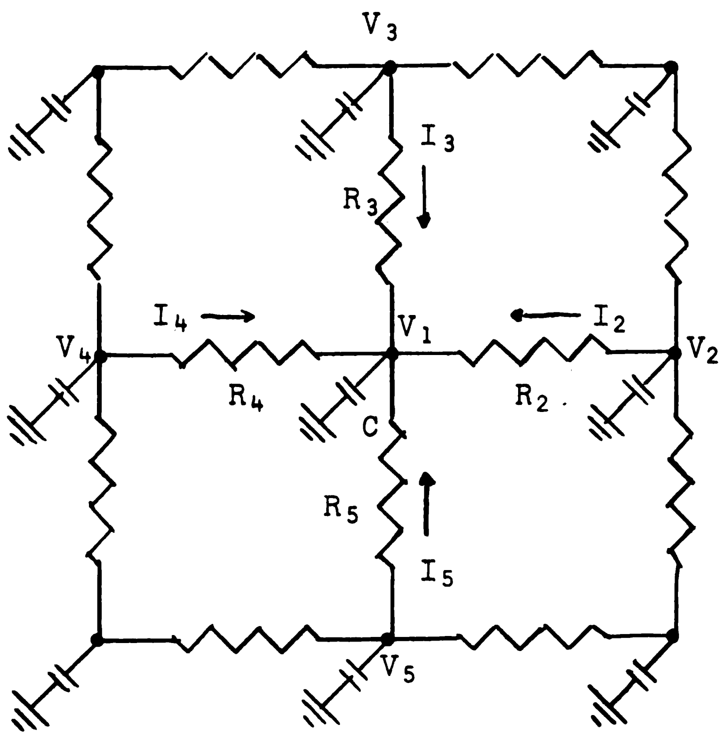


Figure 2.--Electrical Network

The aquifer is assumed to be isotropic and homogeneous. Similarly, let:

$$R_2 = R_3 = R_4 = R_5 = R.$$

Substituting this into Equation (8) we obtain:

$$\frac{1}{R}(V_2 + V_3 + V_4 + V_5 - 4V_1) = C\,\frac{\partial V}{\partial t}\,. \qquad (9)$$

Comparing this with Equation (6):

$$T(h_2 + h_3 + h_4 + h_5 - 4h_1) = Sa^2\,\frac{\partial h}{\partial t}\,,$$

we see that the two equations can be made similar if

T is proportional to $\frac{1}{R}$

h is proportional to V

a^2S is proportional to C.

The flow of water, (Q), through a section of the aquifer is given by:

$$Q = T\ I\ L$$

where:

T = transmissibility of the aquifer

I = hydraulic gradient

L = width of the aquifer section.

Returning to the aquifer grid, Figure 1, we obtain:

$$Q = T\,\frac{(h_5 - h_1)}{\Delta y}\left(\frac{\Delta x}{2} + \frac{\Delta x}{2}\right)$$

$$Q = T(h_5 - h_1)\,\frac{\Delta x}{\Delta y}$$

with $\Delta x = \Delta y$

$$Q = T(h_5 - h_1). \qquad (10)$$

Referring to the electrical network, Figure 2, and applying Ohm's Law:

$$I_5 = \frac{V_5 - V_1}{R_5}$$

If T is proportional to $\frac{1}{R}$ and h is proportional to V, then Q is proportional to the current, I.

A similar derivation is possible for non-homogeneous aquifers, which will yield the same proportionalities that were developed for the homogeneous case.

For convenience the time units used in the analog model studies are much smaller than the real time units involved, years becoming milliseconds.

To allow conversion from hydraulic units to electrical units, the following four proportionality constants have been defined:

K_4, with units days/sec

K_3, with units gpd/amp

K_2, with units ft/volt

K_1, with units gal/coulomb ($K_1 = K_3 \times K_4$).

Then

sec = $1/K_4$ (days)

gpd = $1/K_3$ (amperes)

ft = $1/K_2$ (volts)

gal = $1/K_1$ (coulombs).

These four scale factors can then be adjusted to fit the needs of a particular study, so as to best utilize the analytical equipment available, as well as to use readily available low cost electrical components.

To build a specific model, it is necessary to relate T to R, and S to C. Using the four scale factors, and the proportionalities noted, we obtain:

$$R = \frac{K_3}{K_2} \cdot \frac{1}{T} \tag{1}$$

$$C = 7.48\ a^2\ S\ \frac{K_2}{K_1} \tag{2}$$

where:

R = resistance in ohms

C = capacitance in farads

a = node spacing in feet

S = storage coefficient

T = transmissibility in gpd/ft.

A leaky artesian aquifer, in which there is a significant amount of leakage of water into or out of the aquifer through one of the confining beds may be simulated by connecting a resistor to ground from each node, scaled to the vertical permeability of the confining beds. The value of this resistor is given by:

$$R_g = \frac{K_3}{K_2(P'/m')a^2}$$

where:

P' = vertical permeability of the confining beds

m' = saturated thickness of the confining beds

a, K_3, K_2 as previously defined.

These formulas allow us to build an electric analog model which duplicates the physical characteristics of a particular aquifer.

All aquifers are finite, and allowance must be made for this on our model. A negative boundary, such as might be caused by a fault or a rapid decrease in transmissibility, is simulated by simply terminating the electrical network. A negative boundary is typified by having no flow across it, and this method of simulation meets this criterion. A positive boundary, such as a stream or a lake, is represented by a terminal strip connected to ground, connecting all of the nodes along this positive boundary. A positive boundary is typified by having no change in head across it, and again we see that our method of simulation is valid.

For cases in which the boundaries are not perfect, such as the partial penetration of a stream into the aquifer, resistors may be used to control the amount of current entering or leaving the network along the boundary, just as the permeability of a river bottom controls the amount of water moving between it and the aquifer.

UTILIZATION OF THE ELECTRIC ANALOG MODEL TO OBSERVE OR PREDICT HEAD CHANGES

In an aquifer, the hydraulic head at any particular point will change with time, in response to seasonal fluctuations in precipitation, evapotranspiration, ground water withdrawal, etc. Of these factors, ground water withdrawal is our major concern. The pumpage of water from the aquifer at a certain rate for a certain length of time will produce a decline in the water level in observation wells tapping the aquifer. For each well, a time-drawdown curve results.

In the analog model, a specified amount of current (determined by the pumping rate of the wells) is withdrawn for a given length of time (determined by the length of time the wells are pumped). Current is withdrawn by producing a negative voltage drop across a resistor connected between some voltage source and a node on the analog model. As a result, the voltages at the various nodes of the model change with time, producing a time-voltage curve for each node. As we have shown, this time-voltage curve is analogous to, and with application of the various scale factors can be read directly as, a time-drawdown curve. In most model studies we are concerned with the changes that occur in the various hydrologic parameters, not with the absolute magnitude of the parameters.

The time scale factors used in analog studies result in a time-voltage curve of very short duration. To observe the curve, we utilize three instruments. First, a pulse generator, which produces a voltage pulse for a certain length of time; second, a waveform generator which triggers these pulses at some specified frequency; and third, an oscilloscope which projects the time-voltage curve on a screen for observation. By triggering the voltage pulses at a high enough repetition rate, the time-voltage curve will appear to remain stationary on the oscilloscope, allowing us to read the values of, or record, this curve. Figure 3 is a block diagram of the equipment used for the analysis of the model. The resistor R_p, controls the rate at which current is withdrawn from a particular node, so that the current is proportional to the pumping rate of a well located at that point in the aquifer. If a number of wells were operated under the same pumping schedule, resistors in parallel are used to control the withdrawal rate from the respective nodes. If the withdrawal rate from a particular well changes significantly one or more times during the period being analyzed, a separate pulse generator is used for each pumping rate. The pulse generators are then triggered sequentially, each one producing a voltage pulse whose length is proportional to the length of time that the well was pumped at a particular rate.

The analog model also may be used to investigate the hydrology of the aquifer under equilibrium conditions. A particular period is selected when the aquifer was in hydrologic equilibrium, and the inflow and outflow of water, both natural and artificial is determined. Utilizing a direct current constant voltage supply, electric current is made to flow through the model, proportional to the quantity of water flowing through the aquifer. The voltages observed at the nodes of the model will be analogous to the piezometric surface in the aquifer. The storage ability of the aquifer is not included in this steady-state analysis.

To recapitulate, an electric analog model is constructed, utilizing the known hydrologic data, and the appropriate scale factors. For transient analysis, the model is activated by the use of various electronic equipment. The resultant time-voltage curves are recorded, and compared with the known or expected time-drawdown curves. For steady-state analysis, electric current is made to flow through the model, and the resultant voltage distribution is compared with the known or expected piezometric surface.

It is at this point that the strong point of the analog model enters. If, within the limits of error, the model simulation agrees with the observed or expected conditions in the aquifer, then we may assume that the model is truly representative of the aquifer, and further, that the original conceptualization of the aquifer was correct. If, however, some deviation occurs in the model simulation, we know that our original concept was wrong, and must be modified. Quite frequently, experimentation with the model can give us insight into what form of errors we have made; whether recharge areas were neglected, transmissibility or storage coefficients were incorrectly determined, or some other hydrologic phenomena were not considered. The ease with which the model can be altered, and the form of presentation of the information obtained from the model further recommends its application to ground water problems.

ERROR PRESENT IN STUDY

The error inherent in the electric analog model stems from several sources; the accuracy with which time and voltage can be measured, the precision of the electrical components, and other errors inherent to the electrical network. The finite difference equation, Equation 5, is an approximation, and error is introduced here principally as a function of the ratio of node spacing to aquifer size. All of these errors, for most models, are less than ten percent, and theoretical studies indicate far less than this for most cases (Stallman, 1963).

The most significant source of error is the accuracy of the basic data; water levels, transmissibilities, storage coefficients, pumpage rates, and the other hydrologic parameters. The effect of the error in the physical parameters of the aquifer will vary, and can only be determined through experimentation with the model. The accuracy of water levels is usually given in feet, rather than as a percent. If two water level maps are each considered accurate to ± 5 feet, as is the case in this study, the water level change map obtained by subtracting* them will

*"Subtracting" is the process of determining the difference in the water levels at each point on the two maps, and contouring the result.

only be accurate to within $\pm$ 10 feet. This, unavoidably, is the major source of error in this particular investigation.

DESIGN OF THE ELECTRIC ANALOG MODEL OF THE SAGINAW FORMATION

The design and analysis of the analog model is depicted in the flow chart, Figure 4. To construct the analog model, it was necessary to develop a conceptual model of the aquifer. The transmissibility distribution was specified as shown in Figure 5. This iso-transmissibility map was produced by utilization of the information obtained by W. T. Stuart (Stuart, 1945) and by the analysis of succeeding pumping tests. Where these were not available, specific capacity information was utilized. Although this is not a completely reliable source of information, it can provide general guidelines. Where no field measurements of any kind were available, isopachs of the sandstone, in conjunction with an average permeability were used. It is felt that the values obtained are reasonably representative of the aquifer in all parts of the area studied.

The low transmissibility zones surrounding the area allow us to define a discrete aquifer, and provide us with a natural boundary at which to terminate the model. Because there is negligible horizontal flow across this boundary, we know that all of the water discharged from the aquifer must have entered it within the area studied.

The storage coefficient was assumed to be 10^{-4}, a reasonable value for an artesian aquifer. A leaky-artesian system was assumed, with the rate of flow into or out of the aquifer proportional to the head differential between the piezometric surface and the free water surface. Water was assumed to flow between the aquifer and the rivers in a similar manner. Further, it was assumed that there was no significant depletion in stream flow, and that there was no significant change in the water levels in the glacial material. It was not possible to give any specific values to the leakage rates.

The choice of values for the four analog scale factors was based on: one, the range in the values of the transmissibility and the value of the storage coefficient; two, the electrical components and analysis equipment available; and three, the accuracy required in the study. The values are:

$K_4 = 6.4 \times 10^4$ days/sec

$K_3 = 2 \times 10^{10}$ gallons per day/amp

$K_2 = 10$ ft/volt

$K_1 = K_3 \times K_4 = 1.28 \times 10^5$ gallons/coulomb.

ANALYSIS OF THE MODEL

Steady State Analysis

In order to determine the leakage rate, a steady-state, or equilibrium analysis of the model was initiated, thus eliminating all time-dependent variable from the hydrologic system. A piezometric map for the equilibrium conditions of 1900 was drawn using data obtained from the United States Geological Survey water level records. However, for much of the area studied, reliable records were not available for this period. In these cases, water levels for later years were examined. It was discovered that at many locations there had been very little change in the piezometric surface for a number of years. At one point, for instance, the water levels in 1945 were the same as they had been in 1929. Therefore, it was reasonable to assume that they would have been the same in 1900. This principle was only applicable at locations that had not been significantly effected by ground water withdrawal after 1900.

In 1900 the aquifer was undeveloped, that is, there was no significant pumpage from the aquifer. The shape of the piezometric surface was determined by the natural discharge from, and the recharge to, the aquifer. The piezometric map, Figure 6, indicates that the primary area of discharge from the Saginaw Formation was along the rivers flowing through the area. A flow net analysis was made, obtaining a value for the total rate at which water was being discharged to the rivers at that time. All of the water discharged from the aquifer must have entered it within the area studied, which enabled us to make a preliminary estimate of the recharge rates. A map was drawn showing the differences in head between the piezometric surface of 1900 and the water table in the glacial material (based on topographic maps of 1910). The areas in which the water table was above the piezometric surface were delineated. For convenience, these positive head differences were divided into two groups, 0-10 feet, and 10-20 feet, as shown in Figure 7. All of the water entering the aquifer must do so within the delineated areas, and at a rate proportional to the determined head differences. Assuming that this proportion was the same throughout the area studied, the following relation was then solved:

$$A_1(w) + A_2(2w) = Q$$

where:

A_1 = area within 0-10 foot contour

A_2 = area within 10-20 foot contour

w = leakage in gpd/mi^2

Q = total discharge or total leakage.

Similarly, the flow into each portion of the rivers and the head differences between the rivers and the piezometric surface allowed the determination of the extent of the hydraulic connection between the aquifer and the river for each river segment shown in Figure 6.

With the model constructed along these guidelines, the analog simulation of the piezometric surface for 1900 was measured. It was apparent that an initial error had been made, because the observed piezometric surface was a great deal higher than the real piezometric surface. Cursory examination showed that the extent of the difference could only be explained by an error in the recharge rate, the discharge rate, or both. The transmissibility of the aquifer could not be changed enough (within the limits of feasibility) to produce the desired results.

Because the most unknown factor involved was the leakage rate, it was decided to change this first. The rate was reduced, and in some areas the discharge rate to the rivers was adjusted slightly, until the analog simulation of the piezometric surface agreed closely with the expected. This is shown in Figure 8. Comparison of this with the contour map of the real piezometric surface, Figure 6, reveals a significant difference in one area, the vicinity of downtown Lansing. It was found impossible to reproduce these contours on the model, even by making very drastic changes in the original assumptions. Examination of the original data revealed that the water level measurements used to contour this area were made in shallow wells, penetrating only the upper portion of the aquifer. In this upper portion, the piezometric surface reflected very closely the water levels in the glacial material, rather than the true piezometric surface of the aquifer. This is borne out in other wells drilled at later times. The modification in the piezometric surface produced by correcting this error greatly reduced the total discharge from the formation, accounting for the necessity of reducing the leakage rate to match the analog simulation with the real piezometric surface.

For convenience in the analysis, the areas in which leakage was occurring were divided into eleven regions. These are shown in Figure 9, and the total leakage determined from the model for each region is given in Table 1. The leakage per square mile, per foot of head was determined for each region. This was done by using the area of a particular region, the total leakage in that region, and an "average head" for the region, so that the leakage rate is given by:

$$\text{Leakage} = \frac{\text{Total leakage}}{\text{area X "average head"}} .$$

However, the exact shape of the head distribution was not determined. Thus, the average head value used is a very rough approximation. The values obtained for the leakage per foot of head should be used qualitatively only. The leakage will be taken up at a later time in this paper, and more reliable values will be given. The total flow from the aquifer into each river segment is given in Table 2.

Transient Analysis

In the steady-state analysis the actual conditions were modeled. However, in the transient analysis, it is necessary to measure the changes that occur in the various time-dependent variables. We are concerned not with the total leakage, but with the increase or decrease in the leakage per foot of head change. We are concerned not with the piezometric surface, but with the change in the piezometric surface over a period of time. To use the model for transient analysis it must be modified somewhat. The capacitors must be added to the network. The value of the resistors controlling the leakage rates must be recalculated using the change in leakage per foot of head decline. The head gradients in the rivers, necessary for steady-state analysis, are eliminated.

An original equilibrium condition is selected, and the changes in the piezometric surface from this condition are determined. The 1935 piezometric surface, as shown in Figure 10, was in equilibrium, and it was selected as a base from which future changes in the piezometric surface would be determined and modeled. In addition, piezometric maps for 1945, Figure 11, and for 1964, Figure 12, were drawn. The changes in the piezometric surface from 1900 to 1935, Figure 13, from 1935 to 1945, Figure 14, and from 1935 to 1964, Figure 15, were obtained by subtracting the respective piezometric maps.

To carry the analysis further, it was necessary to make a detailed examination of the pumpage from the aquifer. Whereas most previous reports were concerned only with the total pumpage from the aquifer, it was necessary to impose the various pumping rates on the model in the proper area. A tabulation was prepared of the total pumpage from each individual well, by years, from all of the high-yield wells in the area studied. Because it would be difficult to impose the pumpage from each individual well on the model, wells were arbitrarily grouped together into "pumping centers," all of the wells in a particular pumping center being close to a common center. These are shown in Figure 16. The total pumpage from each of the resultant sixteen pumping centers was then determined. Ideally the various withdrawal rates from each of the pumping centers should be imposed on the model as a continuous function. However, this is impossible to do without very sophisticated equipment. Instead, the pumping rates were divided into a series of step functions, each step representing an average pumping rate from a particular pumping center for a certain length of time. To keep the analysis reasonably simple, a total of five steps was employed, covering the period from 1935 to 1964; 1935-1940, 1941-1945, 1946-1952, 1953-1960, 1961-1964. In some cases the actual pumpage rates from various pumping centers did not fall conveniently into these five steps, and in these cases some generalizations were necessary. However, for the most part, as shown in Figure 17, the actual pumpage rates fitted these five steps quite well.

With the model modified for transient analysis, one final check was made. Under leaky-artesian conditions, the aquifer would reach a given equilibrium condition very rapidly. Thus, if the pumpage rates from 1930-1935 were imposed on the model, the total drawdowns from the undeveloped condition of 1900 to 1935 should result. However, when this was done, the drawdowns observed were much less than expected. Investigation revealed that there was too great a flow from the rivers into the aquifer. It was originally assumed that the flow of water between the aquifer and the surface water bodies was proportional to the head differential. However, the pumpage in 1930-1935, and in subsequent years, lowered the piezometric surface below the bottom of the river channel. The high permeability of the channel material, and the relative impermeability of the adjoining glacial material resulted in the flow into the aquifer being a function of the distance from the river surface to the bottom of the channel, essentially a constant. A method was developed, employing a transistorized switching circuit, for placing a maximum value on the flow of current, in the model, from the river to the aquifer. To facilitate this, the rivers were divided into a series of segments, as shown in Figure 10, similar to those used in the original flow-net analysis. A maximum value was then placed on the current flowing from any one segment into the aquifer. This involved a certain amount of generalization, but it is believed to be justified. The channel depth was substantially less than the head difference between the river surface and the piezometric surface, resulting in a substantial reduction in the flow of current into the aquifer. This resulted in greater draw-downs on the model. With this modification and some adjustment in the amount of water flowing from each river segment into the aquifer, the change in the piezometric surface from 1900 to 1935 was duplicated quite closely, as shown in Figures 13 and 18.

The adjustment in the amount of water flowing from each river segment into the aquifer was felt justified for several reasons. First, the original values placed upon the maximum flow from each segment were based on the discharge in the undeveloped condition of 1900. The total recharge from the river consisted of intercepted discharge (when the piezometric surface was above the river level), and induced recharge (when the piezometric surface dropped below the river level). In most instances the two were assumed to be equal, but for river segments where the head differential had increased significantly, the value of the induced recharge was assumed to be greater. Second, the values used were obtained by adding together the flows from each portion of the segment. The generalization involved would inevitably produce some error on the model. Third, and partially counterbalancing the previous two factors, would be a reduction of the flow caused by a silting up of the river bottom. It is reasonable to expect a net change in the flow rate, and the model indicates that it increased. Table 3 compares the maximum value placed upon the flow from each river segment with the discharge observed in the undeveloped condition.

The increase in the pumpage from 1935 to 1945 was imposed on the model. Several things became apparent. First, the artesian storage coefficient which had been included in the model had no effect on the total drawdowns observed for this 10-year period. Its only effect was to change the shape of the very first portion of the time-drawdown curve. Second, and more importantly, the total drawdowns observed on the model were significantly less than those actually occurring during this period. Several factors could have caused this. A reduction in the transmissibility might produce the additional drawdown. However, the analysis of the 1935 condition eliminated this possibility. Also, the amount of water entering the aquifer from the rivers might have been significantly less in 1945 than in 1935. This could be caused by an additional silting up of the river bottom. It did not appear, however, that this would cause the magnitude of effect required. One important factor had not been considered. It was originally assumed that no changes occurred in the water levels in the glacial material. However, examination of water level records revealed that with the increase in the flow of water from the glacial material to the aquifer, the water levels in the glacial material had begun to drop, in effect draining the glacial material. This meant that the storage capability of the glacial material must be considered. When this drainage effect was imposed on the model, the resulting piezometric change map was more similar to the expected.

However, significant differences still existed between the actual piezometric change and that observed on the model. Examination of the 1945 piezometric map revealed that one area in the northeast part of Lansing was contributing a great deal more water to the aquifer than had been realized. Examination of well logs in the vicinity indicated the possibility of very permeable saturated sands and gravels lying directly on the sandstone. In addition, the sands and gravels in this area appeared to be connected hydrologically with other larger bodies of sand and gravel to the north and west, composing a portion of the Mason Esker. It seemed reasonable then, to assume an extensively recharged body of gravel, connected directly to the aquifer. The model was modified to fit this condition, producing the desired modification in the piezometric change map, shown in Figure 19. This area of recharge was not significant in 1935 because the drawdowns in the area were quite small. However, with increased drawdown, it became more important.

Comparison of the observed and expected piezometric change maps for both 1900-1935, Figures 13 and 18, and 1935-1945, Figures 14 and 19, reveals that in the southern portion of the area, observed drawdowns were greater than expected in both cases. This additional drawdown was not considered significant in the 1935 analysis, because it was within the expected error of the model. However, the appearance of a similar error in both analyses indicated that an error in the original conceptual model might have been made. Reducing the transmissibility to half its original value had little effect on the observed drawdowns. Similarly, changing the leakage rate within reasonable limits had only a minor effect. Investigation of well logs revealed that in the center of this area the Mason Esker rested directly on the sandstone, and appeared to be recharged by the Sycamore Creek. It seemed reasonable that a large quantity of water was entering the aquifer in this region. Experimentation with various values on the model revealed that approximately five times as much water was entering the aquifer in this area as had been originally specified. Figure 20 shows the piezometric change map observed on the model when this additional recharge was added. Comparison with the original, Figure 19, and with the expected, Figure 14, reveals the importance of this recharge area. The modified model was then accepted as being representative of the aquifer in 1945.

In 1945 the aquifer was artesian in all areas. However, continued pumpage lowered the piezometric surface and began to dewater a portion of the aquifer. This area of water table conditions continued to expand, reaching by 1964 the extent shown in Figure 12. The inclusion of this dewatering in the model analysis was a difficult problem. It was felt that it should be included because dewatering would produce a reduction in the drawdowns occurring in the aquifer, but to do so in a precise manner would involve a great deal of electronic circuitry. To determine the importance of this dewatered area, it was first assumed that the aquifer remained a leaky-artesian system. The increased pumpage from 1935 to 1964 was imposed on the model, and the resultant drawdowns recorded. Then, capacitors that would simulate the water table conditions were added to the model, and it was assumed that this condition existed from 1935 to 1964. This would permit the evaluation of the maximum effect that the water table conditions exhibited, because they actually existed for a shorter time. The increase in pumpage from 1935 to 1964 was again imposed on the model, and the resultant drawdowns compared with those obtained under assumed leaky-artesian conditions. Very little difference was observed, generally less than 10 feet over the 30-year period. This error is well within the limits of accuracy of the data, and it was felt that the effect of the water table conditions was not significant.

The lack of significance of the water table storage coefficient was attributed to several factors. First, the total dewatered area is very small in relation to the total area of the aquifer, less than two percent. Second, the total amount of water released from water table storage is less than two percent of the total amount of water withdrawn from the aquifer over this 30-year period. Third, it has already been shown that the most significant factor affecting the drawdown distribution is the leakage to the aquifer from the overlying material, and this would not be significantly affected by the dewatering.

However, as the aquifer is developed further, the areas of water table conditions will become increasingly important. It was felt that to avoid excessive drawdowns in this portion of the model during future analyses, the water table storage coefficients should be included in the model, under the assumption that this portion of the aquifer was water table in 1935.

The observed drawdowns were then compared with the expected drawdowns, Figure 15, and found to agree quite closely. A few minor changes were made in the resistors controlling the leakage from the glacial material, and the final observed drawdowns determined, as shown in Figure 21. The model was then accepted as being representative of the aquifer in 1964.

FINAL ANALYSIS OF LEAKAGE RATE

It was desired to determine the leakage that was occurring from the glacial drift, in units of gallons per day per square mile, per foot of head difference. To do so, the values of the resistors controlling the leakage were recorded. Each resistor controlled the leakage over one square mile. The leakage was then determined by:

$$q = \frac{V}{R} \times K_3$$

where:

q = leakage in gpd/mi^2

V = total voltage drop across resistor

R = measured value of resistor

K_3 = scale factor (2×10^5 gpd/amp).

If the voltage equivalent to a one-foot head differential is used, namely, 0.1 volts, the expression becomes:

$$q = \frac{0.1}{R} \times K_3$$

where "q" is now in gpd/mi^2/ft.

This calculation was made for each region of similar leakage, and the results are shown in Figure 22. The term

"Potential Leakage" is used, because this is the leakage rate that can be expected to exist when the piezometric surface in an area is below the water table in the glacial material. In many areas, this condition does not presently exist.

It is felt that the values given in Figure 22 are more representative than those given in Table 1, for several reasons. First, the data used in their determination, namely the piezometric decline over many years, are more accurate than the information used in the study of the 1900 piezometric surface. Second, the total leakage is much greater, thus an error in the leakage rate in a given area is more likely to be detected. Third, the area in which leakage is occurring is better known than it was in the study of the 1900 condition. This is due to better knowledge of both the position of the water table and of the elevation of the piezometric surface.

CONCLUSIONS

During the analysis of the electric analog model, several significant facts were revealed about the hydrology of the Saginaw Formation. The single most important source of recharge to the aquifer is from the leakage through the upper confining beds. The variation in the leakage rate, as determined from the transient analysis of the model, is shown in Figure 22. This leakage has lowered the water levels in the saturated material overlying the confining beds. Because the leakage is quite uniform, the horizontal movement of water through the aquifer is greatly reduced. This means that the transmissibility of the aquifer is not as significant a factor as it was originally considered to be. Often, in an attempt to make the drawdowns observed on the model agree with the expected results, the transmissibility of the model was changed by as much as 100 per cent. This had very little effect on the drawdown configuration. The degree to which the transmissibility of the aquifer becomes unimportant is related more to the leakage rate than to the pumpage rate.

The rivers also were considered to be an important source of recharge to the aquifer. It is now realized that the natural recharge from this source is limited, not by the water available, but by the nature of the recharge. On the model, the total recharge from each river segment had to have a maximum value placed on it. This maximum had already been reached for a large portion of the river courses in 1945. The rivers thus serve as a constant source of natural recharge, but cannot be counted on for further development without a concentrated program of artificial recharge.

The artesian storage coefficient of the aquifer was found to have no effect upon the total drawdowns, and the water table storage coefficients of the dewatered portion only a small effect. The storage coefficient of the glacial material is of great significance. However, the order of magnitude of the storage coefficient is much more important than minor variations. That is, we know that the storage coefficient must be in the order of 10^{-1}, but whether it is 5×10^{-2} or 1.5×10^{-1} does not appear significant. This statement is based on experimentation with different values on the model, and the observation of the resultant variations in the piezometric change maps for the various periods.

As has been mentioned, the aquifer was in equilibrium in 1935. In addition, the model analysis indicates that the aquifer was in near equilibrium in 1945. That is, had pumping rates continued at the 1945 level, a new equilibrium would have been reached.

In summary, an electric analog model of the Saginaw Formation was constructed on the basis of a conceptual model of the aquifer. The analog model was analyzed, and modified within the limits of hydrologic feasibility to make the observed changes in the piezometric surface agree with the actual changes which occurred. The final analog model, and the resulting conceptual model, is then considered to be an accurate representation of the aquifer, and should be useful as a predictive tool in the planning of future water resource development in the Lansing area. By imposing expected future withdrawal rates and other changing hydrologic conditions on the model, an estimate of future drawdowns can be obtained. In addition, other schemes, such as the feasibility of artificial recharge to the aquifer may be investigated. As more knowledge is gained about the aquifer through future field investigations, the model will be updated.

TABLE 1.--Leakage rates for recharge regions shown in Figure 9, for undeveloped conditions of 1900.

Region	Leakage gpd/mi^2	Leakage Rate $gpd/mi^2/ft$
1	25,000	4000
2	40,000	3300
3	40,000	5200
4	50,000	5000
5	60,000	7000
6	20,000	2000
7	15,000	1500
8	40,000	5000
9	32,000	4000
10	25,000	4000
11	25,000	4500

TABLE 2.--Flow from aquifer to river in undeveloped condition of 1900.

River Segment From Figure 6	Flow Into Segment mgd
1-2	0.28
2-3	0.12
3-4	0.58
4-5	0.05
5-6	0.30
6-7	0.58
7-8	0.29
8-9	0.27
9-10	0.15
10-11	0.26
11-12	0.17
13-14	0.05
14-15	0.05
15-16	0.16
16-17	0.14
17-18	0.20
18-6	0.24
19-20	0.08
20-21	0.05
21-22	0.19
22-23	0.19
23-24	0.24
24-25	0.14
25-18	0.10
total	4.88 mgd

TABLE 3.--River recharge rates.

River Segment from Figure 10	Flow from Aquifer to River in Undeveloped Condition of 1900 mgd	Maximum Recharge Rate Specified on Analog Model mgd
1	0.14	0.28
2	0.30	0.60
3	0.31	0.62
4	0.17	0.34
5	0.04	0.08
6	1.13	3.60
7	0.36	0.72
8	0.18	0.36
9	0.18	0.36
10	0.22	0.44
11	0.07	0.14
12	0.25	0.50
13	0.19	0.38
14	0.44	0.88
15	0.08	0.16
16	0.14	0.56
17	0.23	0.56
18	0.45	0.90
Total	4.88 mgd	11.48 mgd

Figure 3
Block Diagram of Electronic
Equipment used in Analysis

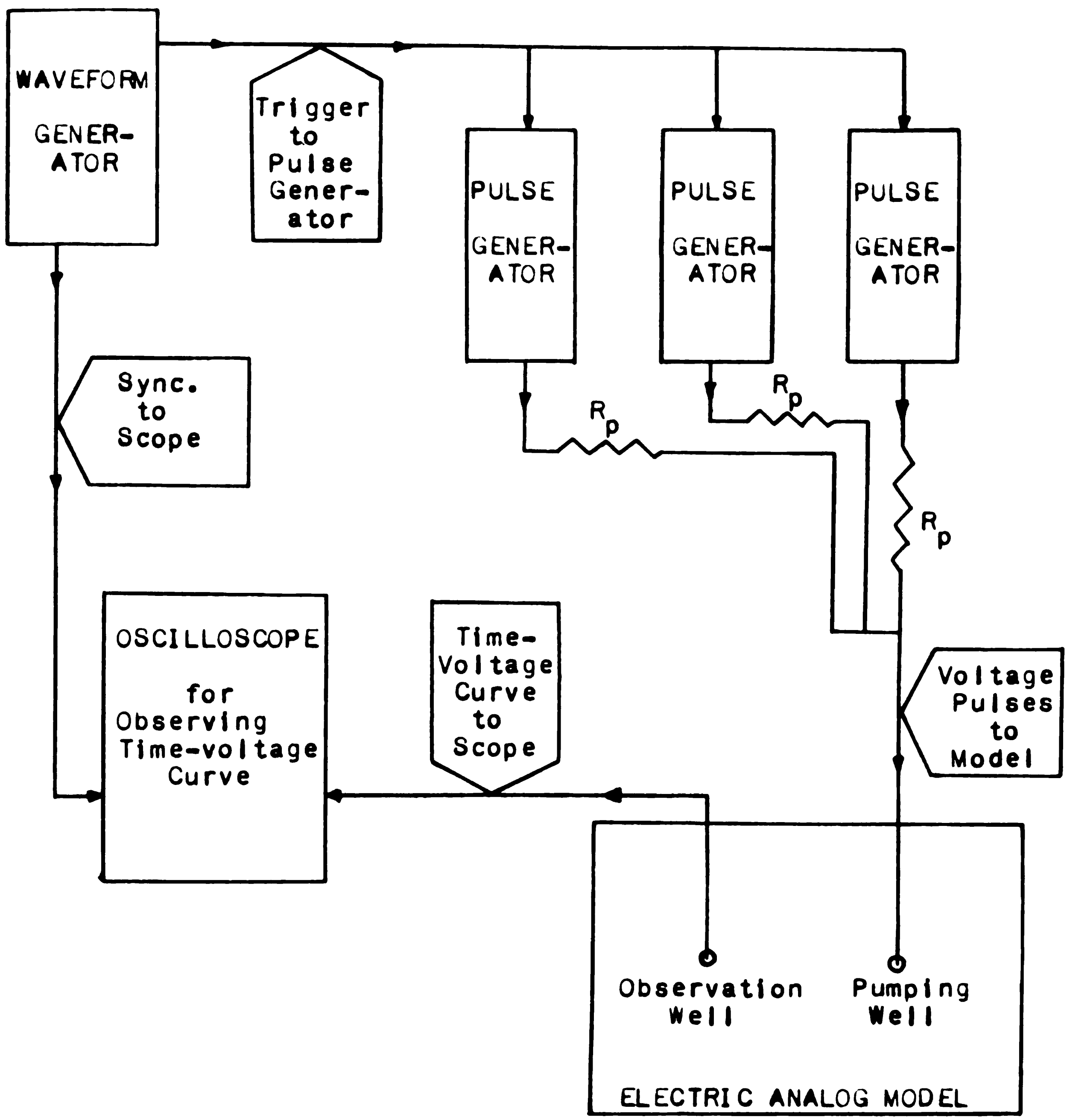
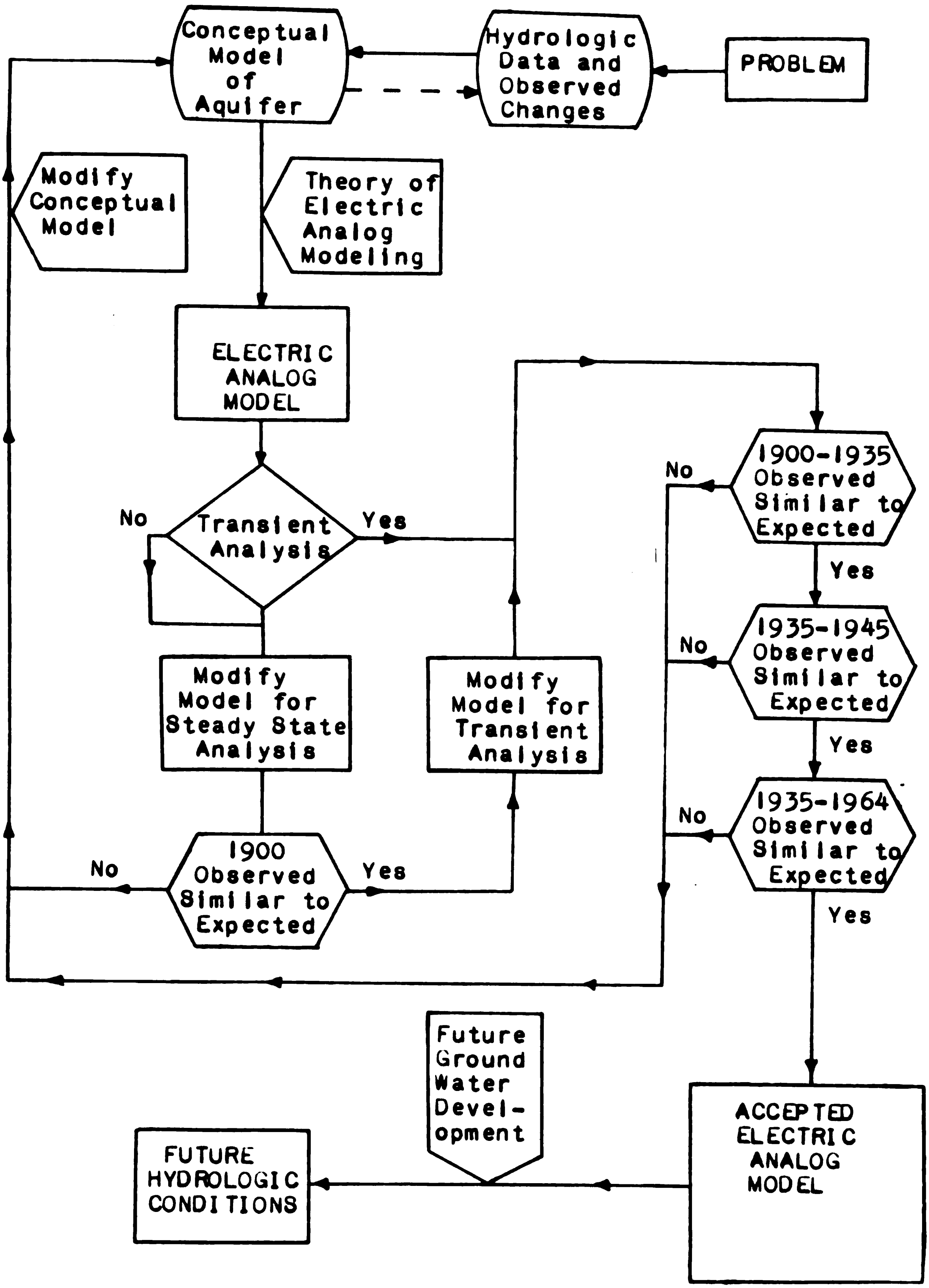


Figure 4
Design and Analysis of Analog Model



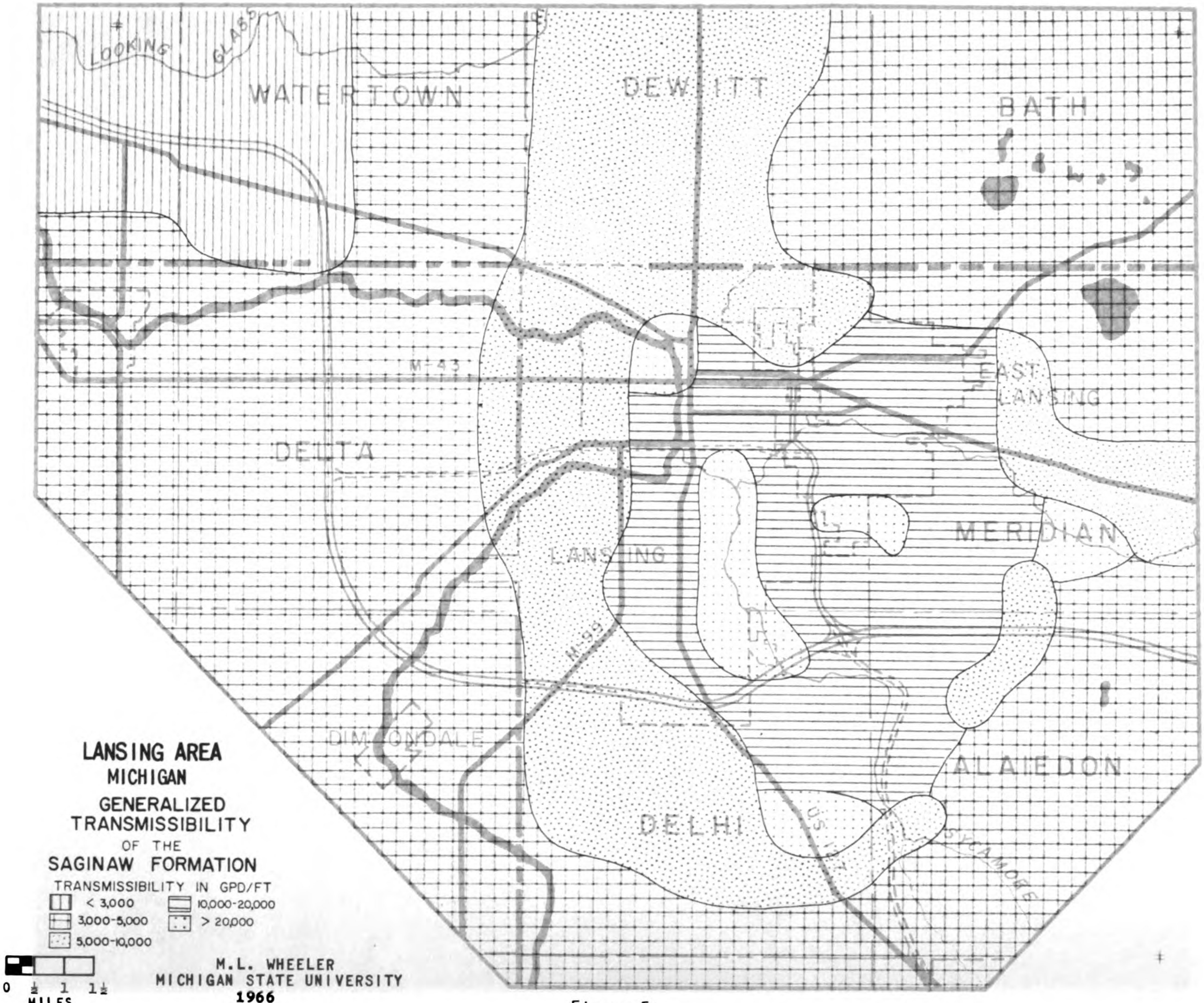

LOOKING GLASS
WATERTOWN
DEWITT
BATH
M-43
DELTA
EAST LANSING
LANSING
MERIDIAN
M-99
DIMONDALE
ALAIEDON
DELHI
US 127
SYCAMORE
LANSING AREA
MICHIGAN
GENERALIZED
TRANSMISSIBILITY
OF THE
SAGINAW FORMATION
TRANSMISSIBILITY IN GPD/FT
< 3,000
3,000-5,000
5,000-10,000
10,000-20,000
> 20,000
0 ½ 1 1½
MILES
M.L. WHEELER
MICHIGAN STATE UNIVERSITY
1966

Figure 5

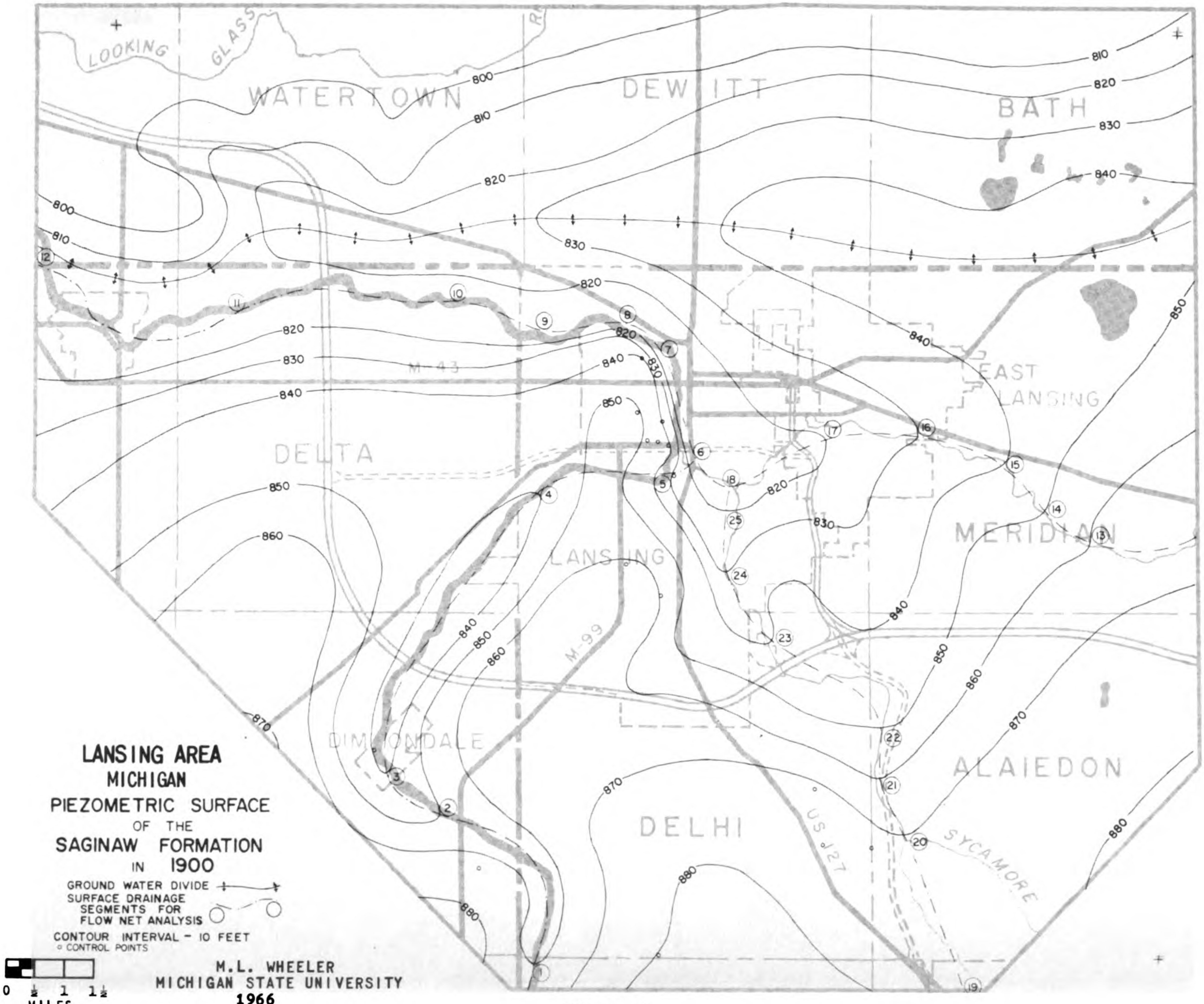

LOOKING GLASS
WATERTOWN
DEWITT
BATH
DELTA
LANSING
EAST LANSING
MERIDIAN
DIMONDALE
DELHI
ALAIEDON
SYCAMORE
M-43
M-99
US 127
800
810
820
830
840
850
860
870
880
LANSING AREA
MICHIGAN
PIEZOMETRIC SURFACE
OF THE
SAGINAW FORMATION
IN 1900
GROUND WATER DIVIDE
SURFACE DRAINAGE SEGMENTS FOR FLOW NET ANALYSIS
CONTOUR INTERVAL - 10 FEET
○ CONTROL POINTS
0 ½ 1 1½
MILES
M.L. WHEELER
MICHIGAN STATE UNIVERSITY
1966

Figure 6

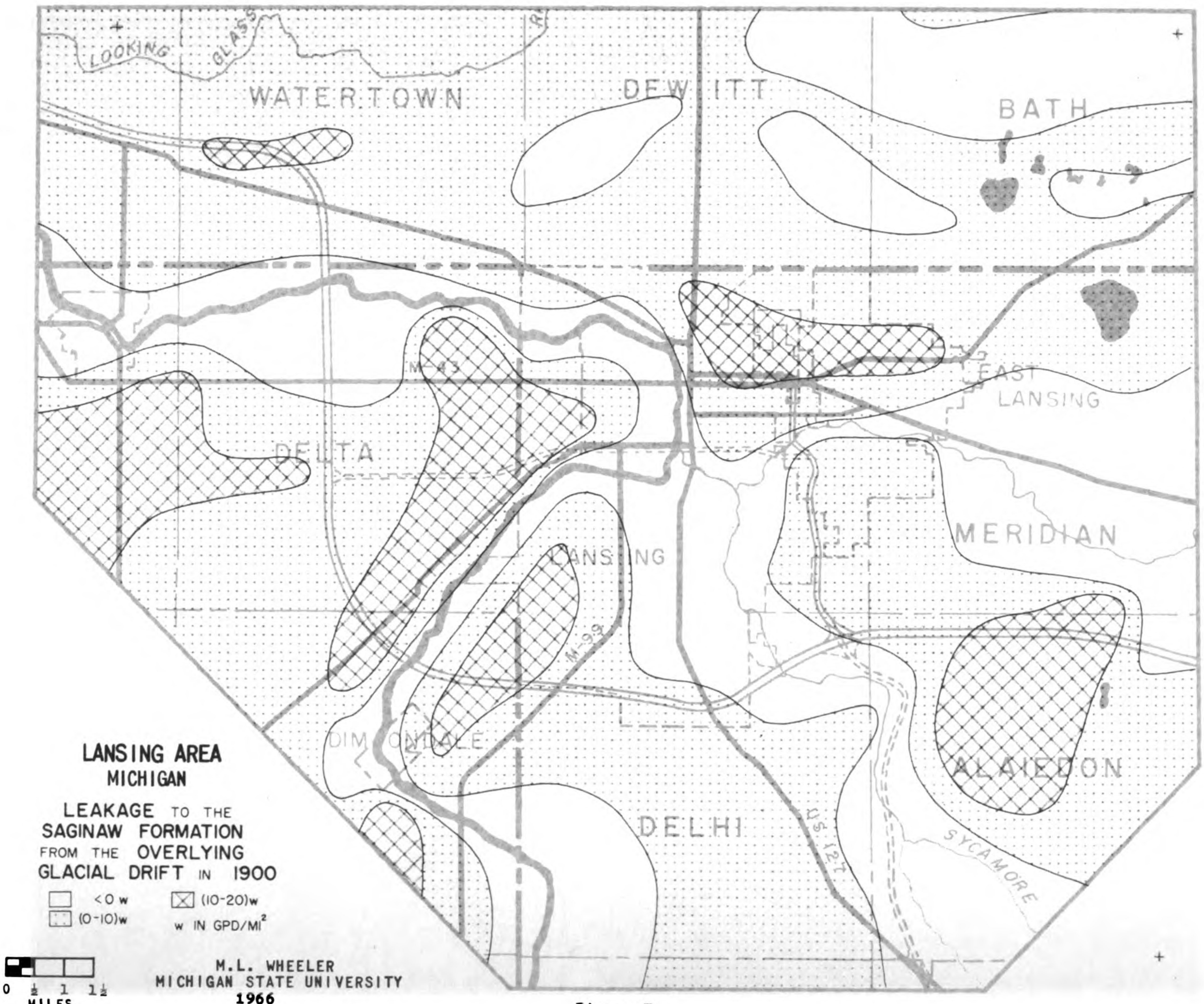

LOOKING GLASS
WATERTOWN
DEWITT
BATH
EAST LANSING
M-43
DELTA
LANSING
MERIDIAN
M-99
DIMONDALE
DELHI
US 127
ALAIEDON
SYCAMORE
LANSING AREA
MICHIGAN
LEAKAGE TO THE SAGINAW FORMATION FROM THE OVERLYING GLACIAL DRIFT IN 1900
<0 w
(0-10)w
(10-20)w
w IN GPD/MI²
0 ½ 1 1½
MILES
M.L. WHEELER
MICHIGAN STATE UNIVERSITY
1966

Figure 7

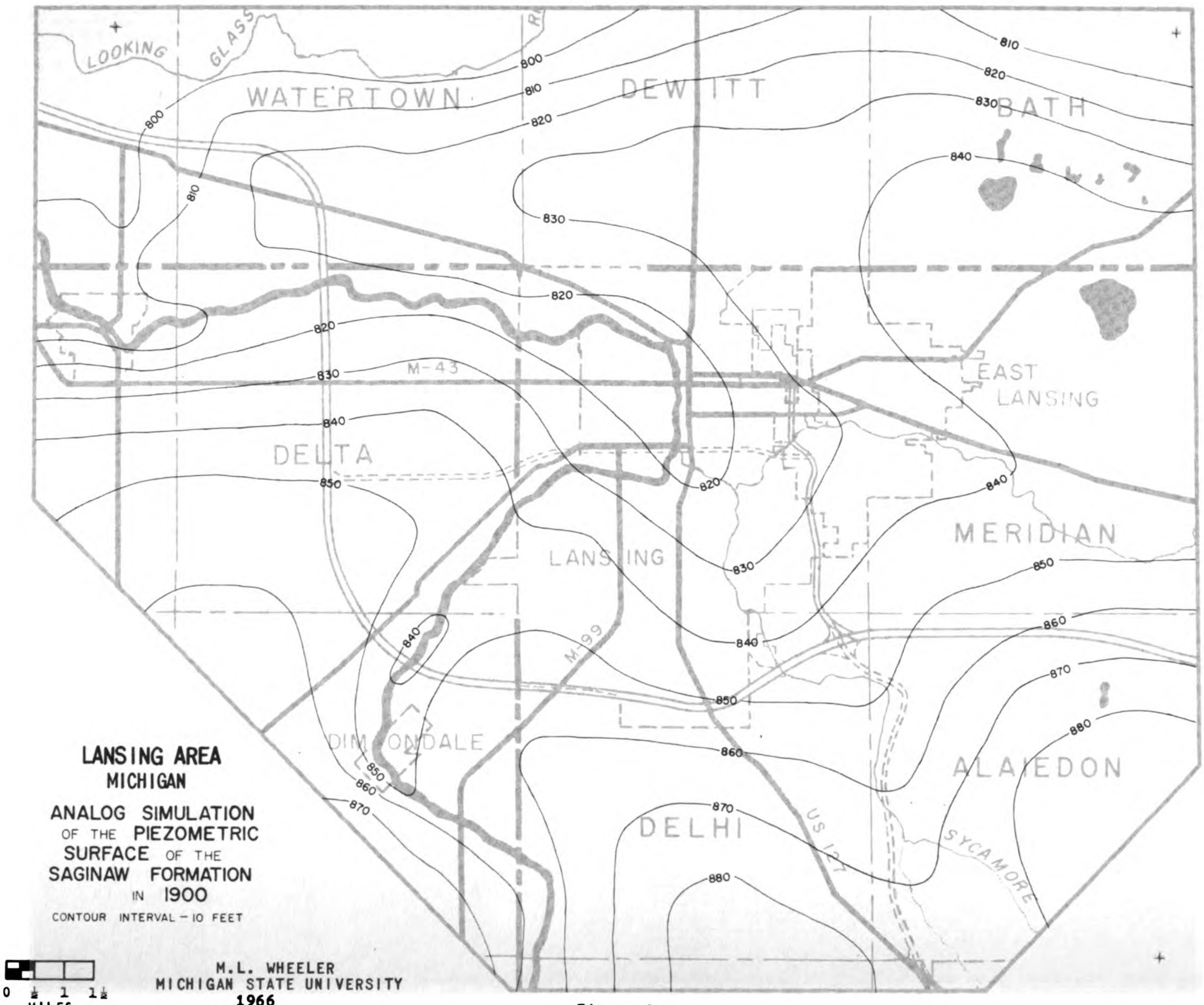

LANSING AREA
MICHIGAN
ANALOG SIMULATION OF THE PIEZOMETRIC SURFACE OF THE SAGINAW FORMATION IN 1900
CONTOUR INTERVAL – 10 FEET
0 ½ 1 1½ MILES
M.L. WHEELER
MICHIGAN STATE UNIVERSITY
1966
WATERTOWN
DEWITT
BATH
DELTA
LANSING
EAST LANSING
MERIDIAN
DIMONDALE
DELHI
ALAIEDON
LOOKING GLASS
SYCAMORE
M-43
M-99
US 127
800
810
820
830
840
850
860
870
880

Figure 8

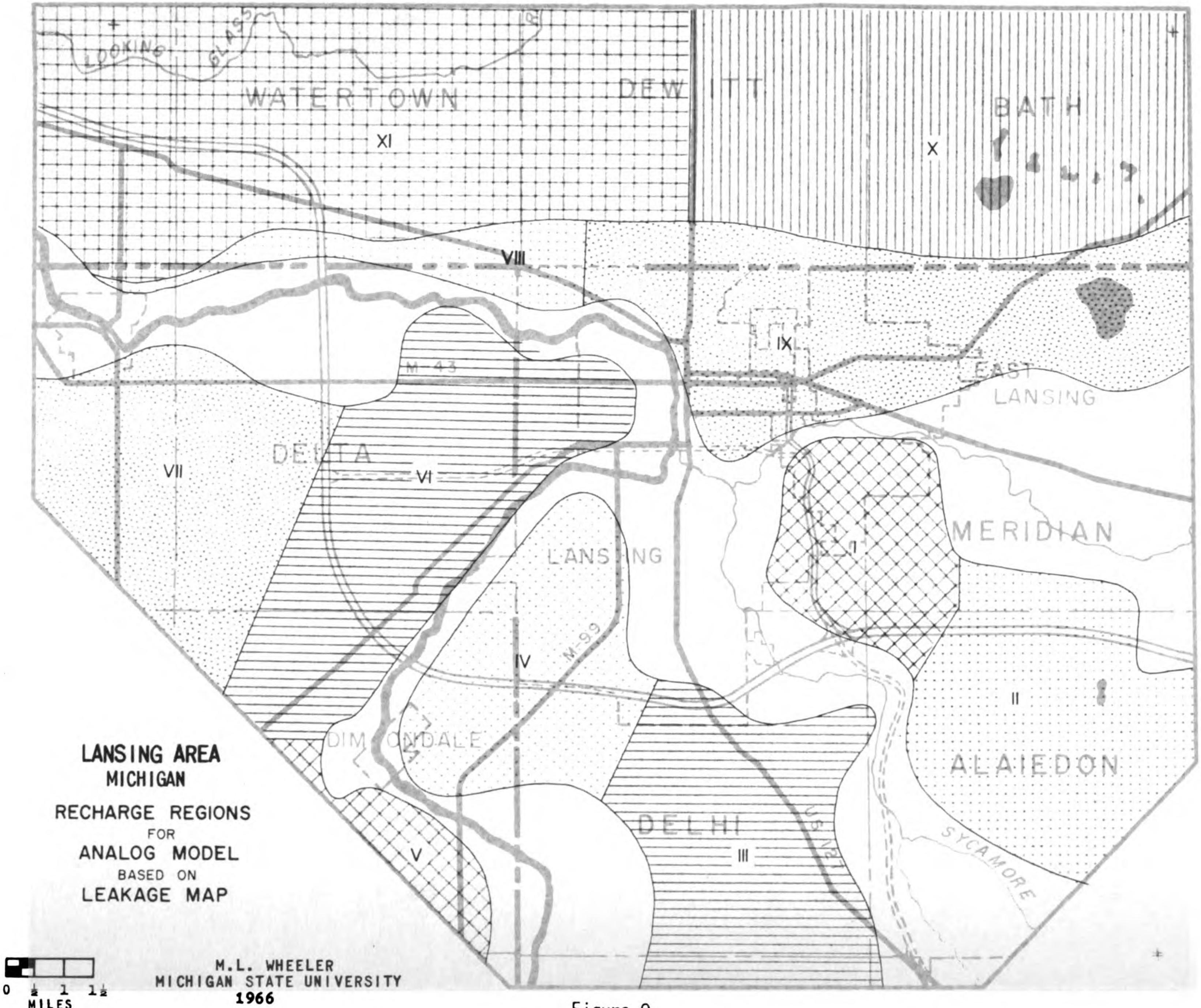

LOOKING GLASS R
WATERTOWN
DEW ITT
BATH
XI
X
VIII
IX
EAST LANSING
M-43
DELTA
VII
VI
MERIDIAN
LANSING
I
M-99
IV
II
DIMONDALE
ALAIEDON
LANSING AREA
MICHIGAN
RECHARGE REGIONS
FOR
ANALOG MODEL
BASED ON
LEAKAGE MAP
DELHI
III
US 127
SYCAMORE
V
0 ½ 1 1½
MILES
M.L. WHEELER
MICHIGAN STATE UNIVERSITY
1966

Figure 9

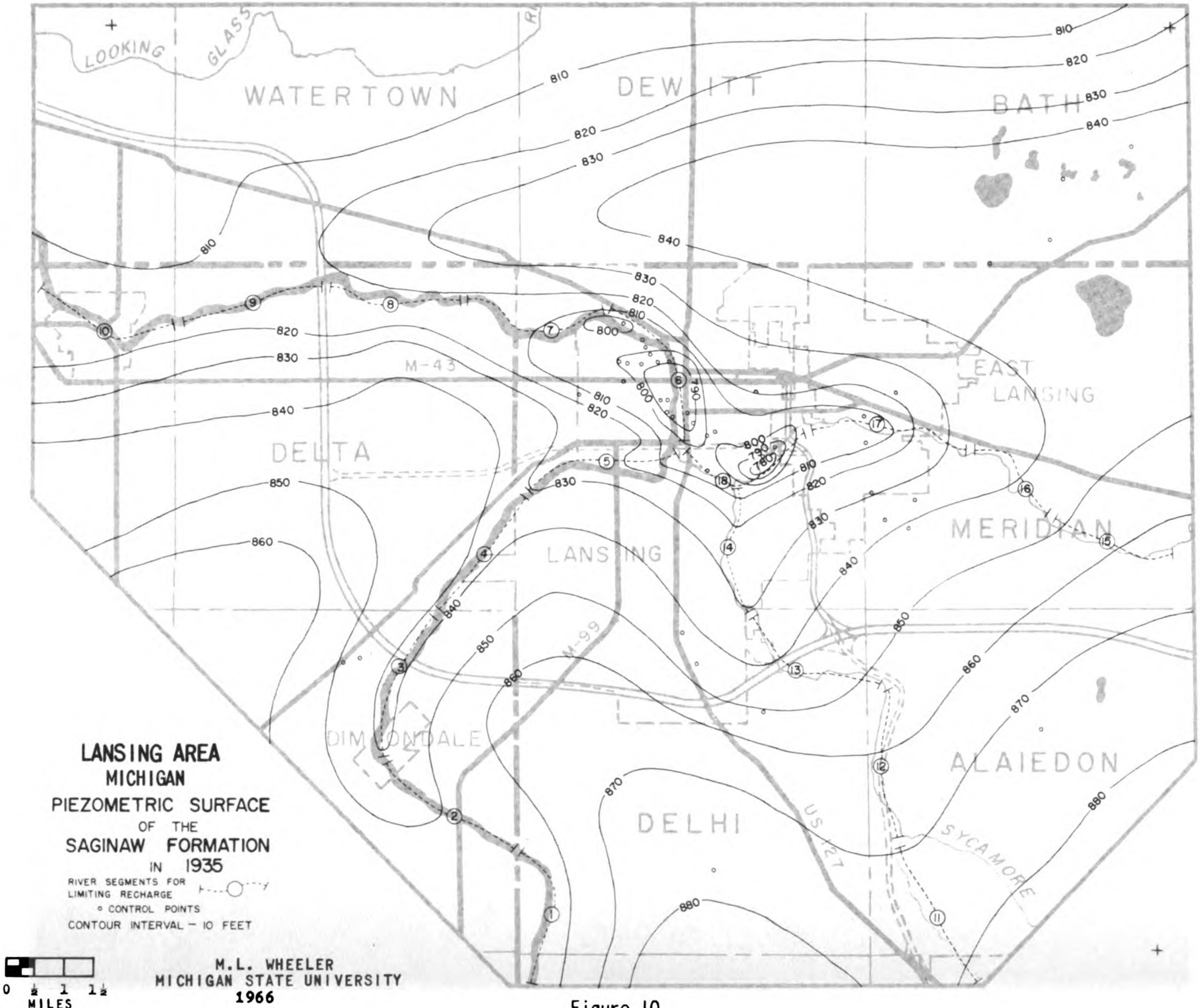

LANSING AREA
MICHIGAN
PIEZOMETRIC SURFACE
OF THE
SAGINAW FORMATION
IN 1935
RIVER SEGMENTS FOR LIMITING RECHARGE
○ CONTROL POINTS
CONTOUR INTERVAL – 10 FEET
0 ½ 1 1½
MILES
M.L. WHEELER
MICHIGAN STATE UNIVERSITY
1966
WATERTOWN
DEWITT
BATH
DELTA
LANSING
EAST LANSING
MERIDIAN
DIMONDALE
DELHI
ALAIEDON
LOOKING GLASS
SYCAMORE
M-43
M-99
US 127
810
820
830
840
850
860
870
880
800
790
780

Figure 10

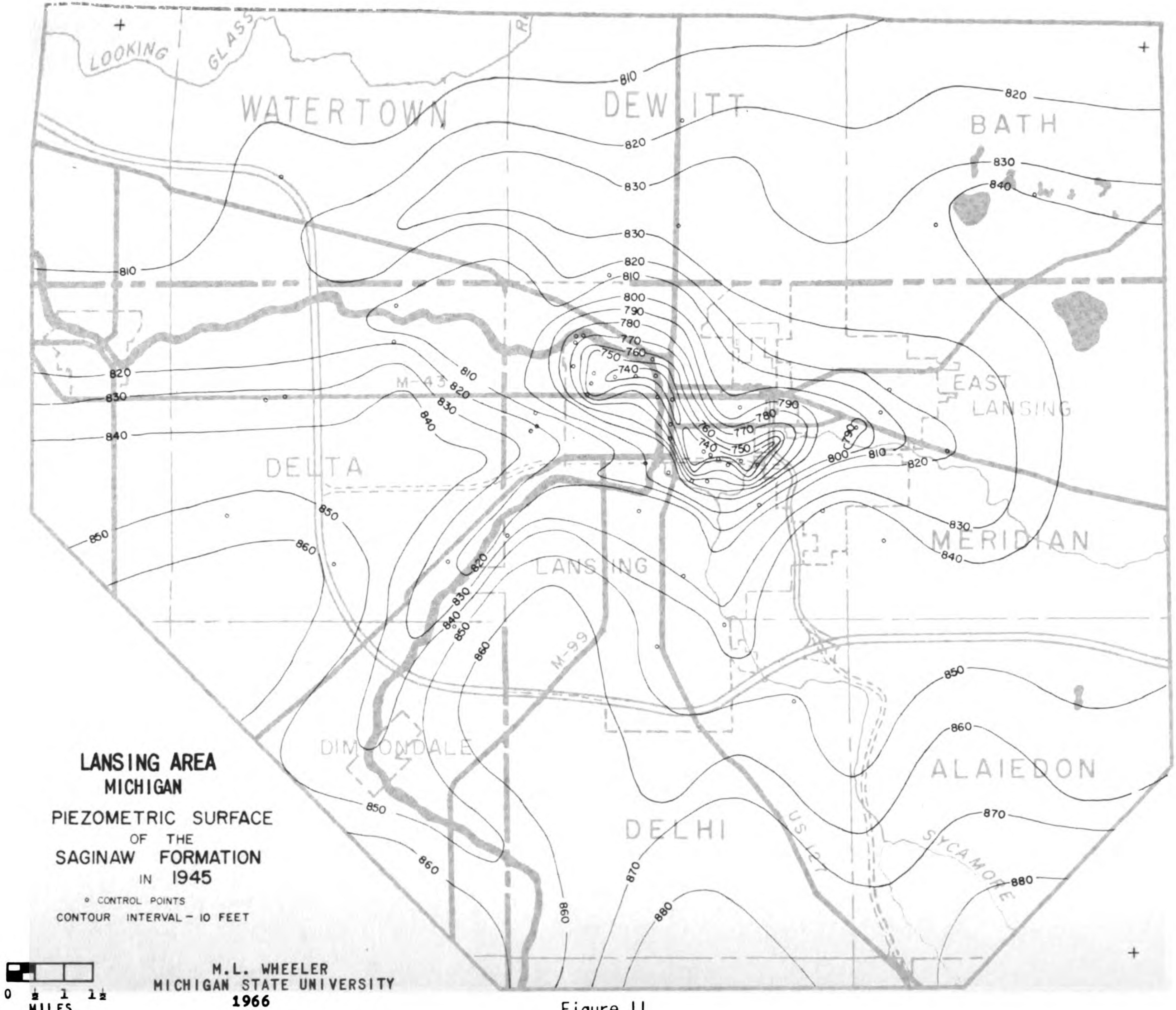

LANSING AREA
MICHIGAN
PIEZOMETRIC SURFACE
OF THE
SAGINAW FORMATION
IN 1945
CONTROL POINTS
CONTOUR INTERVAL - 10 FEET
0 ½ 1 1½
MILES
M.L. WHEELER
MICHIGAN STATE UNIVERSITY
1966
WATERTOWN
DEWITT
BATH
DELTA
LANSING
EAST LANSING
MERIDIAN
DIMONDALE
DELHI
ALAIEDON
LOOKING GLASS
SYCAMORE
M-43
M-99
US 127
740
750
760
770
780
790
800
810
820
830
840
850
860
870
880

Figure 11

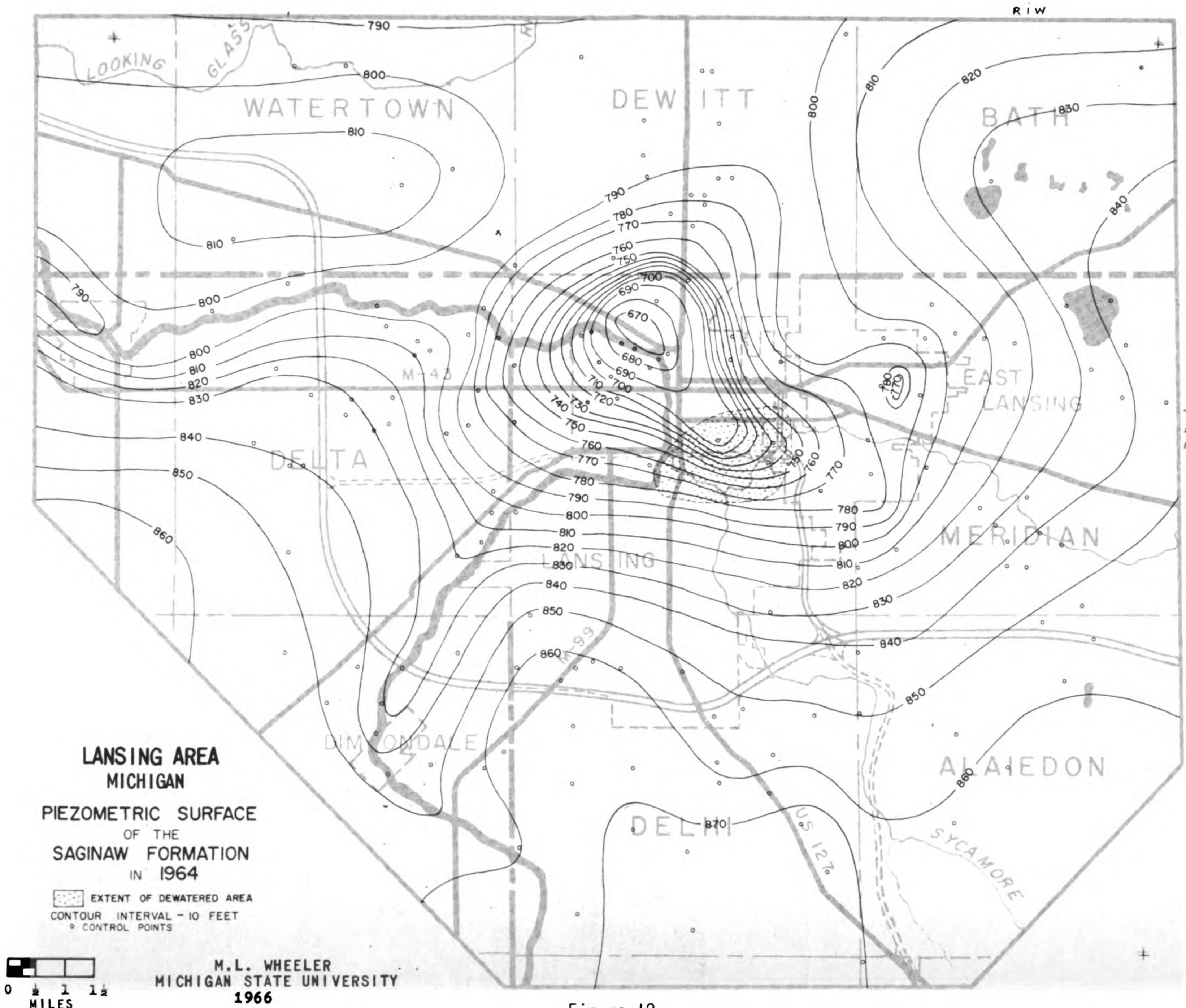

LANSING AREA
MICHIGAN
PIEZOMETRIC SURFACE
OF THE
SAGINAW FORMATION
IN 1964
EXTENT OF DEWATERED AREA
CONTOUR INTERVAL - 10 FEET
CONTROL POINTS
0 ½ 1 1½
MILES
M.L. WHEELER
MICHIGAN STATE UNIVERSITY
1966
WATERTOWN
DEWITT
BATH
DELTA
LANSING
EAST LANSING
MERIDIAN
DIMONDALE
DELHI
ALAIEDON
LOOKING GLASS
SYCAMORE
M-43
M-99
US 127
R1W
T4N

Figure 12

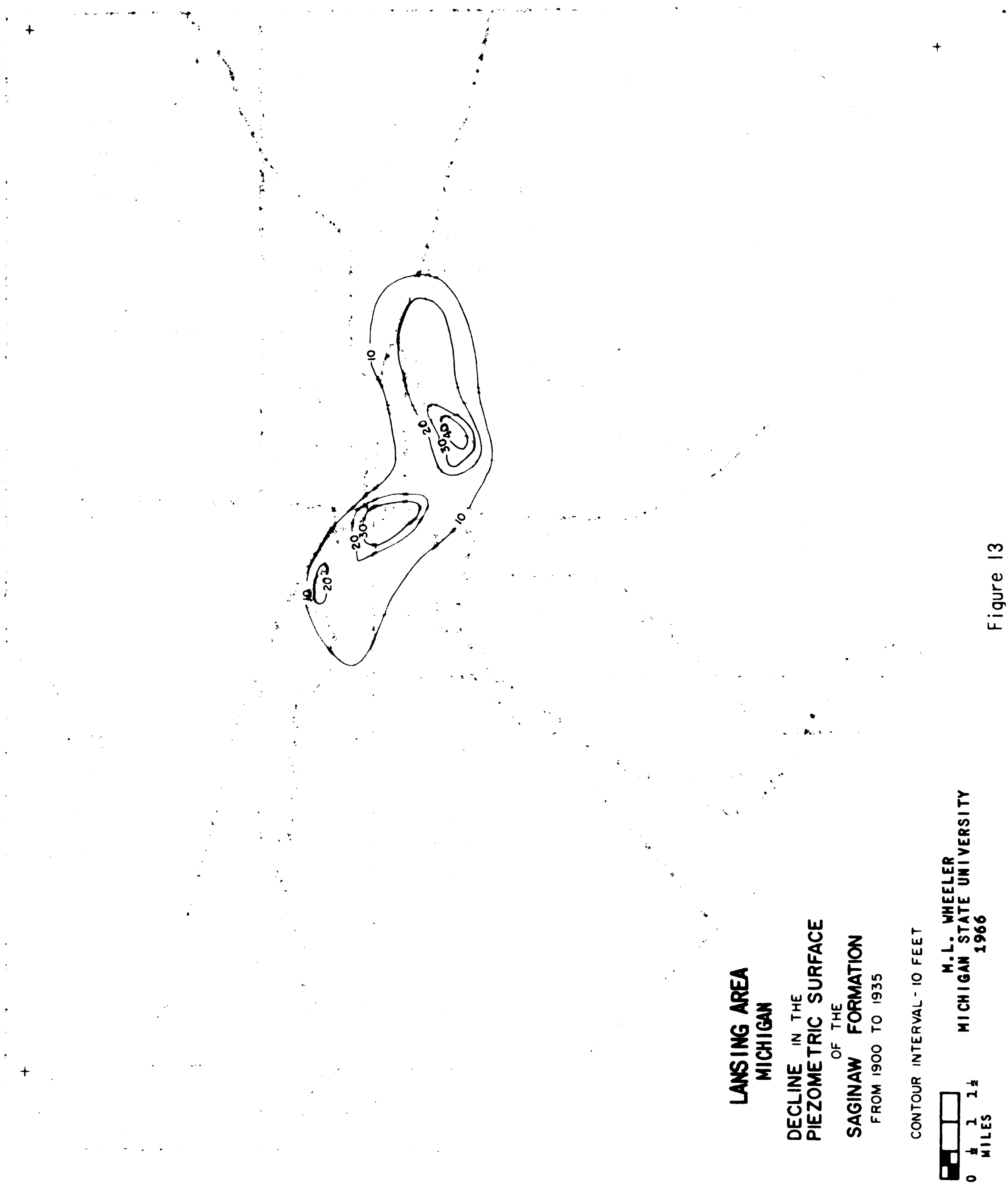

10
20
30
40
10
20
30
20
10
LANSING AREA
MICHIGAN
DECLINE IN THE
PIEZOMETRIC SURFACE
OF THE
SAGINAW FORMATION
FROM 1900 TO 1935
CONTOUR INTERVAL - 10 FEET
0 ½ 1 1½
MILES
M.L. WHEELER
MICHIGAN STATE UNIVERSITY
1966

Figure 13

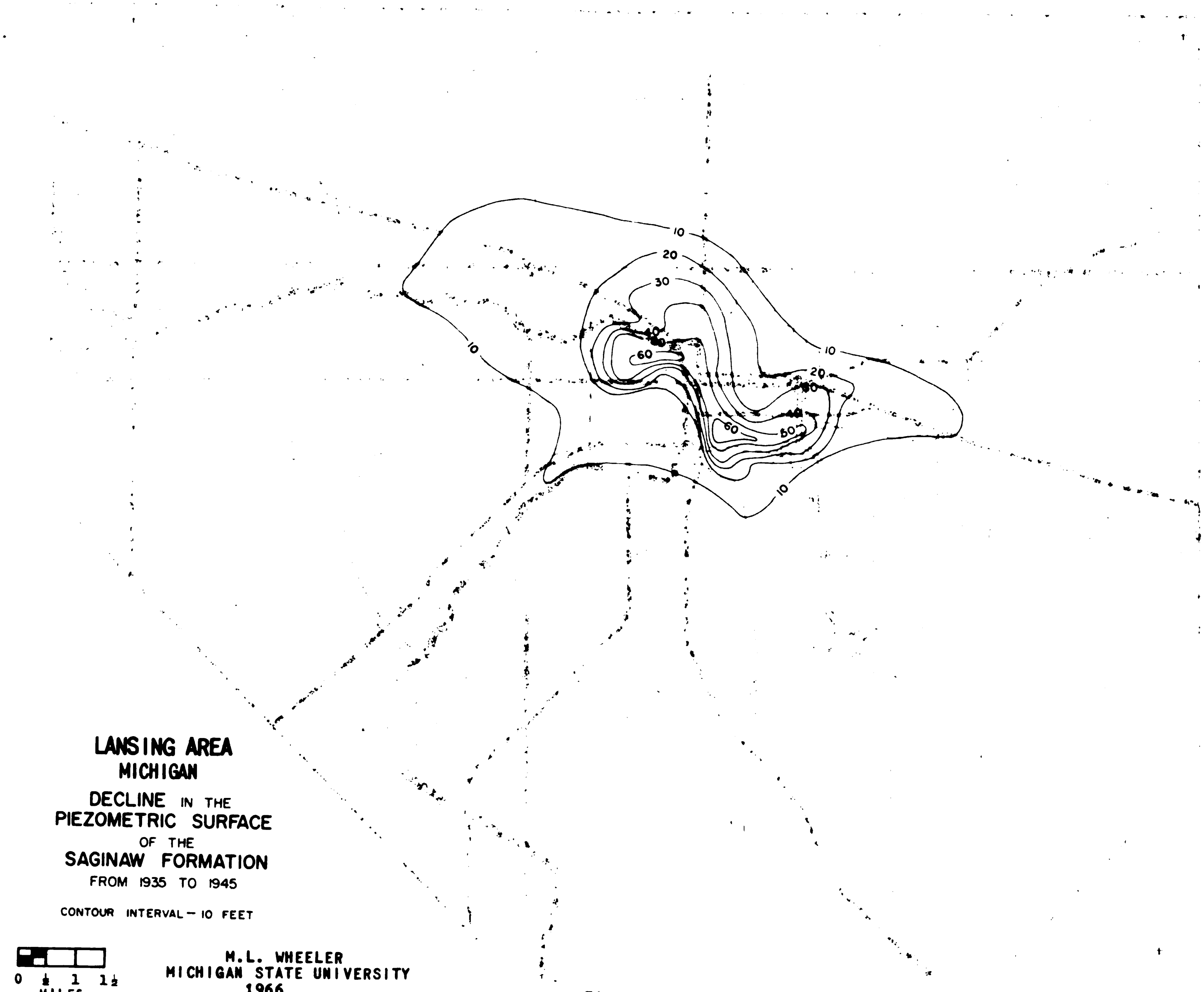

10
20
30
40
60
LANSING AREA
MICHIGAN
DECLINE IN THE
PIEZOMETRIC SURFACE
OF THE
SAGINAW FORMATION
FROM 1935 TO 1945
CONTOUR INTERVAL – 10 FEET
0 ½ 1 1½
MILES
M.L. WHEELER
MICHIGAN STATE UNIVERSITY
1966

Figure 14

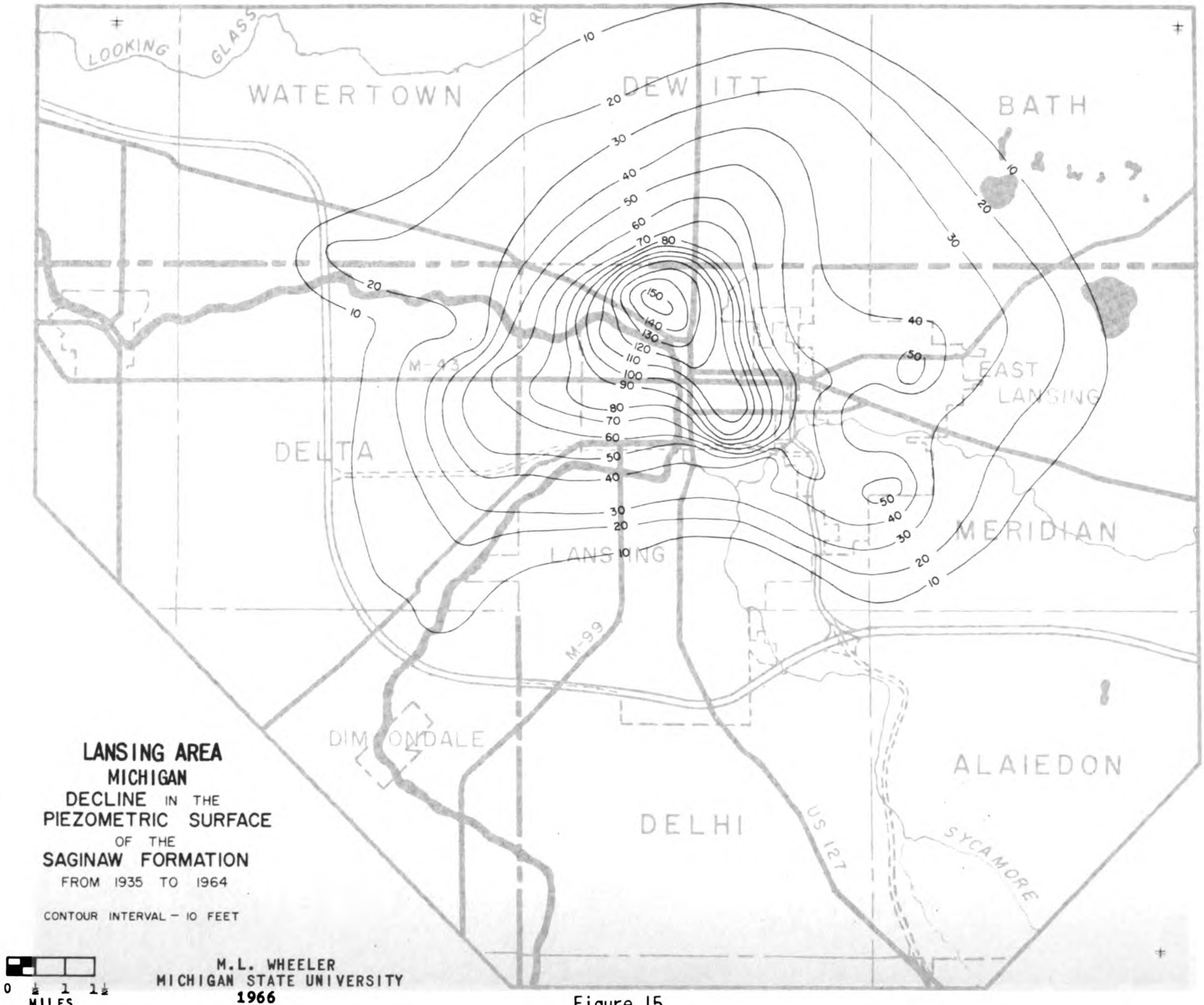
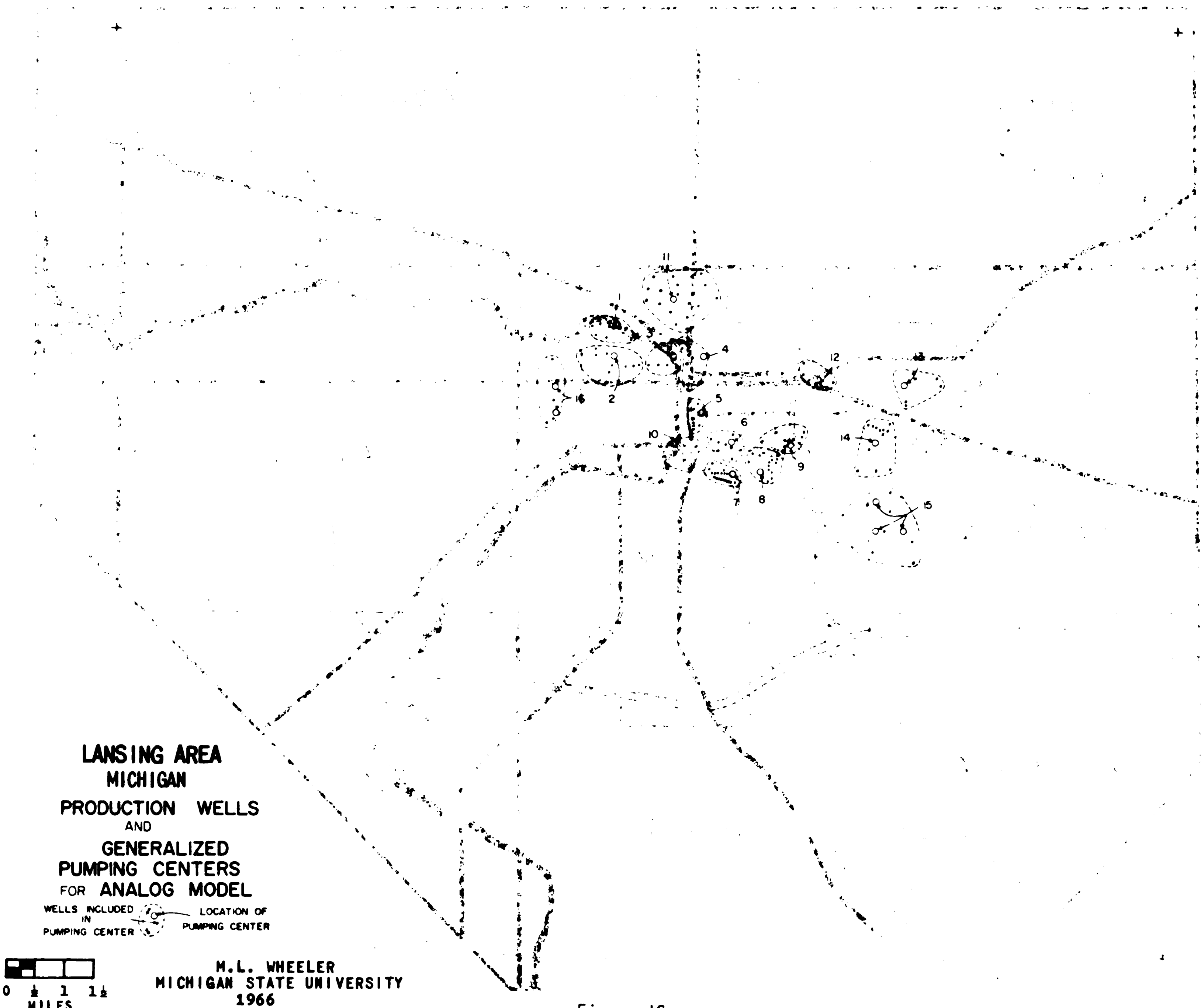

LANSING AREA
MICHIGAN
DECLINE IN THE
PIEZOMETRIC SURFACE
OF THE
SAGINAW FORMATION
FROM 1935 TO 1964
CONTOUR INTERVAL – 10 FEET
0 ½ 1 1½
MILES
M.L. WHEELER
MICHIGAN STATE UNIVERSITY
1966
LOOKING GLASS
WATERTOWN
DEWITT
BATH
EAST LANSING
MERIDIAN
DELTA
LANSING
DIMONDALE
DELHI
ALAIEDON
SYCAMORE
M-43
M-99
US 127
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150

Figure 15

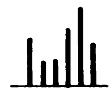


LANSING AREA
MICHIGAN
PRODUCTION WELLS
AND
GENERALIZED
PUMPING CENTERS
FOR ANALOG MODEL
WELLS INCLUDED IN PUMPING CENTER
LOCATION OF PUMPING CENTER
0 ½ 1 1½
MILES
M.L. WHEELER
MICHIGAN STATE UNIVERSITY
1966
1
2
3
4
5
6
7
8
9
10
11
12
14
15
16

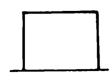
Figure 16

Figure 17

AVERAGE DAILY GROUND WATER WITHDRAWAL FROM PUMPING CENTERS



BAR GRAPH INDICATES ACTUAL AVERAGE DAILY WITHDRAWAL FOR EACH YEAR, 1930-1964



STEP FUNCTION APPROXIMATING ACTUAL WITHDRAWAL

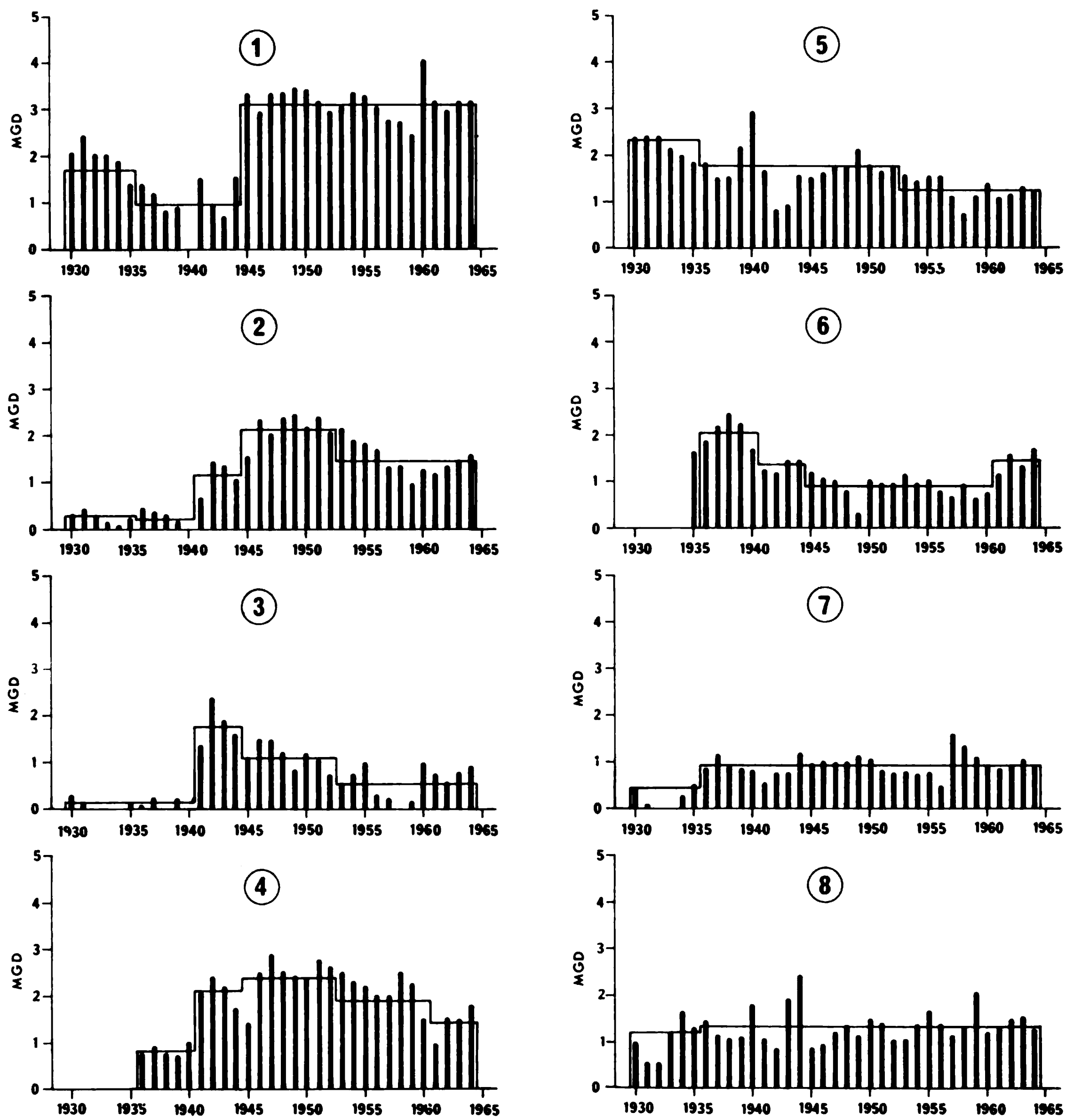
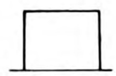


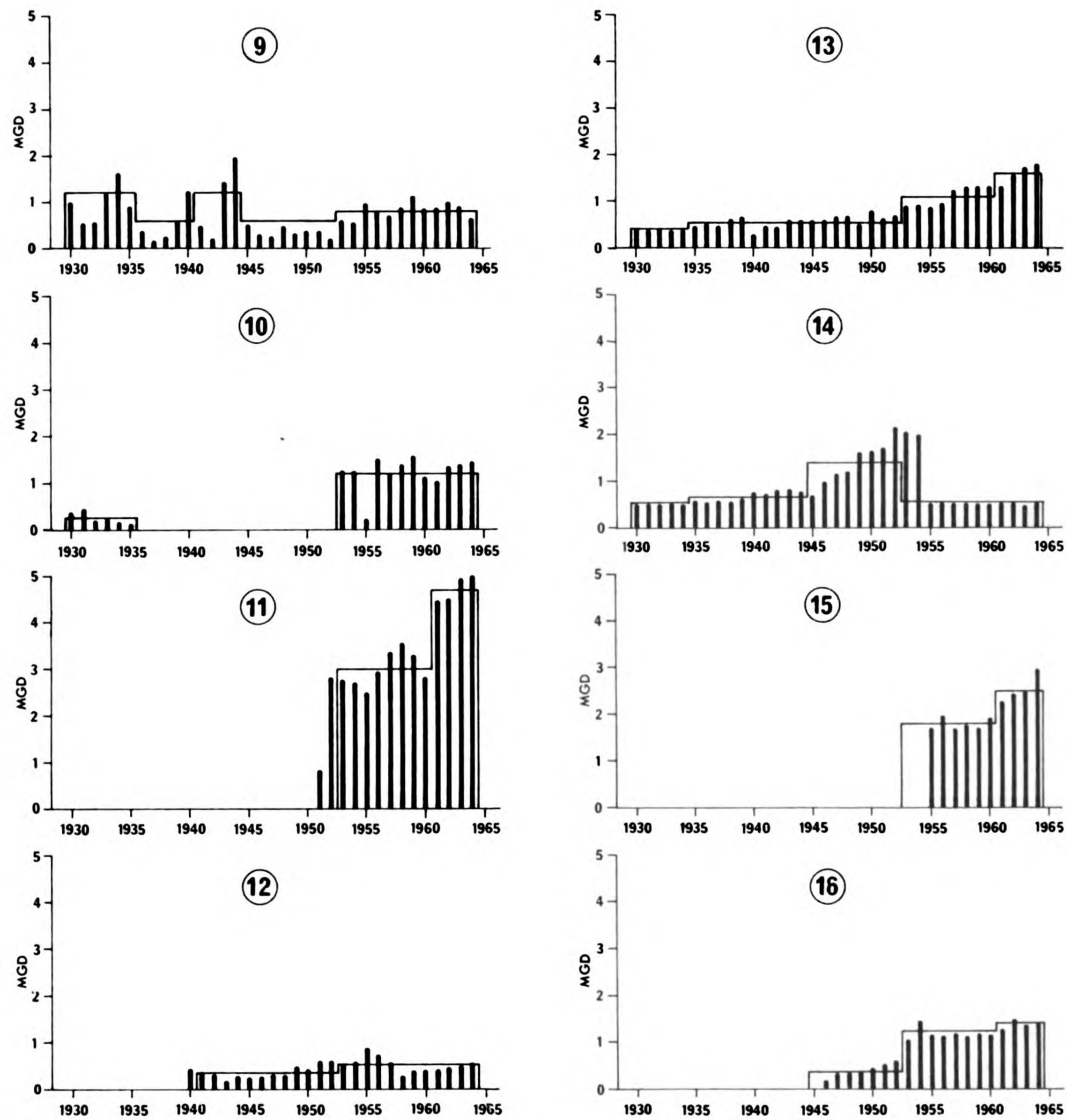
Figure 17, continued

AVERAGE DAILY GROUND WATER WITHDRAWAL FROM PUMPING CENTERS

BAR GRAPH INDICATES ACTUAL AVERAGE DAILY WITHDRAWAL FOR EACH YEAR, 1930-1964



STEP FUNCTION APPROXIMATING ACTUAL WITHDRAWAL



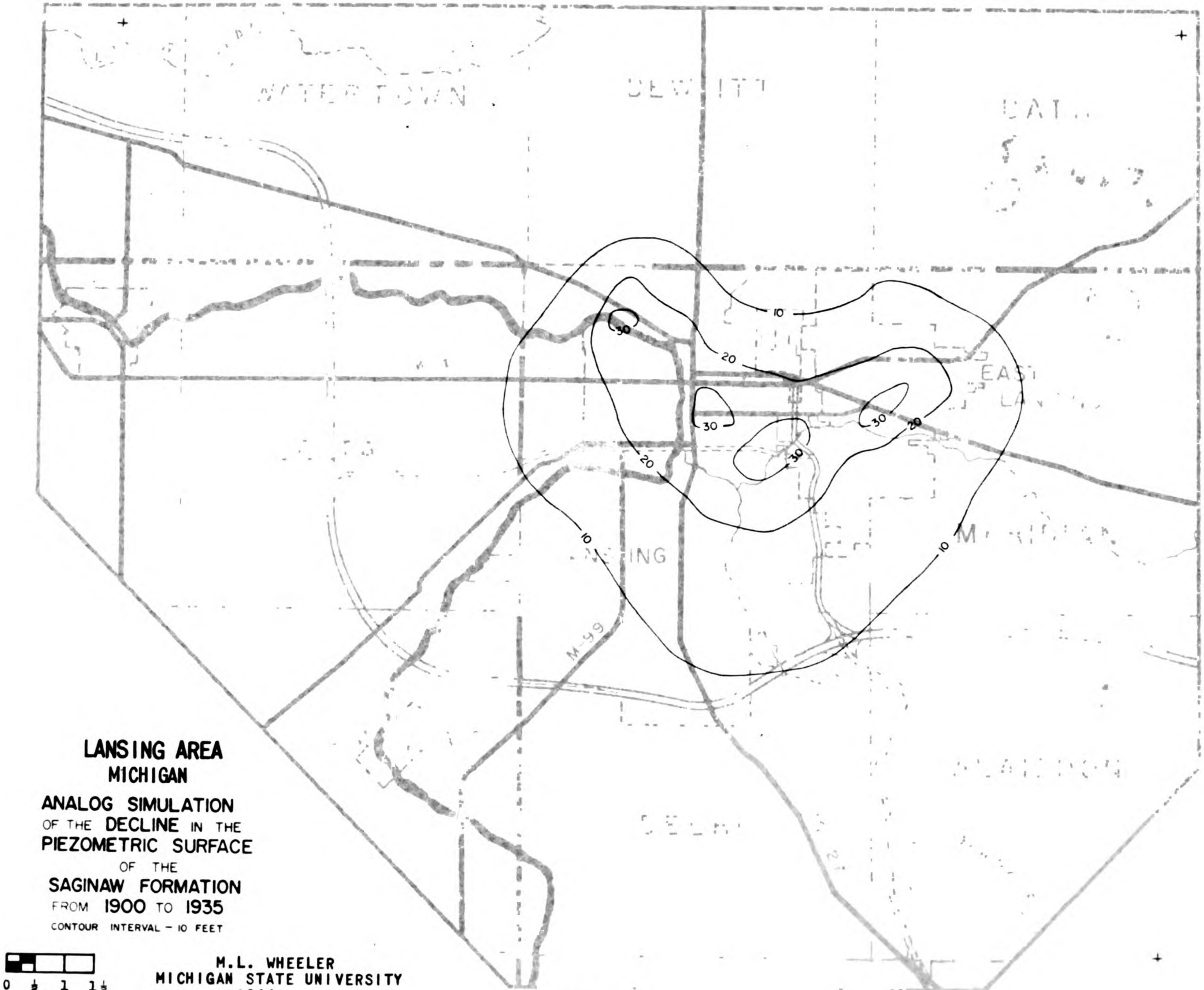

LANSING AREA
MICHIGAN
ANALOG SIMULATION
OF THE DECLINE IN THE
PIEZOMETRIC SURFACE
OF THE
SAGINAW FORMATION
FROM 1900 TO 1935
CONTOUR INTERVAL – 10 FEET
0 ½ 1 1½
MILES
M.L. WHEELER
MICHIGAN STATE UNIVERSITY
1966
EAST LANSING
LANSING
M-99
10
20
30

Figure 18

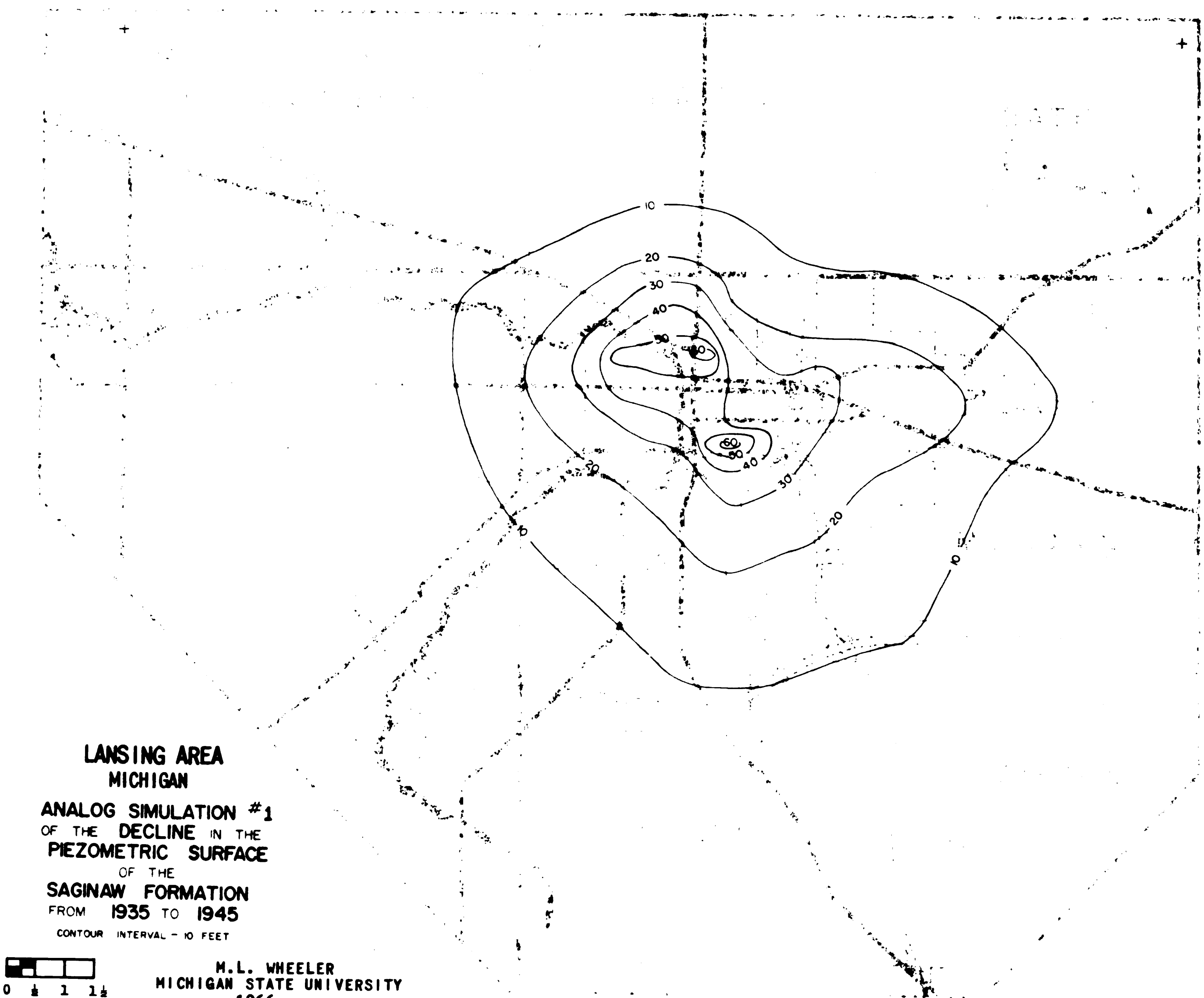

10
20
30
40
50
60
LANSING AREA
MICHIGAN
ANALOG SIMULATION #1
OF THE DECLINE IN THE
PIEZOMETRIC SURFACE
OF THE
SAGINAW FORMATION
FROM 1935 TO 1945
CONTOUR INTERVAL - 10 FEET
0 ½ 1 1½
MILES
M.L. WHEELER
MICHIGAN STATE UNIVERSITY
1966

Figure 19

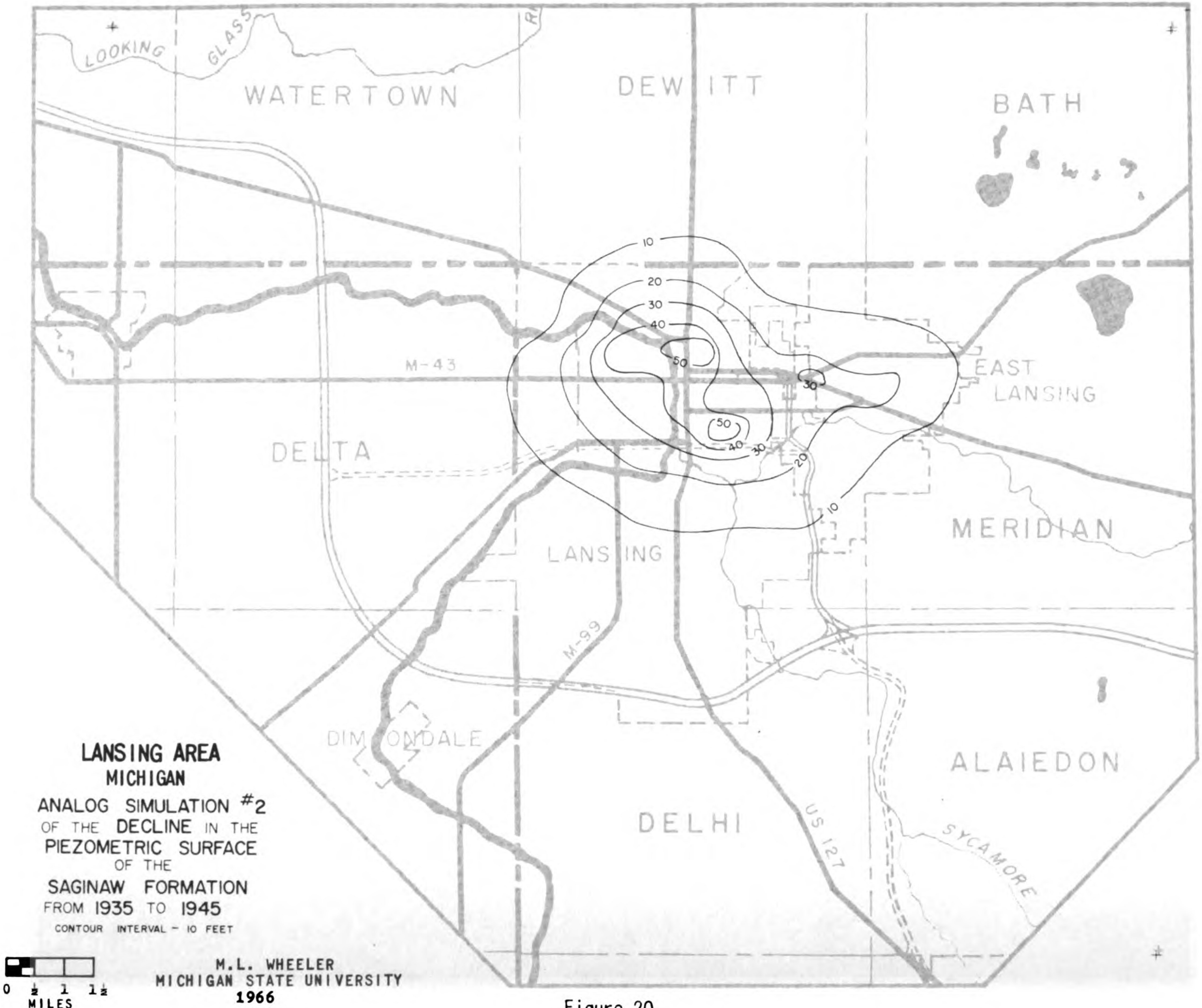

LOOKING GLASS
WATERTOWN
DEW ITT
BATH
M-43
EAST LANSING
DELTA
MERIDIAN
LANS ING
M-99
DIM ONDALE
ALAIEDON
DELHI
US 127
SYCAMORE
10
20
30
40
50
LANSING AREA
MICHIGAN
ANALOG SIMULATION #2
OF THE DECLINE IN THE
PIEZOMETRIC SURFACE
OF THE
SAGINAW FORMATION
FROM 1935 TO 1945
CONTOUR INTERVAL - 10 FEET
0 ½ 1 1½
MILES
M.L. WHEELER
MICHIGAN STATE UNIVERSITY
1966

Figure 20

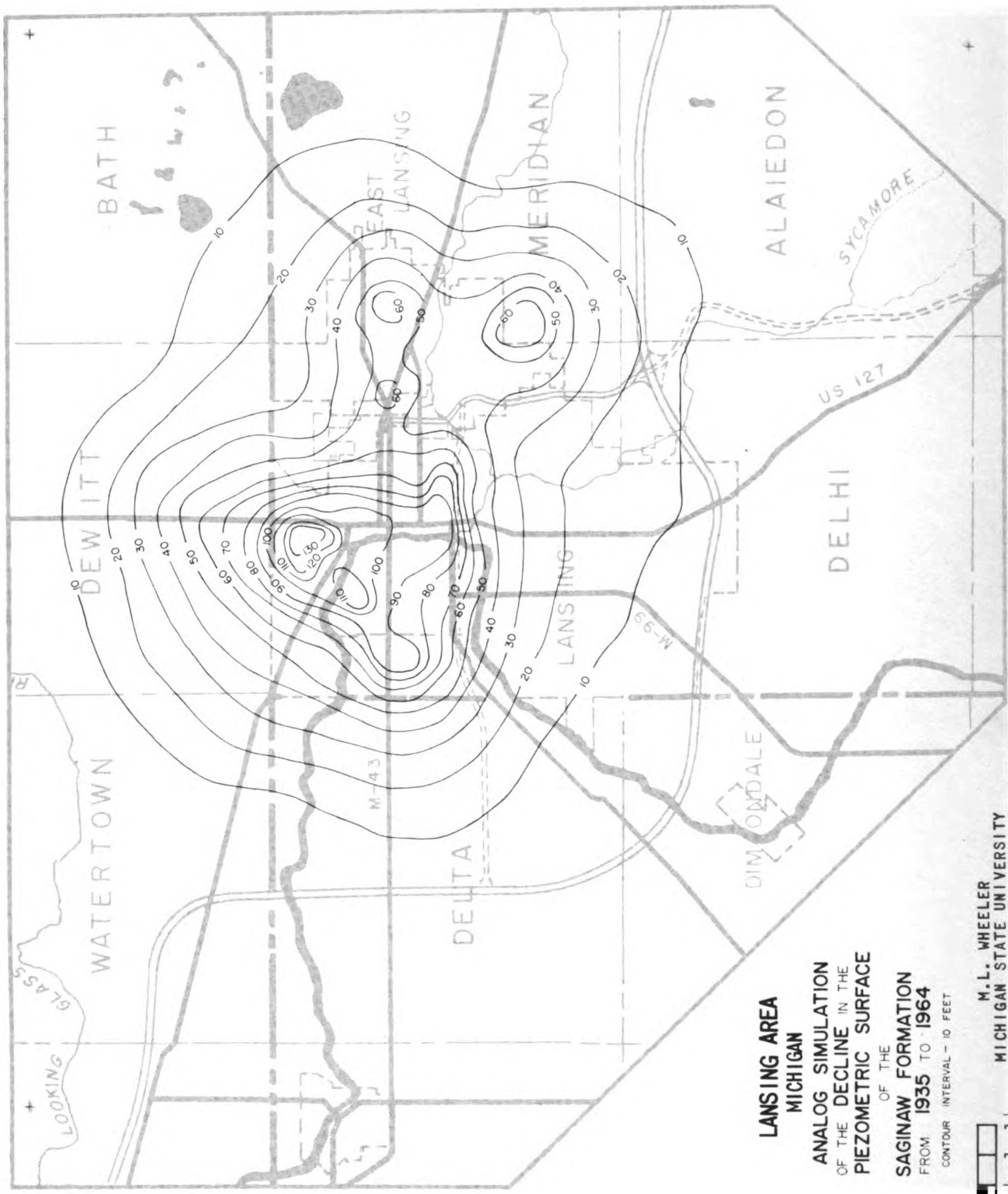
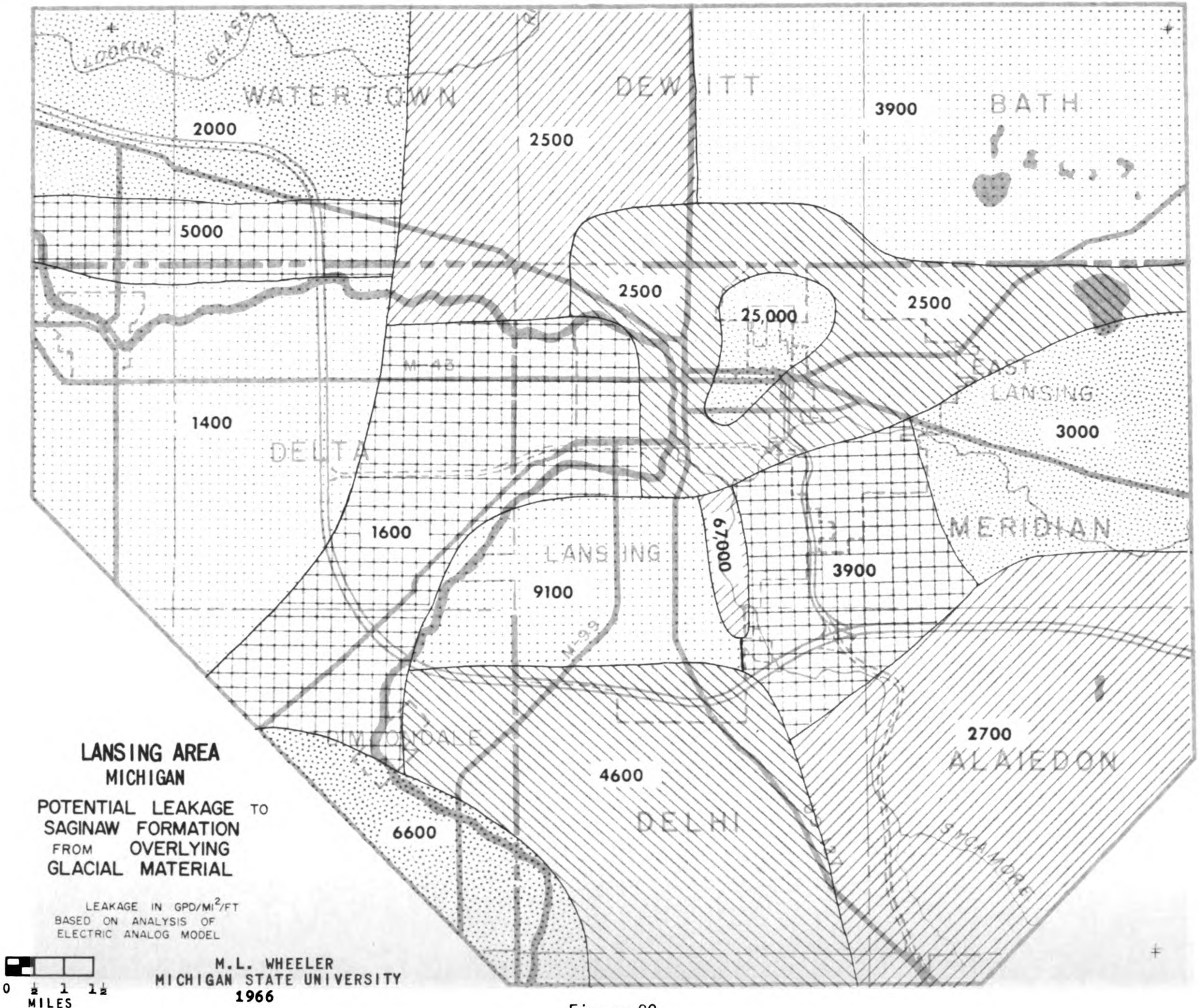

LANSING AREA
MICHIGAN
ANALOG SIMULATION
OF THE DECLINE IN THE
PIEZOMETRIC SURFACE
OF THE
SAGINAW FORMATION
FROM 1935 TO 1964
CONTOUR INTERVAL - 10 FEET
M.L. WHEELER
MICHIGAN STATE UNIVERSITY
1966
0 ½ 1 1½
MILES
BATH
EAST LANSING
MERIDIAN
ALAIEDON
DEWITT
WATERTOWN
DELTA
LANSING
DELHI
DIMONDALE
SYCAMORE
LOOKING GLASS
US 127
M-43
M-99
10
20
30
40
50
60
70
80
90
100
110
120
130

Figure 21



LOOKING GLASS
WATERTOWN
DEWITT
BATH
2000
2500
3900
5000
2500
25,000
2500
M-43
EAST LANSING
1400
DELTA
3000
1600
67,000
MERIDIAN
LANSING
3900
9100
M-99
2700
MIDDLEDALE
ALAIEDON
4600
6600
DELHI
SYCAMORE
LANSING AREA
MICHIGAN
POTENTIAL LEAKAGE TO SAGINAW FORMATION FROM OVERLYING GLACIAL MATERIAL
LEAKAGE IN GPD/MI²/FT BASED ON ANALYSIS OF ELECTRIC ANALOG MODEL
0 ½ 1 1½
MILES
M.L. WHEELER
MICHIGAN STATE UNIVERSITY
1966

Figure 22

BIBLIOGRAPHY

BIBLIOGRAPHY

Firouzian, Assadolah. 1963. Hydrological Studies of the Saginaw Formation in the Lansing, Michigan Area. Unpublished Master of Science Thesis, Michigan State University.

Mencenberg, Frederick E. 1963. Groundwater Geology of the Saginaw Group in the Lansing, Michigan Area. Unpublished Master of Science Thesis, Michigan State University.

Stallman, Robert W. 1963. Calculation of Resistance and Error in an Electric Analog of Steady Flow Through Nonhomogeneous Aquifers. Geological Survey Water Supply Paper 1544-G.

Stuart, W. T. 1945. Groundwater Resources of the Lansing Area, Michigan. Geological Survey Division, Department of the Interior.

Walton, William C. and Prickett, Thomas A. Hydrogeologic Electric Analog Computers. Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, November, 1963, pp. 67-90.

APPENDIX

UTILIZATION OF THE ELECTRIC ANALOG MODEL TO PREDICT FUTURE HYDROLOGIC CONDITIONS

The electric analog model is valuable as a research tool. The model study has greatly enhanced the knowledge of the hydrology of the Saginaw Formation, both qualitatively and quantitatively. It should be realized, however, that the hydrologic facts learned from the study can only be considered reliable within the area presently affected by ground water withdrawal. The reliable extension of these facts to other areas is contingent upon further field investigation.

The model study revealed the relative importance of the various hydrologic parameters. However, further expansion of the cone of depression may change this order of importance, as well as the effect that each factor has upon the hydrologic conditions. For example, at present the variation of the transmissibility within the aquifer does not have a significant effect upon the configuration of the piezometric surface. As a result, errors of as much as 100 percent might exist, without being detected. An increase in the importance of the transmissibility, such as could be caused by completely draining a portion of the glacial material, might produce significant errors in the model analysis.

Error is introduced into the analysis by the nature of the electrical network, and by the type of equipment used in the analysis. These errors can be avoided by proper adjustment when known conditions are being evaluated. However, extension of the analysis to unknown hydrologic conditions will introduce an indeterminable amount of error.

One factor in the hydrology of the area has been all but ignored in the analysis of the model; that of additional rainfall recharge to the glacial material. The drainage of the material will be counterbalanced by an increase in rainfall recharge, caused by the lowering of the hydraulic gradients within the material. Allowance was made for this by specifying the storage coefficient of the glacial material to be higher than it is believed to be. However, the long-term effect of the additional recharge to the glacial material cannot be evaluated.

The errors which are at present considered likely to occur in the future analysis of the model are, for the most part, conservative errors. That is, they will tend to produce more drawdown in the model then would actually occur in the aquifer. This is desirable when considering the feasibility of certain development proposals. However, the results obtained from the model analysis should <u>never</u> be used without additional field investigation of the aquifer, and subsequent rechecking of the model.

Within the limitations stated, it is then possible to use the model as a predictive agent, investigating the future hydrologic conditions. In the evaluation of the safe yield of the aquifer, it is necessary to know the position of the piezometric surface at some future time. In addition, this knowledge would enhance well field planning, and improve distribution system design.

The expected increase in the average daily withdrawal from the aquifer from 1964 to 1975 was determined for each of the present supply systems. This was done through the use of estimates made by each supply system, based on present demands and expected changes in the nature of the demand. The locations of the additional well fields required were determined, and divided into additional pumping centers. These are well fields that are currently undergoing development, or ones which will be by 1970. The locations of the pumping centers are shown in Figure 23, and the expected withdrawal rate for each is given in Table 4. It is assumed that all of the withdrawal in excess of the 1964 rate will be from the additional pumping centers, and that the present well fields will continue to produce at the 1964 rate.

The increase in pumpage was imposed on the model, and the change in the piezometric surface from 1935 to 1975 was recorded. This map was then subtracted from the map of the piezometric surface in 1935, producing a map of the predicted piezometric surface in 1975. This is shown in Figure 24.

TABLE 4.--Expected ground water withdrawal by 1975.

Pumping Center No. (From Figure 23)		Average Daily Withdrawal Expected by 1975 mgd
1	....	3.20
2		1.50
3		0.60
4		1.90
5	....	1.30
6		1.50
7		0.95
8		1.30
9		0.80
10	....	1.20
11		4.70
12		0.50
13		1.60
14		0.55
15	....	2.50
16		1.40
17		1.40
18		2.60
19		2.60
20	....	3.00
21		1.70
22		1.80
23		1.50
24		1.70
25	....	1.80
	Total	43.60 mgd

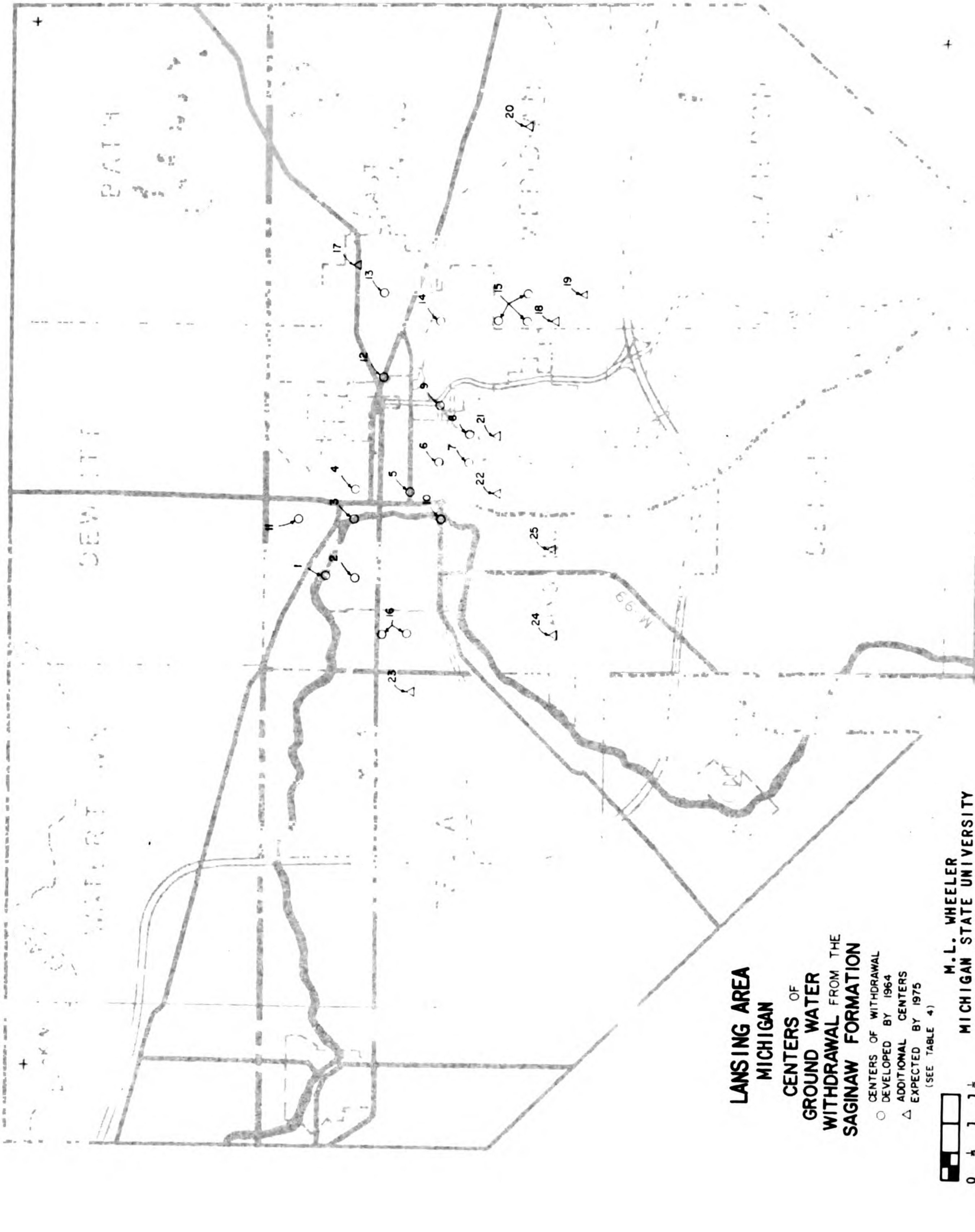
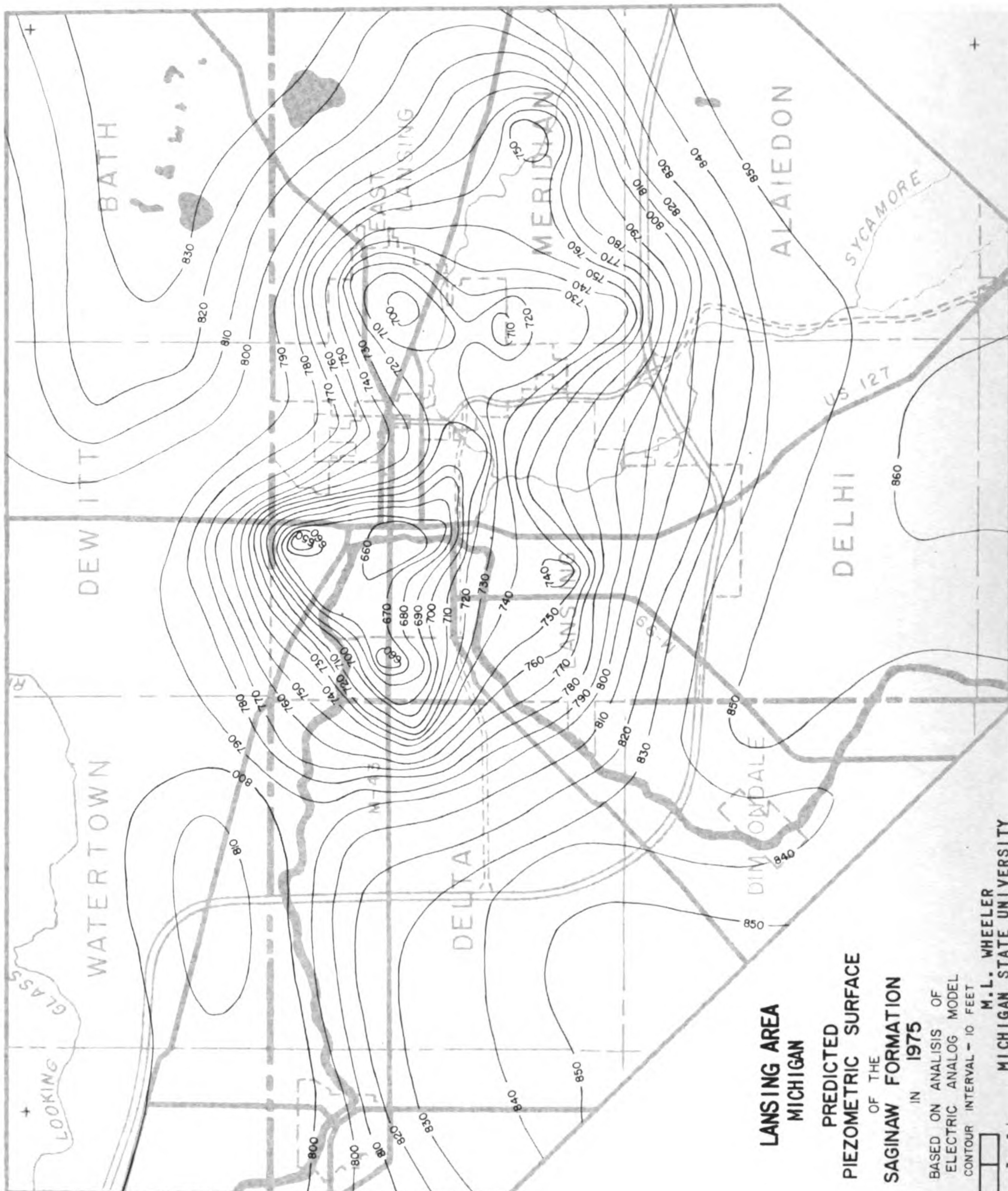

LANSING AREA
MICHIGAN
CENTERS OF
GROUND WATER
WITHDRAWAL FROM THE
SAGINAW FORMATION
○ CENTERS OF WITHDRAWAL DEVELOPED BY 1964
△ ADDITIONAL CENTERS EXPECTED BY 1975
(SEE TABLE 4)
0 ½ 1 1½
MILES
M.L. WHEELER
MICHIGAN STATE UNIVERSITY
1966

Figure 23



LANSING AREA
MICHIGAN

PREDICTED
PIEZOMETRIC SURFACE
OF THE
SAGINAW FORMATION
IN 1975

BASED ON ANALISIS OF
ELECTRIC ANALOG MODEL
CONTOUR INTERVAL - 10 FEET

0 ½ 1 1½
MILES

M.L. WHEELER
MICHIGAN STATE UNIVERSITY
1966

Figure 24