In cooperation with the
Tri-County Regional Planning Commission

Simulation of Ground-Water Flow in the Vevay Township Area, Ingham County, Michigan

By Carol L. Luukkonen and Andreanne Simard

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Conversion Factors, Vertical Datum, and Definitions

Inch/Pound to SI

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
cubic foot (ft^3)	0.02832	cubic meter (m^3)
Flow rate		
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
foot per second (ft/s)	0.3048	meter per second (m/s)
inch per hour (in/h)	0 .0254	meter per hour (m/h)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day (m/d)
Transmissivity*		
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C = (°F-32)/1.8

Vertical coordinate information is referenced to the "North Geodetic Vertical Datum of 1929 (NGVD 29)."

Horizontal coordinate information is referenced to the Michigan State Plane Coordinate System, south zone, North American Datum of 1927 (MSP 27).

Altitude, as used in this report, refers to distance above the vertical datum.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

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ABSTRACT

Ground water is the primary source of water for domestic, public-supply, and industrial use within the Tri-County region that includes Clinton, Eaton, and Ingham Counties in Michigan. Because of the importance of this ground-water resource, numerous communities, including the city of Mason in Ingham County, have begun local Wellhead Protection Programs. In these programs, communities protect their ground-water resource by identifying the areas that contribute water to production wells and potential sources of contamination, and by developing methods to manage and minimize threats to the water supply. In addition, some communities in Michigan are concerned about water availability, particularly in areas experiencing water-level declines in the vicinity of quarry dewatering operations. In areas where Wellhead Protection Programs are implemented and there are potential threats to the water supply, residents and communities need adequate information to protect the water supply.

In 1996, a regional ground-water-flow model was developed by the U.S. Geological Survey to simulate ground-water flow in Clinton, Eaton, and Ingham Counties. This model was developed primarily to simulate the bedrock ground-water-flow system; ground-water flow in the unconsolidated glacial sediments was simulated to support analysis of flow in the underlying bedrock Saginaw aquifer. Since its development in 1996, regional model simulations have been conducted to address protection concerns and water availability questions of local water-resources managers. As a result of these continuing model simulations, additional hydrogeologic data have been acquired in the Tri-County region that has improved the characterization of the simulated ground-water-flow system and improved the model calibration. A major benefit of these updates and refinements is that the regional Tri-County model continues to be a useful tool that improves the understanding of the ground-water-flow system in the Tri-County region, provides local water-resources managers with a means to answer ground-water protection and availability questions, and serves as an example that can be applied in other areas of the state.

A refined version of the 1996 Tri-County regional ground-water-flow model, developed in 1997, was modified with local hydrogeologic information in the Vevay Township area in Michigan. This model, updated in 2003 for this study, was used to simulate ground-water flow to address ground-water protection and availability questions in Vevay Township. The 2003 model included refinement of glacial and bedrock hydraulic characteristics, better representation of the degree of connection between the glacial deposits and the underlying Saginaw aquifer, and refinement of the model cell size.

The 2003 model was used to simulate regional ground-water flow, to delineate areas contributing recharge and zones of contribution to production wells in the city of Mason, and to simulate the effects of present and possible future withdrawals. The areal extent of the 10- and 40-year areas contributing recharge and the zones of contribution for the city of Mason's production wells encompass about 2.3 and 6.2 square miles, respectively. Simulation results, where withdrawals for quarry operations were represented by one well pumping at 1.6 million gallons per day, indicate that water levels would decline slightly over 1 foot approximately 2 miles from the quarry in the glacial deposits and in the Saginaw aquifer. With a reduction of the local riverbed conductance or removal of local river model cells representing Mud Creek, water-level declines would extend further west of Mud Creek and further to the north, east, and south of the simulated quarry. Simulation results indicate that water withdrawn for quarry dewatering operations would decrease ground-water recharge to nearby Mud Creek, would increase ground-water discharge from Mud Creek, and that local water levels would be lowered as a result.

INTRODUCTION

Ground water is the primary source of water for domestic, public-supply, and industrial use within the Tri-County region that includes Clinton, Eaton, and Ingham Counties, Michigan. Numerous communities in the region, including the city of Mason in Ingham County, have begun local Wellhead Protection Programs (Michigan Department of Environmental Quality, 2004) because of the importance of the ground-water resource. Understanding regional ground-water flow is important because communities need to protect the ground-water resource by identifying the areas that contribute water to production wells and potential sources of contamination, and by developing methods to manage and minimize threats to the water supply.

Ground-water-flow models provide a means to answer questions about a ground-water system of interest, such as the extent and location of areas contributing recharge to pumping wells or the potential effects of withdrawals on water levels. Thus, ground-water-flow models can be used to address questions about protection and availability of ground-water resources. Flow models can be developed to answer questions concerning regional flow conditions or questions concerning local flow conditions. When a regional model is available, some questions about local flow conditions can be answered; however, regional models commonly are not detailed enough in the area of interest to adequately describe local flow conditions. With collection and incorporation of additional information in the area of interest and refinement of the model grid spacing, a regional model can be used to answer questions about local flow conditions.

In 1996, the U.S. Geological Survey (USGS), in cooperation with the Tri-County region Groundwater Management Board, completed an analysis of ground-water resources of the Tri-County region, which includes Clinton, Eaton, and Ingham Counties (fig. 1) (Holtschlag and others, 1996). As part of this study, a computer model was developed to describe ground-water flow and the effects of pumping on ground-water levels and directions of ground-water flow in the Saginaw aquifer. The 1996 model simulates regional flow in the Saginaw aquifer, including the response to major ground-water withdrawals associated with production wells. In 1997, this model was refined to better represent flow within the nine-township area surrounding Lansing (Luukkonen and others, 1997).

As part of their Wellhead Protection Plan (WHPP), the city of Mason, which is in Vevay and Alaiedon Townships, needs to determine the areas contributing water to their production wells. The Saginaw aquifer, which is in the Grand River and Saginaw Formations of Pennsylvanian age (fig. 2), is the primary source of ground water for the city of Mason residents. The bottom of the Saginaw aquifer and Saginaw confining unit was determined to be the surface of the Parma-Bayport aquifer (Westjohn and Weaver, 1996). The 1996 and 1997 regional Tri-County ground-water-flow models for the counties of Clinton, Eaton, and Ingham have been used by local water-resources managers to answer ground-water-flow questions. However, the grid spacing of the 1996 and 1997 models is too coarse to adequately represent the local flow conditions for the city of Mason and Vevay Township area. Because individual hydrologic features within the Vevay Township area, such as sand-and-gravel units or eskers, are not represented in these regional models, the model-simulation results may not accurately reflect the actual areas contributing water to production wells or the potential effects of ground-water withdrawals because of quarry operations on water levels.

The USGS, in cooperation with the Tri-County Regional Planning Commission, began a study in 2003 to refine the 1997 regional model with additional hydrologic details in the Vevay Township area. Vevay Township encompasses both the city of Mason and a quarry and, in this report, will be used to describe both parts of the study area. Refinement of the hydraulic characteristics of the glacial deposits, as well as the refinement of the model cell size, would assist in the determination of potential effects of quarry dewatering and in understanding ground-water flow in glacial deposits. The purpose of this study was to address the concerns of water-resources managers about protection and availability of their ground-water resources, to update an existing regional model so that it continues to be a useful tool to simulate the regional ground-water-flow system, and to provide an example of how to address water-resources issues at regional and local scales that can be applied in other areas of the state.

Purpose and Scope

The purpose of this report is to describe the results of this study, which involved simulation of ground-water flow, the delineation of contributing areas to production wells, and the potential effects of quarry dewatering in the Vevay Township area. The hydrogeologic setting and modifications to an available regional ground-water-flow model used for simulation are described. The methods presented here can be applied in other areas of the state.

A conceptual model of the ground-water-flow system was developed on the basis of available data and hydrologic data collected during this study. The numerical model representing the steady-state response to pumping from the Saginaw aquifer was modified based on the conceptual model. The 1997 Tri-County regional ground-water-flow model was refined and updated to better represent ground-water flow in the Vevay Township area. The updated 2003 model is used to delineate contributing areas for the city of Mason's production wells and to determine potential effects of quarry dewatering operations on water levels and flow. Model simulations included particle-tracking analyses to define the areal extent of the steady-state areas contributing recharge and zones of contribution to production wells for 10-year and 40-year time-of-travel intervals. Quarry withdrawals also were simulated in the model to determine the potential effects of dewatering operations under various pumping scenarios.

Previous Studies

An early study describing contributing areas to city of Mason's production wells was conducted by Ingham County Health Department, Division of Environmental Health (1992). C.J. Linck and Associates (1990) provided information on the geology and hydrology of the city of Mason area and Strata Environmental Services (2001) provided information on the geology, hydrology, and water levels in the southeastern part

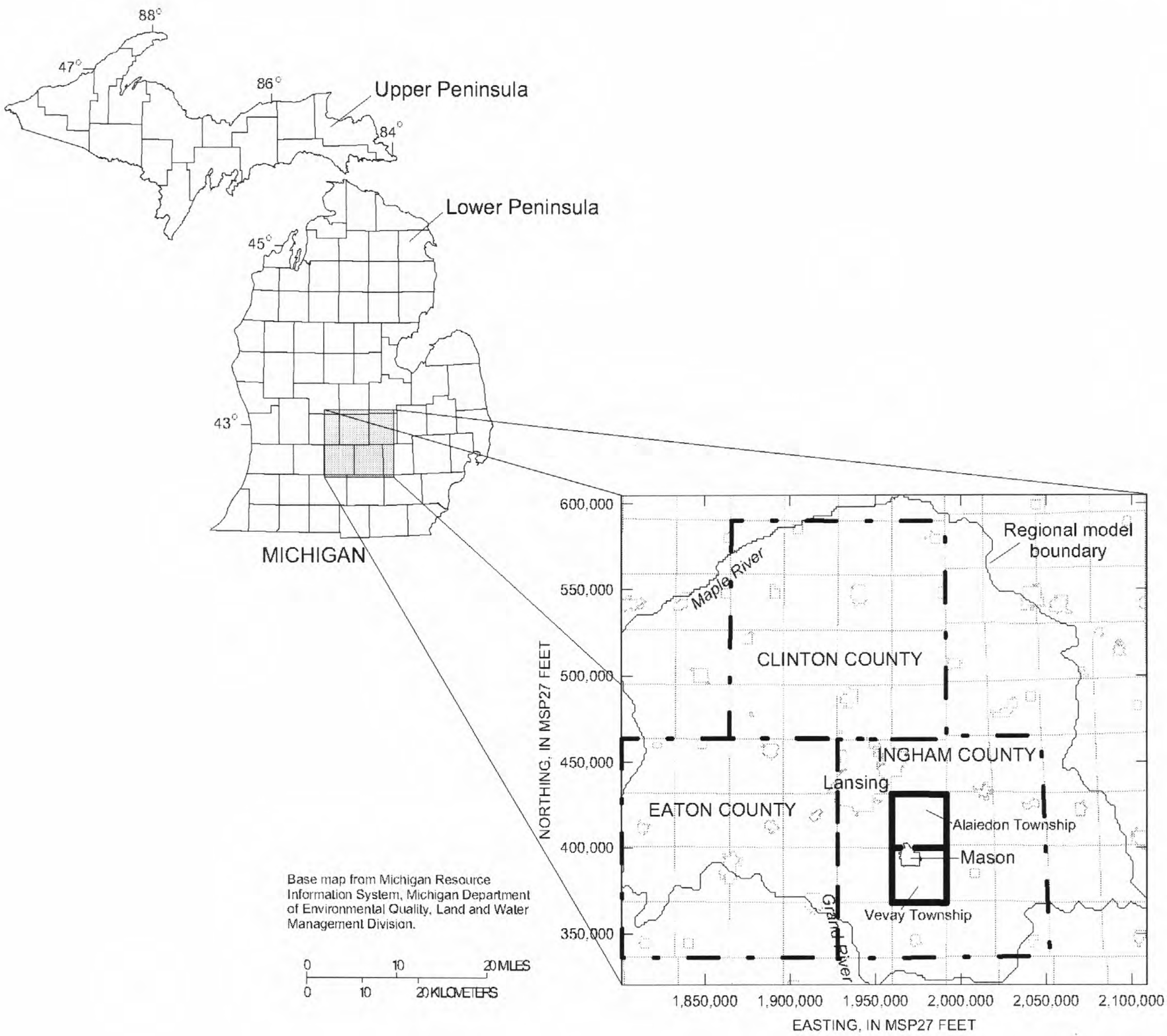


Figure 1. Location of the city of Mason, Vevay Township, and the Tri-County regional model area in the Lower Peninsula of Michigan.

Period	Stratigraphic Nomenclature	Hydrogeologic Unit (generalized thickness range)
Quaternary	Glacial deposits	Aquifers in the glacial deposits (0-300 feet)
Pennsylvanian	Grand River Formation	Saginaw aquifer (150-400 feet)
	Saginaw Formation	Saginaw confining unit (5-100 feet)
	Parma Sandstone	Parma-Bayport aquifer (50-100 feet)
Mississippian	Bayport Limestone	
	Michigan Formation	Michigan confining unit (50-350 feet)
	Marshall Sandstone	Marshall aquifer (100-150 feet)

Figure 2. Stratigraphic nomenclature and hydrogeologic units, Tri-County region, Michigan. [Note: Figure denotes relation between units present in the Tri-County region and not the complete depositional history from the Mississippian through Quaternary periods. The Parma Sandstone is considered by some researchers to form the basal part of the Pennsylvanian Saginaw Formation. Other researchers have assigned the lower part of the Parma Sandstone to the late Mississippian. Dashed line indicates the uncertainty in the placement of the Parma Sandstone into the Pennsylvanian or the Mississippian periods. The Parma Sandstone is hydraulically connected to the Bayport Limestone and these units together form the Parma-Bayport aquifer.]

of Vevay Township near the quarry. Various reports provide information on aquifer tests, hydrogeological features, and other hydrologic characteristics of the city of Mason area (C.J. Linck and Associates, 1999 and 2002; and Layne-Northern Company, 1986a, 1986b, and 1988). The study by Holtschlag and others (1996) describes the regional ground-water-flow model developed for the Tri-County region.

Description of the Study Area

The study area primarily is in Vevay Township, which includes most of the city of Mason and the quarry operation. Part of the city of Mason is in Alaiedon Township. Vevay and Alaiedon Townships are in Ingham County, Michigan and are in the central part of the Lower Peninsula (fig. 1). In this area, precipitation averages 31 in/yr and is fairly evenly distributed throughout the year. August is the month of highest average precipitation (3.4 in.) and February is the month of lowest average precipitation (1.4 in.) (Midwestern Regional Climate Center, 2004a). The Tri-County region averages about 39 in/yr of snowfall (Michigan State Climatologist's Office, 2004). Mean daily average temperatures range from a low of 21.7° F in January to a high of 71° F in July (Midwestern Regional Climate Center, 2004c).

Land-surface altitudes range from a low of approximately 870 ft above NGVD 29 in the northern part of the township to a high of approximately 1,015 ft in the southern part of the township. Agriculture is the primary land use in the Vevay Township area. Sycamore, Willow, and Mud Creeks are the major surface-water features in the Vevay Township area (fig. 3). Willow Creek and Mud Creek are tributaries to Sycamore Creek, which drains into the Red Cedar River in the northwestern part of Ingham County.

Hydrogeologic Setting

Pennsylvanian rocks are the uppermost bedrock unit in the Tri-County area. The discontinuous lenses of sandstone, shale, coal, and limestone in the Pennsylvanian bedrock unit have been formally divided into two formations. The uppermost massive, coarse-grained sandstones form the Grand River Formation; all remaining Pennsylvanian bedrock units are considered part of the underlying Saginaw Formation. These assignments are somewhat uncertain, however, because no lithologic differences or stratigraphic horizons mark a change from one formation to the next (Westjohn and Weaver, 1996). Therefore, for this study, the Grand River and Saginaw Formations are referred to as the Saginaw Formation. Interpretation of geophysical logs for the central Lower Peninsula of Michigan indicates that the lower part of the Pennsylvanian rock sequence is predominantly shale, whereas the upper part is predominantly sandstone. Thus, for the purposes of the Michigan Basin RASA's computer simulation of ground-water flow and for this study, the Saginaw Formation is subdivided into an upper sandstone unit and a lower confining unit (Westjohn and Weaver, 1996). The bottom of the Saginaw Formation is formed by the top of the Parma Sandstone and the Bayport Limestone, which are stratigraphically continuous and hydraulically connected (Westjohn and Weaver, 1996).

Within Vevay Township, the altitude of the surface of the Saginaw Formation ranges from 778 ft in the northeast primarily along Mud Creek to 980 ft in the southwestern part of the township on the basis of analysis of domestic and production-well logs. The thickness of the Saginaw Formation ranges from 7 to 266 ft. The sandstone is thickest along the northern and southern edges of the city of Mason and in south-central Vevay Township. The sandstone is thinnest in east-central and southeast Vevay Township.

The glacial deposits consist of all deposits between the top of the Saginaw Formation and the land surface. The thickness of the glacial deposits in the Tri-County region ranges from 0 to 300 ft. The thickest glacial deposits are in the northwestern part of the Tri-County region. The deposits range in texture from lacustrine clay or till to coarse alluvial and outwash deposits. None of these deposits are regionally continuous (Mandle and Westjohn, 1988).

Aquifers in the glacial deposits are important ground-water sources in some areas of the township. In the Vevay Township area, the glacial deposits range in thickness from 6 to 140 ft and vary in texture from till to gravel. These deposits are thickest in the central part of the city of Mason and along the western part of Vevay Township. These deposits are thinnest to the north and south of the city of Mason and in the central and southwestern parts of the township. Numerous eskers, which are important in the hydrogeological characterization of the glacial deposits, are located in Vevay Township. Eskers consist of permeable sand and gravel and, thus, affect the hydraulic conductivity of the glacial aquifer and may affect ground-water flow directions. An esker is a long, narrow riverbed deposit that was formed inside or on top of a melting glacier. The eskers range in length from less than a mile to tens of miles, and in height from a few feet up to several hundred feet. Eskers frequently are excavated for construction purposes. Eskers are oriented in the direction of glacial flow. The Mason Esker is an 18-mi long narrow ridge of coarse gravel that extends from the city of Mason to North Lansing (Schaetzl, 2003).

The Saginaw aquifer underlies the glacial deposits. The source of ground water for the city of Mason's production wells and for most residential wells is the Saginaw aquifer. The aquifer includes the water-bearing sandstones in the Saginaw Formation (fig. 2). The bottom of the Saginaw aquifer is formed by the top of the Parma-Bayport aquifer.

Acknowledgments

The authors gratefully acknowledge the assistance during the course of this study of Joseph Dean, city of Mason Public Works Director; Kenneth Baker, city of Mason Public Works Supervisor; and Ronald Weesies, Vevay Township Supervisor. Christine Spitzley, of the Tri-County Regional Planning Commission, and Brant Fisher, of the Drinking Water and Radiological Protection Division, Michigan Department of

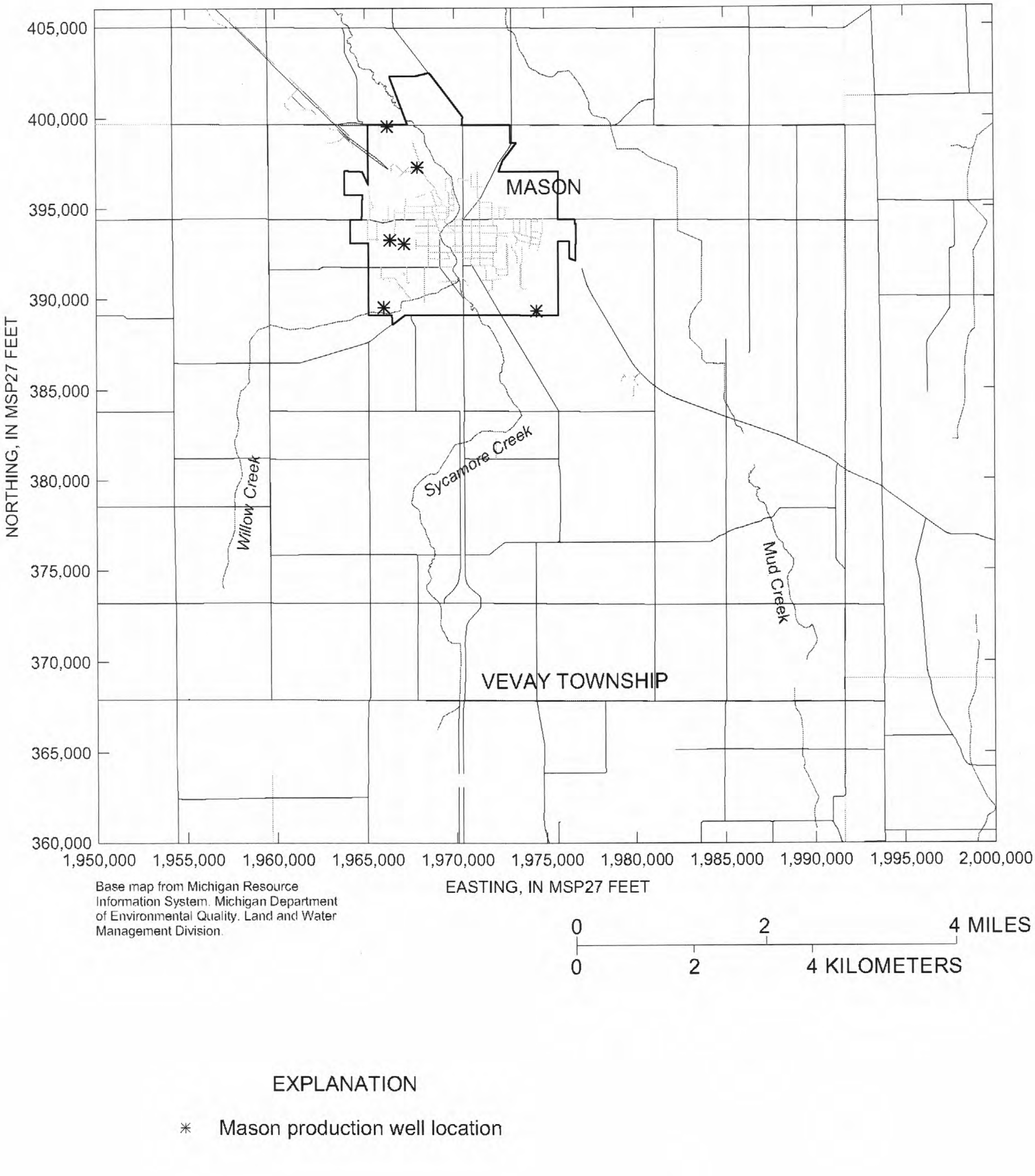


Figure 3. Location of surface-water features and Mason production wells, Vevay Township, Michigan.

Table 1. Ground-water-level observations collected from synoptic survey and weekly measurement locations, Vevay Township, Michigan. Locations of wells are shown on figure 3. [altitudes are shown in feet above NGVD 29]

Well number	Land-surface altitude	Water-level altitude	Measuring date
1	920.64	894.92	May 2003
2	917.27	898.56	May 2003
3	912.75	873.27	May 2003
4	909.	878.95	May 2003
5	893.61	878.71	May 2003
6	910.98	879.76	May 2003
7	893.46	878.37	May 2003
8	893.67	878.49	May 2003
9	909.97	901.90	May 2003
10	923.85	900.56	May 2003
11	912.92	873.37	May 2003
12	902.35	884.27	May 2003
13	906.91	884.45	May 2003
14	945.9	940.61	May 2003
15	950.	924.11	May 2003
16	920.	918.93	May 2003
17	898.48	881.66	May 2003
18	908.82	887.03	Sept. 2003
19	908.37	872.16	June 2003

Environmental Quality, are thanked for providing information about the requirements for Wellhead Protection Programs and delineation of contributing areas. Dr. Grahame Larson, Michigan State University, provided information about the location of eskers in Ingham County. The authors would like to thank Garry Rowe, Ingham County Health Department, for locating, obtaining permission, measuring, and surveying wells used for water-level measurements, and the homeowners and businesses that permitted access to their wells for water-level measurements. Finally, the authors would like to thank the Ingham Conservation District for allowing weekly access to their wells for water-level measurements.

Simulation of Ground-Water Flow

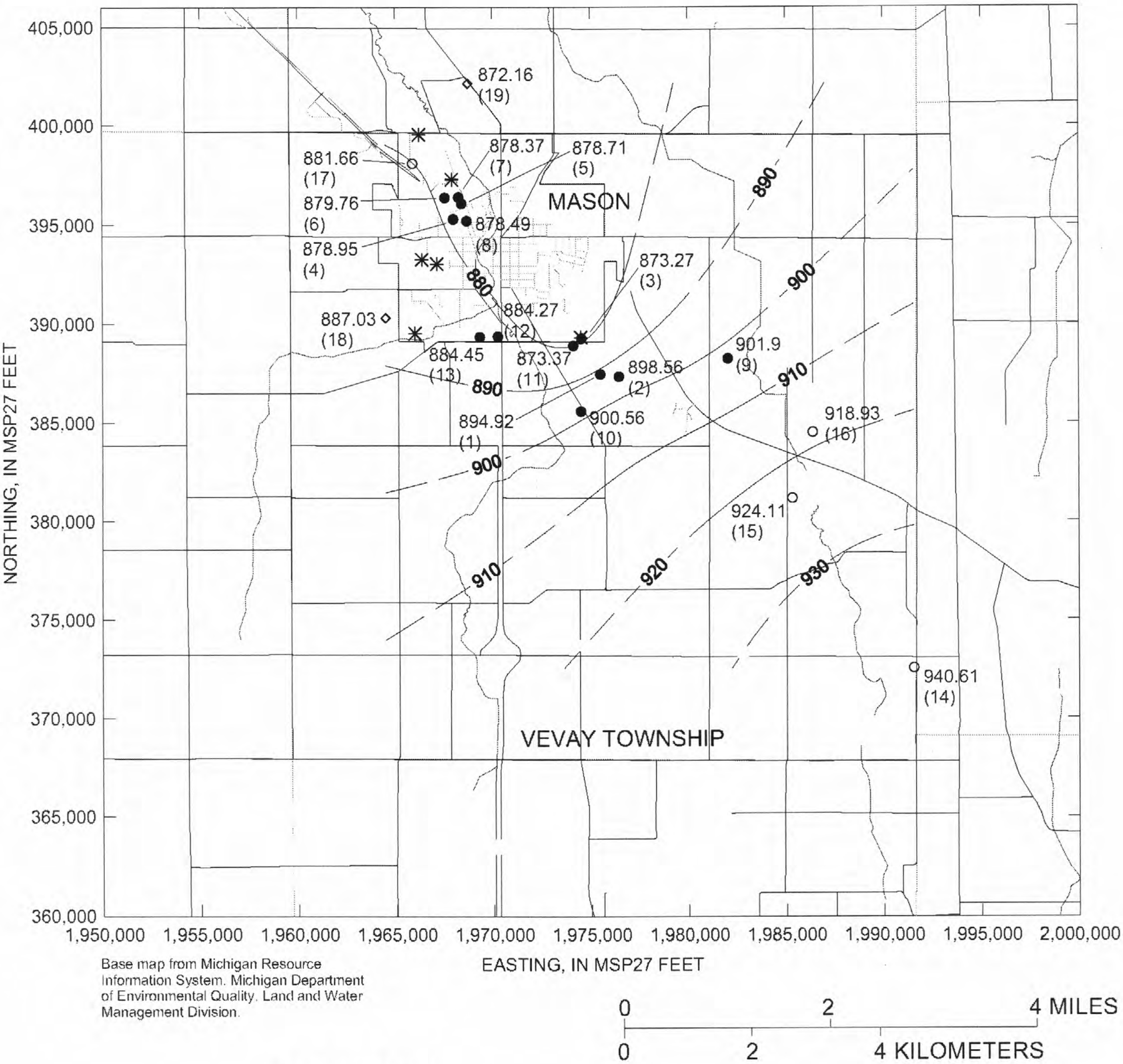
Simulation of ground-water flow is made possible first by developing a conceptual model of the flow system and then developing a numerical model that is consistent with the conceptual model. The conceptual model for this study describes flow within Vevay Township based on an analysis of available field data. Water levels were measured in 19 wells within the Saginaw aquifer in Vevay Township during this study (table 1). Most ground-water flow in the Saginaw aquifer is from southeast to northwest from areas of high to low hydraulic head, although some flow is towards the production wells in the city of Mason (fig. 4).

The conceptual model needs to represent the important hydrogeological conditions in the flow system as closely and as simply as possible. The numerical model incorporates information from the conceptual model and simulates ground-water flow indirectly by means of a governing equation that represents the physical processes that occur in the ground-water-flow system, along with equations that describe water levels and/or flows along the model boundaries (Anderson and Woessner, 1992).

Conceptual and Numerical Model

Conceptual Model

The conceptual model (fig. 5) describes ground-water flow in the Vevay Township area. The following information summarizes the model conceptualization information provided in Holtschlag and others (1996). This model includes



Base map from Michigan Resource Information System, Michigan Department of Environmental Quality, Land and Water Management Division.

EXPLANATION

—880— WATER-LEVEL CONTOUR -- Shows altitude of ground-water levels. Dashed where approximate. Contour interval is 10 feet. Datum is NGVD 29.

● 894.92 (1) Synoptic ground-water-level measurement location, well number, and water-level altitude, in feet above NGVD 29 (measurement collected May 12, 2003)

○ 940.61 (14) Weekly ground-water-level measurement location, well number, and water-level altitude, in feet above NGVD 29 (measurement collected May 15, 2003)

◇ 887.03 (18) Additional ground-water-level measurement location, well number, and water-level altitude, in feet above NGVD 29

✳ Mason production well location

Figure 4. Potentiometric surface in the Saginaw aquifer in Vevay Township, Michigan, May 2003.

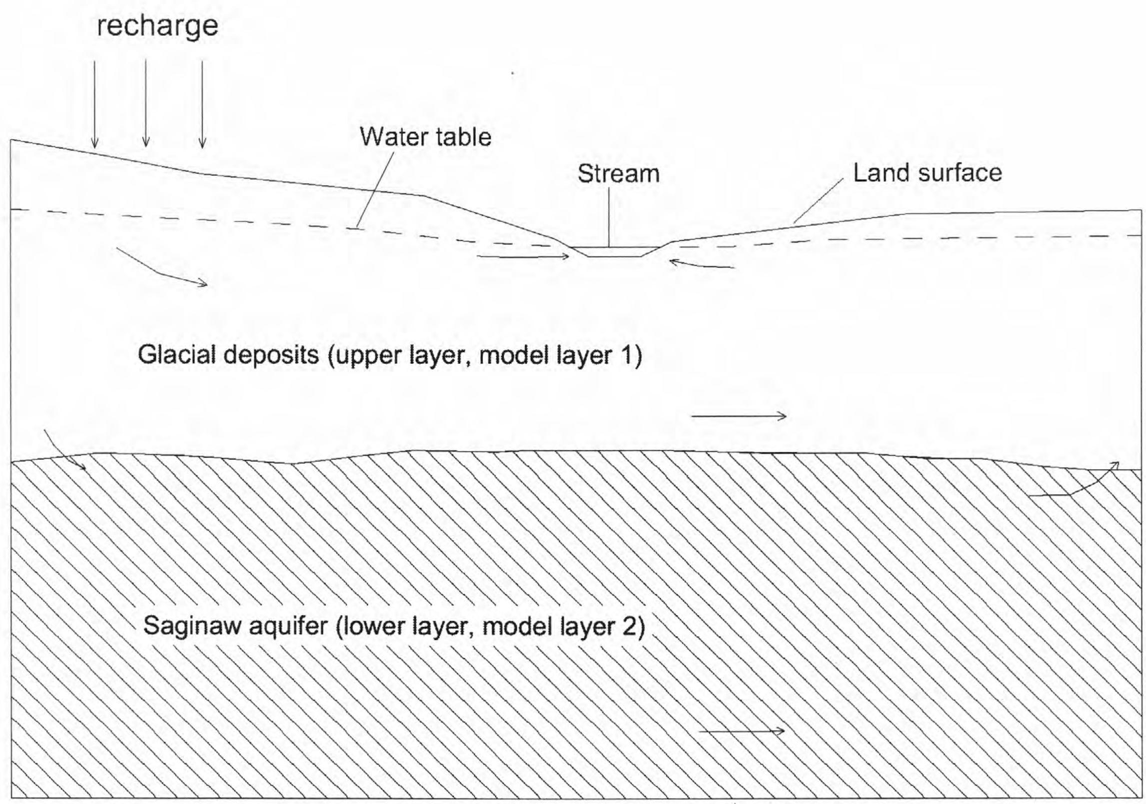


Figure 5. Generalized section showing the conceptual model of the ground-water-flow system underlying Vevay Towship, Michigan.

aquifers and confining units, and ground-water-flow boundaries. Geologic units within Vevay township area can be divided into layers that control ground-water flow. Two layers (upper and lower) were used to conceptualize the ground-water-flow system (fig. 5). The upper layer consists of the aquifers in the glacial deposits and the lower layer represents the Saginaw aquifer. The ground-water-flow system model boundaries are the same as those used in the 1996 and 1997 models. The northern regional boundary is formed by the Maple River and the southern regional boundary is formed by the Grand River (fig. 1). Boundaries to the east and west are formed by areas where the sandstones of the Saginaw aquifer are thin, and flow into or out of the regional area is minimal.

Numerical Model

Steady-state ground-water flow is assumed. This assumption means that there is no net gain or loss of water stored in the ground-water-flow system. The recharge from precipitation and inflow from outside the model area equals the discharge to streams and wells and flow out of the model area across model boundaries. Steady-state ground-water flow was simulated using the U.S. Geological Survey Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, MODFLOW-96, (McDonald and Harbaugh, 1988, and Harbaugh and McDonald, 1996). The areas contributing water to the production wells were delineated using the particle-tracking post-processor package MODPATH (Pollock, 1989).

1996 Tri-County Regional Model

Holtschlag and others (1996) developed a three-dimensional steady-state ground-water-flow model to describe the regional response of the Saginaw aquifer to ground-water withdrawals within the Tri-County region (fig. 1). The ground-water-flow system is simulated in the 1996 model by dividing the region into a grid containing 67,120 active cells. Each uniformly spaced cell of the model grid represents a land-surface block 1,320 ft on a side. The model has two layers: the upper layer (layer 1) represents flow within the glacial deposits and the lower layer (layer 2) represents flow in the Saginaw aquifer (fig. 5). For model simulations, the top of the upper layer is the altitude of the water table, which defines the top of the unconfined glacial aquifer. The bottom of the lower layer is formed by the bottom of the Pennsylvanian bedrock unit. External boundary conditions for the upper and lower layers are constant head and no flow. For the upper layer, no-flow boundaries are at drainage divides and ground-water divides; constant-head cells are along the Grand River on the south and Maple and Grand Rivers on the north (fig. 1). No-flow boundaries form the external boundary for the lower layer except where constant-head cells are along the Grand River on the south. Water enters the glacial deposits as recharge from precipitation and moves to streams or to the Saginaw aquifer in response to water-level gradients. Ground water exits the model at streams or wells or through model boundaries. The 1996 model was designed primarily to simulate ground-water flow within the Saginaw aquifer. Details on model development, parameters, and calibration are described by Holtschlag and others (1996).

1997 Tri-County Regional Model

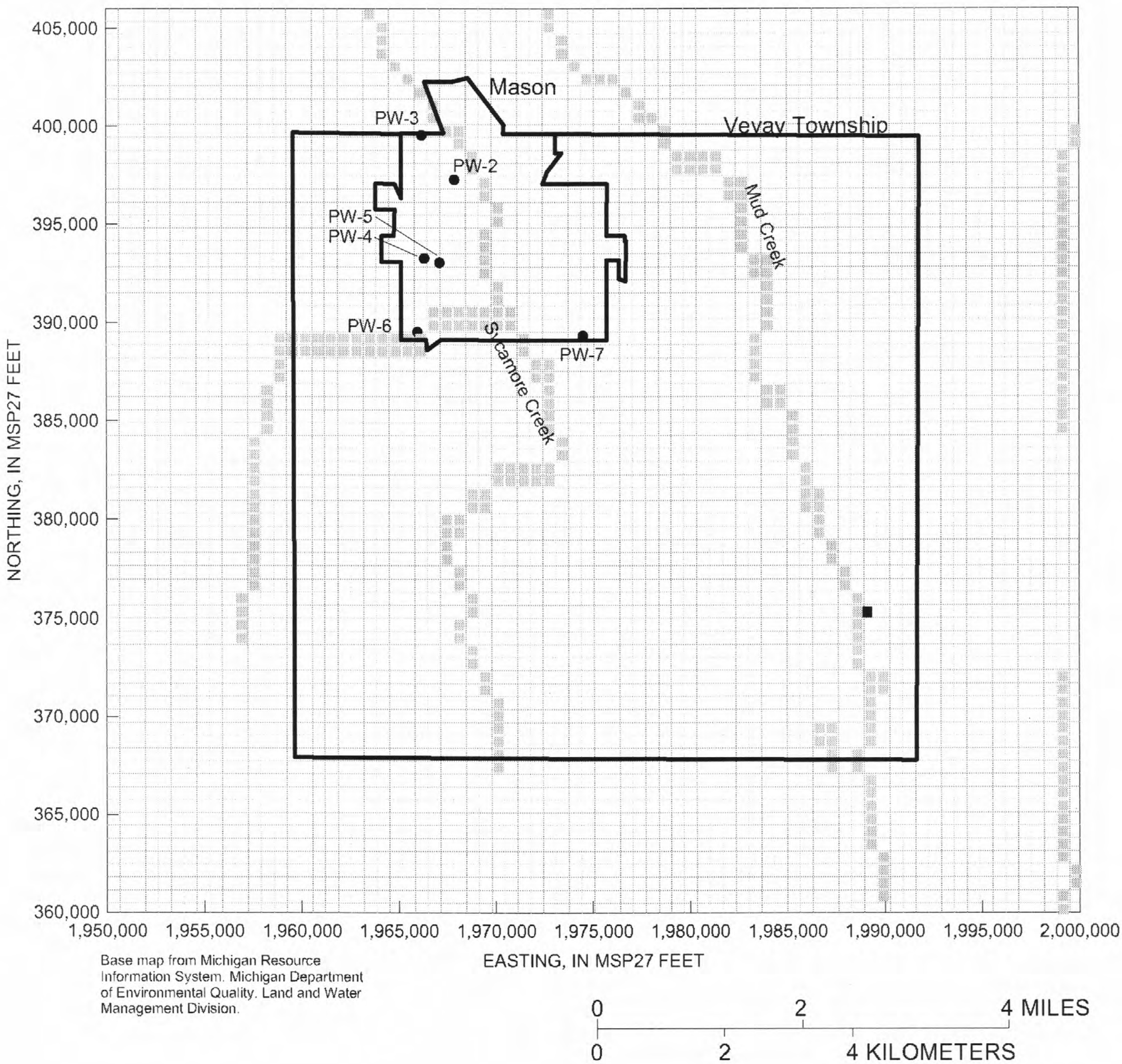
In 1997, the 1996 regional model was refined to better represent flow within the nine-township area surrounding Lansing (Luukkonen and others, 1997) (fig. 1). The uniform cell size in the 1996 model was modified to a variably spaced grid to provide more local detail in ground-water-flow system simulation in the nine-township area. Thus, the 1997 model has a variably spaced grid with cells that are 660- by 660-ft in the center of the model and cells that are 1,320- by 1,320-ft near the model boundaries. Riverbed conductances were changed to reflect the revised cell sizes and simulated pumping rates were updated to reflect 1997 pumping conditions. All other model characteristics and parameters remained the same as in the 1996 model.

2003 Tri-County Regional Model

After review of well drillers' logs and historical information available for the Vevay Township area, some refinements to the 1997 Tri-County regional model were determined necessary to represent local flow within the township. These refinements included reduction of the grid spacing within the township, modification of the hydraulic properties of the glacial deposits and the Saginaw aquifer, and modification of the leakance representing the connection between the Saginaw aquifer and the glacial deposits. The bedrock surface also needed to be refined to better reflect actual altitudes within the Vevay Township area.

Within Vevay Township, which is outside of the nine-township area near the center of the model and outside of the area with the reduced grid spacing, the variably spaced grid cells in the 1997 model were 1,320 by 660 ft. Grid spacing was reduced along rows so that cells were 660 ft on a side within the township for the 2003 model (fig. 6). This reduction in grid spacing was extended beyond the reduction in the 1997 model and beyond Vevay Township boundaries 1.8 mi to the east and 1.9 mi to the south (fig. 7). Grid spacing was reduced to enable representation of smaller-scale flow conditions in the model. Riverbed conductances in the regridded area were modified to reflect the smaller cell sizes.

Ground-water withdrawal rates by city of Mason's production wells (fig. 6) were updated to reflect average rates representative of mid-May 2003 pumping conditions (table 2). May 2003 pumping rates were selected so that model-simulation results and observed ground-water levels collected during this study could be compared under similar hydrologic conditions (table 1). Ground-water-recharge rates were not changed from the values used in the 1996 and 1997 regional models. Average ground-water-recharge rates were determined from an analysis relating base-flow characteristics of streams to land use and basin characteristics in the Lower Peninsula of Michigan (Holtschlag, 1994). Because few areas within Vevay



EXPLANATION

- Denotes approximate cell locations for Vevay Townshp area of 2003 regional model
- ● Approximate location of production well
- ■ Approximate location of well simulating quarry withdrawals
- Approximate location of simulated river cell

Figure 6. Model cell size and the locations of simulated production and quarry withdrawals, 2003 model, Vevay Township, Michigan.

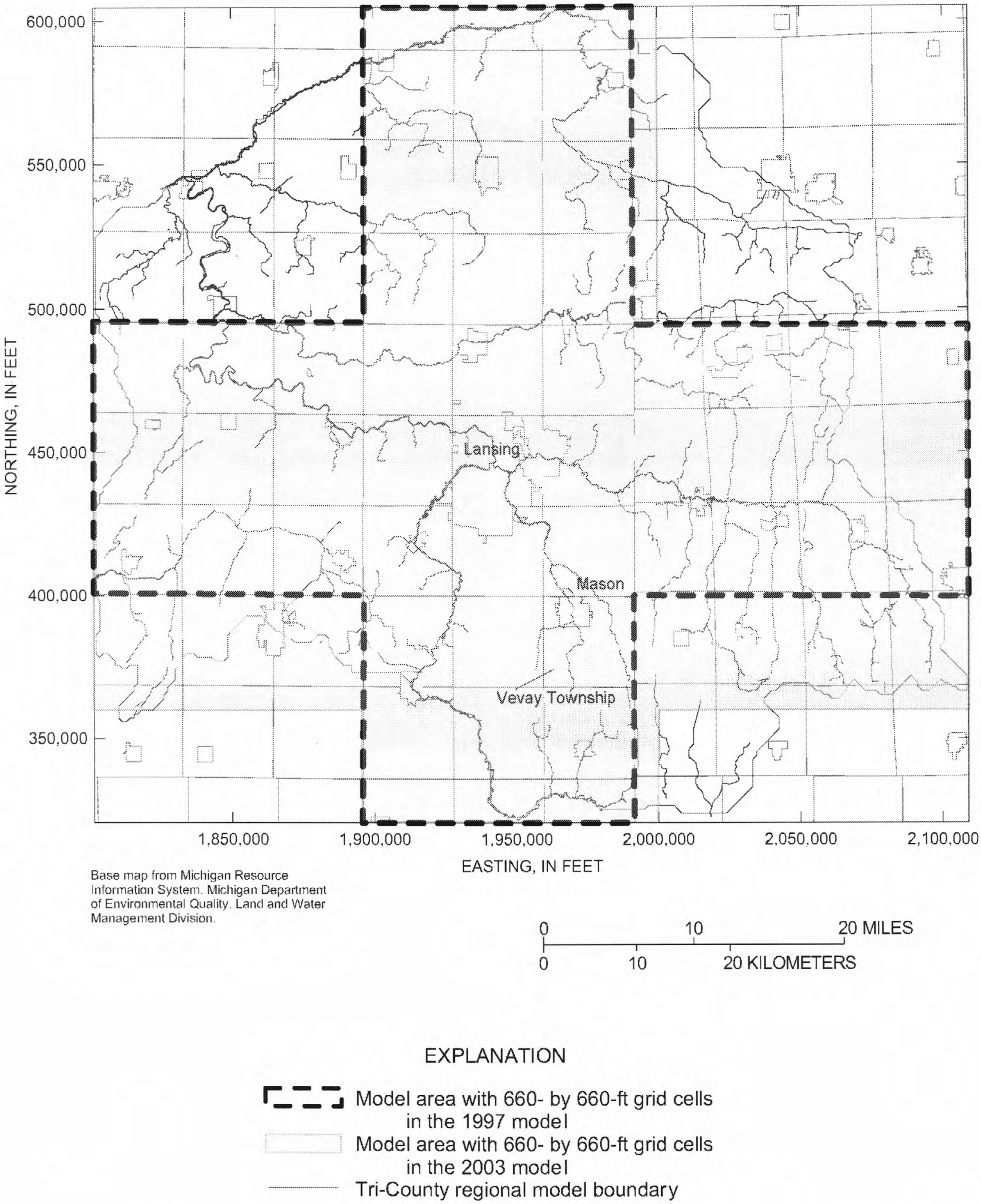


Figure 7. Areas of 660- by 660-ft grid cells in the 1997 and 2003 regional ground-water-flow models, Tri-County region, Michigan.

Table 2. Simulated pumping rates for production wells, city of Mason, Michigan
[pumping rates in cubic feet per day; NP, well not simulated as pumping]

Well number	Estimated mid-May 2003 pumping rate	Estimated well capacity
PW-1	NP	NP
PW-2	NP	NP
PW-3	1,470.6	67,379.7
PW-4	40,106.9	67,379.7
PW-5	NP	45,240.6
PW-6	60,160.4	96,256.7
PW-7	48,796.8	67,379.7

Township are covered by impervious surfaces that could limit recharge and recharge is simulated using steady-state average conditions, the estimate by Holtschlag (1994) is assumed to be representative of average ground-water recharge rates in this area. The minimum average annual recharge in the Tri-County region is 4.4 in/yr and the maximum is 16.5 in/yr; the spatial average ground-water recharge rate is 6.7 in/yr. In Vevay Township, the average annual recharge rates range from 5.8 in/yr to 15.1 in/yr (Holtschlag, 1994).

In the 1997 regional model, ground-water flow in the glacial deposits was simulated to support flow analysis in the Saginaw aquifer. Glacial features, such as eskers, were not represented because of the regional nature of the 1997 model. Because eskers that locally could affect ground-water-flow directions and rates are present within the township, these features were represented in the 2003 model. Areas in the upper layer representing the glacial deposits within the model that coincided with an esker (consisting primarily of sand and gravel) were assigned a representative hydraulic conductivity for sand and gravel of 80 ft/d (Freeze and Cherry, 1979). Within the township in the 1997 model, the horizontal hydraulic conductivity (Holtschlag and others, 1996, and Luukkonen and others, 1997) was updated to reflect the addition of the eskers. The horizontal hydraulic conductivity of the glacial deposits ranges from 20 to 80 ft/d in the 2003 model (fig. 8).

In the 1997 regional model, ground-water flow between the glacial deposits and the Saginaw aquifer was assumed to be related to the vertical hydraulic conductivity of the glacial deposits alone. Thus, areas of the glacial deposits that are composed mostly of clay would limit recharge to the Saginaw more than areas composed mainly of sand and gravel. In parts of the township, the uppermost unit in the Grand River and Saginaw Formations is shale that also could limit water movement from the glacial deposits to the Saginaw aquifer. The vertical leakance, or the vertical hydraulic conductivity divided by the distance between model layer centers, was modified to better reflect the ability of water to move between the glacial deposits and the underlying Saginaw aquifer. Representative values for the vertical hydraulic conductivities assigned to wells were determined from Holtschlag and others (1996) and Freeze and Cherry (1979). Using well driller's logs, the lowermost glacial material and the uppermost bedrock material were determined. Well locations where the lowermost glacial unit is clay and the uppermost bedrock unit is shale were assigned a vertical hydraulic conductivity of 0.005 ft/d. Well locations where the lowermost glacial unit is sand or gravel and the uppermost bedrock unit is sandstone were assigned a vertical hydraulic conductivity of 0.015 ft/d. Intermediate values of vertical conductance were assigned to the remaining wells within the township. Within the township, the range of vertical hydraulic conductivities is from 0.005 ft/d to 0.015 ft/d (fig. 9).

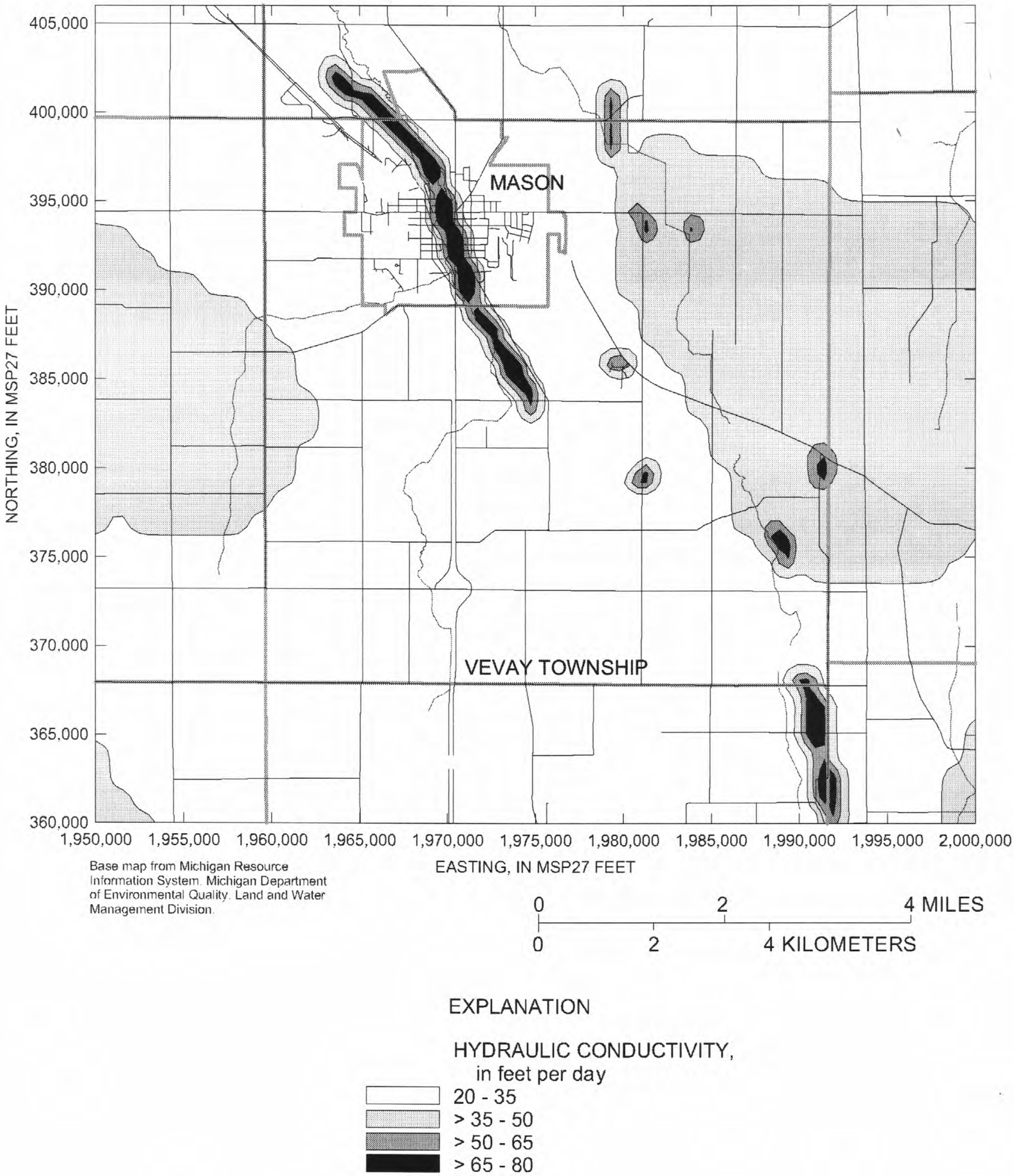


Figure 8. Estimated horizontal hydraulic conductivity of the glacial deposits, Vevay Township, Michigan.

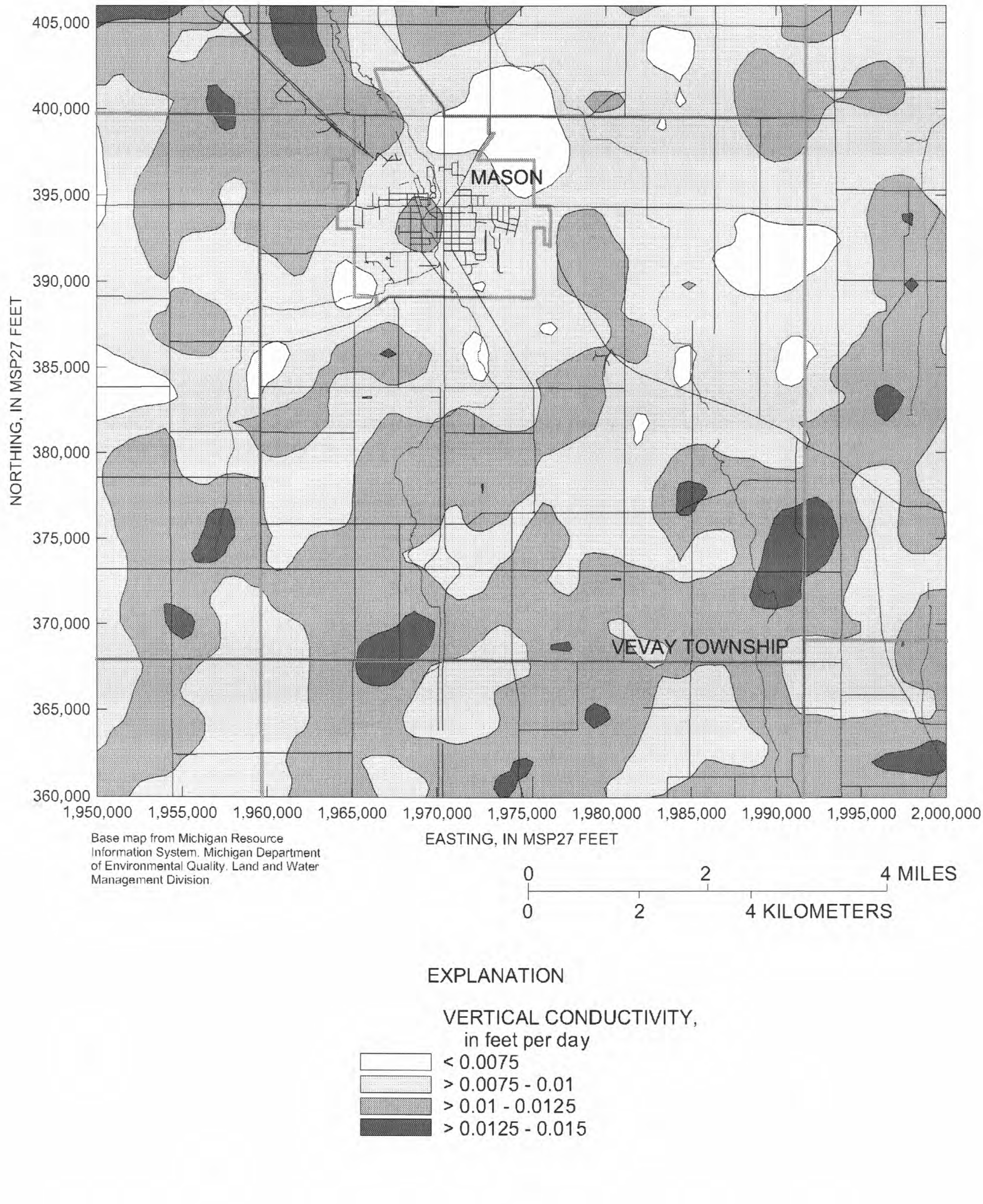


Figure 9. Estimated vertical hydraulic conductivity between the glacial deposits and the Saginaw aquifer, Vevay Township, Michigan.

Table 3. Estimates of transmissivity for the Saginaw aquifer, city of Mason, Michigan
[N/A, data not available]

Site location	Estimated transmissivity (feet squared per day)	Estimated storativity	Source
Franklin Farms	884	0.00023	C.J. Linck and Associates (1999)
Kipp Road	934	0.00041	C.J. Linck and Associates (2002)
Ash Street	790	0.00015	C.J. Linck and Associates (1999)
Well 85-A	707	N/A	Layne-Northern Company (1986a)
Well 85-B	795	N/A	Layne-Northern Company (1986a)
Wyeth - Number 1	1,728	N/A	Layne-Northern Company (1986b)
Wyeth - TW-65-A	670	0.00014	Layne-Northern Company (1986b)
Wyeth - Number 2	959	0.0001	Layne-Northern Company (1988)

In the 1997 regional model, the horizontal flow of water in the Saginaw aquifer was assumed to be proportional to the composite sandstone thickness in the Grand River and Saginaw Formations because detailed site-specific information was not available on location, extent, and thickness of the shale units. The discontinuous lenses of shale can limit the movement of water through the Saginaw aquifer. Thus, in areas with more abundant or thicker shale lenses, the composite sandstone thickness, and the resulting aquifer transmissivity (the product of the hydraulic conductivity and the aquifer thickness), will be less than in areas with more sandstone and thinner shale lenses. The overall thickness of the Grand River and Saginaw Formations varies across the Tri-County region; however, the resulting aquifer transmissivity values described above are reasonable for use in the numerical model. Using information from aquifer tests in the city of Mason (table 3), along with more detailed and site-specific sandstone thickness information, the estimated transmissivity of the Saginaw aquifer was modified from estimated values in the 1997 model. The resulting estimates of transmissivity range from 270 to 1,400 ft^2/d within the township (fig. 10).

Information available from well drillers' logs can be used to refine the altitude of the bedrock surface in the 1997 regional model. Modifying the altitude of the bedrock surface affects layer thicknesses, and, therefore, the transmissivity of the glacial deposits and the Saginaw aquifer. Information from well logs indicates that the bedrock surface is lowest along Mud Creek in the northeastern part of the township and is highest in the southwestern part of the township. Information from well logs indicates a generally higher bedrock surface than that in the 1997 model; however, the general trend of lower bedrock levels in the northern part of the township and higher levels in the southern part is consistent between the 1997 model and the well-log information.

Model Calibration and Sensitivity

Model calibration is the process of reducing the difference between observed and simulated water levels and flows by adjusting model parameters. For this study, model fit is evaluated by comparing the magnitude and distribution of the residuals between observed and simulated water levels. Flow information was not collected as part of this study, and, thus, only water levels were used to evaluate model fit. This comparison is necessary to show whether the model accurately represents the ground-water-flow system. Calibration details for the 1996 and 1997 models are described in Holtschlag and others (1996) and Luukkonen and others (1997). For this study, the 1997 model was updated in the Vevay Township area with hydrogeological data collected from well drillers' logs and previous studies. However, the ground-water-flow system in the Vevay Township area represents a small part of the regional ground-water-flow system simulated with the

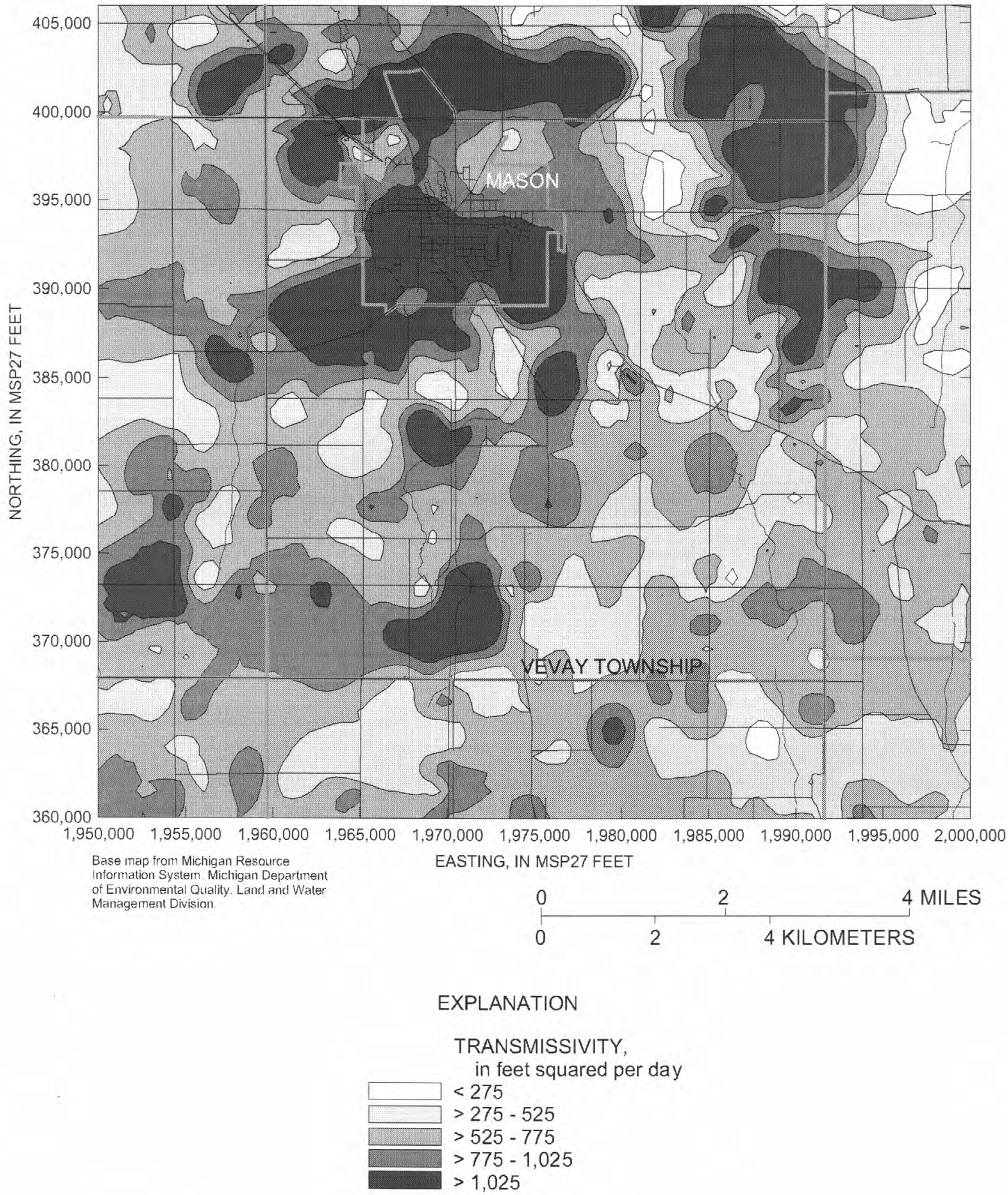


Figure 10. Estimated transmissivity of the Saginaw aquifer, Vevay Township, Michigan.

Table 4. Water-level residuals, determined as observed minus simulated value, in feet, Vevay Township, Michigan

Site number	Observed water level	Simulated water level (2003 model)	Residual (2003 model)	Simulated water level (1997 model)	Residual (1997 model)
1	894.92	899.08	-4.2	894.68	0.2
2	898.56	902.59	-4.0	894.82	3.7
3	873.27	879.75	-6.5	891.68	-18.4
4	878.95	880.53	-1.6	878.82	0.1
5	878.71	880.57	-1.9	876.22	2.5
6	879.76	880.78	-1.0	877.17	2.6
7	878.37	880.46	-2.1	875.28	3.1
8	878.49	880.86	-2.4	877.75	0.7
9	901.90	898.89	3.0	882.83	19.1
10	900.56	909.30	-8.7	898.32	2.2
11	873.37	885.21	-11.8	892.05	-18.7
12	884.27	889.59	-5.3	890.05	-5.8
13	884.45	888.69	-4.2	889.56	-5.1
14	940.61	942.58	-2.0	937.78	2.8
15	924.11	921.91	2.2	908.84	15.3
16	918.93	911.76	7.2	898.08	20.8
17	881.66	882.31	-0.7	876.65	5.0
18	887.03	884.04	3.0	889.25	-2.2
19	872.16	876.49	-4.3	867.81	4.4

2003 regional model. Water levels were measured in the Vevay Township area during May 2003, but were not measured in the rest of the regional model area. Therefore, for this study, model fit was determined by comparison of observed and simulated water levels using the 1997 model and the refined 2003 model. Model parameters were not adjusted other than refinements described above because observed water levels only were measured in the Vevay Township area. Model sensitivity is indicated by the changes observed in simulated water levels because of refinements to the layer hydraulic characteristics.

The simulated ground-water levels resulting from mid-May 2003 pumping conditions were compared to observed values in local wells (table 4). It is important to note, however, that model simulations represent the result of the long-term average input properties in the model, whereas water-level measurements represent the flow system at one point in time. The distribution of water-level residuals (the observed water level minus the simulated water level) shows agreement between observed and simulated values (the majority of residuals are less than 5 ft (table 4 and fig. 11)). This agreement between observed and simulated water levels is consistent with the agreement between observed and simulated water levels in the 1996 regional model (Holtschlag and others, 1996).

In addition to the comparison of observed and simulated water levels, model fit can be determined by comparing the sum of squared residuals (SOSR) for different model simulations. A lower SOSR generally indicates a closer agreement between observed and simulated water levels. Water-level

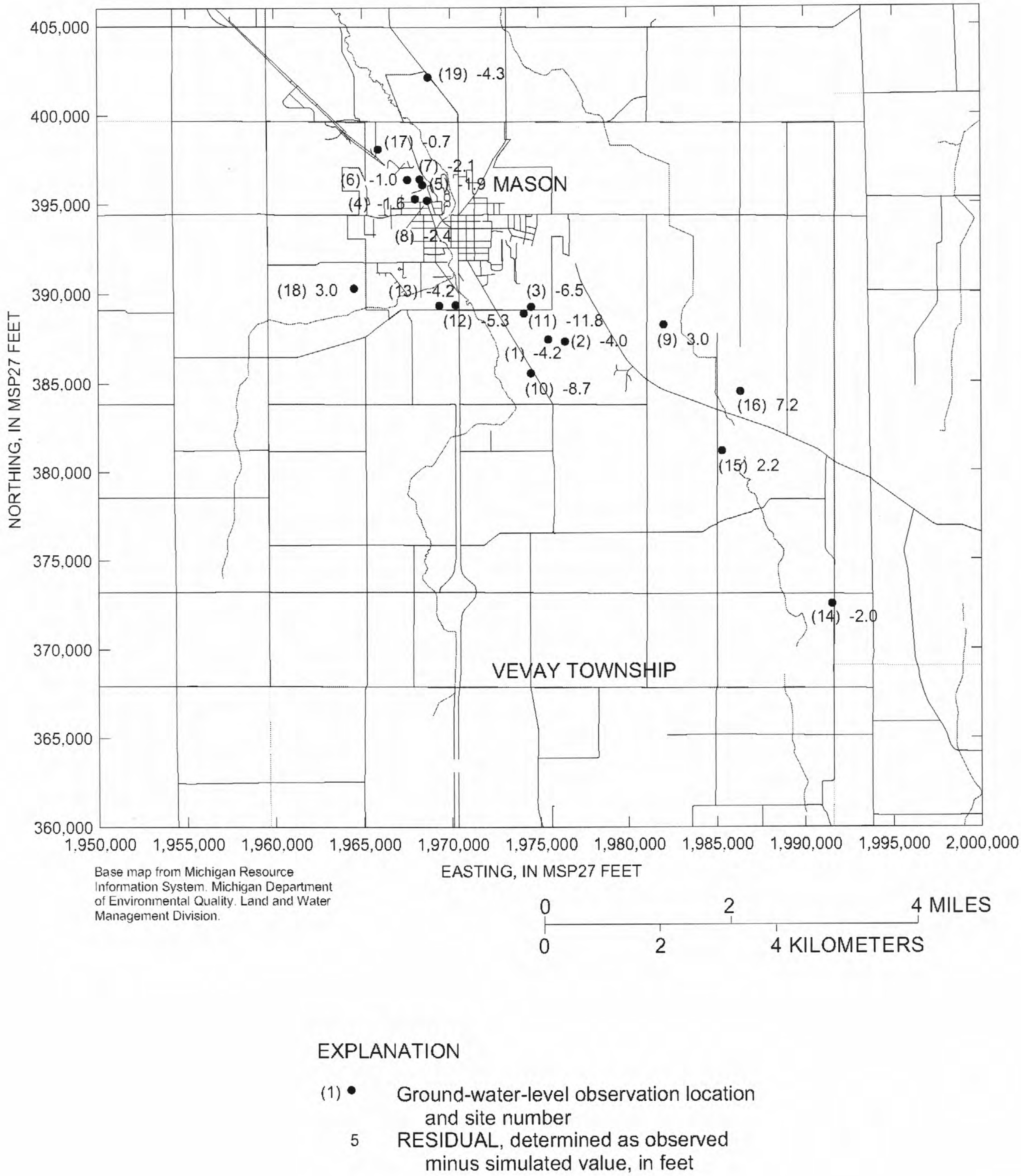


Figure 11. Distribution of water-level residuals in the Saginaw aquifer in Vevay Township, Michigan.

residuals using the 1997 model are shown in table 4. The SOSR for the 1997 model is 1,878, whereas the SOSR for the 2003 model is 452. Most simulated water levels are closer to the observed water levels in the refined 2003 model; thus, these results indicate that the changes made to the hydraulic characteristics improved the representation of ground-water flow in the Vevay Township area.

Simulated ground-water levels for the glacial deposits and the Saginaw aquifer are shown in figure 12. Ground-water flow primarily is from south to north in the township, although in the area around the city of Mason, flow enters from the south and the southwest. Simulated water levels generally are higher than observed values. The largest residuals are in the southern part of the city of Mason, primarily in the vicinity of PW-7 (fig. 3). These differences observed near the production well likely can be attributed to simulating withdrawals in the model at a constant rate whereas actual withdrawals fluctuate during the course of a day. In addition, model-simulated water levels represent the average water level within the cell, but actual water levels in a cell may vary from a low within an area influenced by a well to higher values outside the radius of influence of a well.

Model Assumptions and Limitations

The 1997 Tri-County regional ground-water-flow model (Holtschlag and others, 1996, and Luukkonen and others, 1997) was refined and used to simulate the steady-state response of the Saginaw aquifer and the overlying glacial deposits in the Vevay Township area to withdrawals from the city of Mason's production wells and to withdrawals from a nearby quarry. The accuracy of the hydraulic parameters and boundary conditions is dependent on the accuracy of regional and local information collected and incorporated into the model. The accuracies of layer surfaces and hydraulic conductivity estimates are limited by the available data at well and boring locations. In the vicinity of the quarry, no well logs were available; therefore, actual hydraulic properties of the glacial deposits and the Saginaw aquifer may differ from those simulated. Further improvement from the 2003 model in modeling hydrogeologic conditions within the Vevay Township area could be achieved by the collection and incorporation of more detailed information.

In this study, hydraulic properties in the aquifers were assumed to be isotropic because available information indicated that this representation was appropriate. Vertical variations in aquifer properties within layers and any variations in water levels or flow within the aquifers are not represented in the model. Each grid cell represents the average hydrologic and hydraulic properties in the volume of aquifer represented by the cell; thus, any variations in properties within the volume represented by the grid cell cannot be represented with the model. Similarly, local flows over distances smaller than the dimensions of the grid cell cannot be represented accurately.

Recharge was assumed to follow regional patterns found in the Lower Peninsula of Michigan (Holtschlag, 1994); thus, local variations in recharge rates, such as those associated with impermeable surfaces or differences in surficial materials, are not represented in the model. Simulated well pumpages are assumed to come from the centers of the grid cells. Furthermore, within the model, wells are assumed to fully penetrate the model layer and it is assumed that flow to the well is horizontal. The model-simulated water surface is flatter than the actual surface; vertical gradients and the actual pumping intervals within a layer are not represented. Small pumpages from domestic wells were not included because of the difficulty in obtaining reliable data, the limitations in representing small-scale flow systems, and because most of the water is returned locally through septic systems.

Model simulations are restricted to steady-state conditions. All stresses within and inputs to the ground-water-flow system, including well pumpages and recharge, remain constant throughout the simulation. Estimated recharge rates used in the model do not include annual or seasonal variations; estimated rates in model simulation represent long-term average recharge rates. No net gain or loss of flow is simulated in the system and no changes in storage occur. Although the 2003 model in its current form cannot be used to simulate transient-flow conditions, transient simulations that accounted for changes in withdrawal rates, storage, or recharge would improve understanding of dewatering effects on water levels, streamflow, and problems observed in wells near the quarry.

The location and size of the areas contributing recharge to wells are affected by the hydrogeologic characteristics, storage properties, and boundary conditions of the ground-water-flow systems, as well as the location, depth, and discharge rate of the simulated well. Thus, the simulated areal extent of the areas contributing recharge and the zones of contribution are dependent on the estimated values for the hydraulic characteristics, such as transmissivity and riverbed conductance, and on the pumping rates of the individual wells. Simulated well pumping rates in this model represent well capacities and do not represent seasonal variations. With annual or seasonal variations in pumping rates or locations, the size of areas contributing recharge could change. In addition, areas contributing recharge could change in size or location with changes in recharge rates or in how the ground-water-flow systems are represented.

The accuracy of particle-tracking simulations is limited by the accuracy of the numerical model on which the simulations are based, the estimates of the effective porosity of the flow system, and how closely the cell flow velocities approximate the local ground-water flow velocities. The particle-tracking program considers ground-water flow by advection only. If the effects of dispersion were included, the areas contributing recharge could be larger. Because flow through fractures is not explicitly simulated in the model, ground-water flow and travel times in fractured bedrock may not be represented accurately.

Further improvement of the determination of potential effects of quarry dewatering could be achieved with additional information on the amount and scheduling of offsite

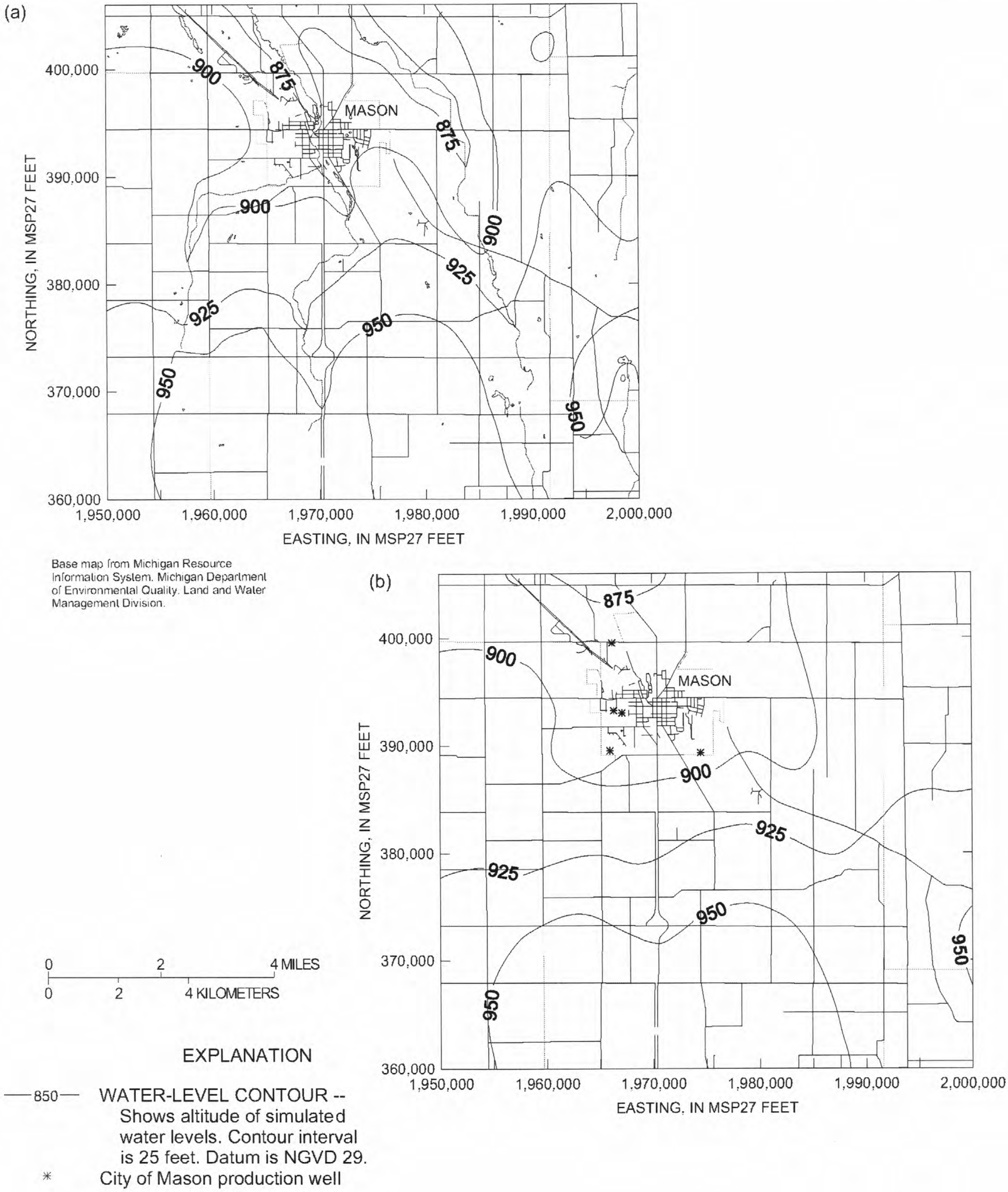


Figure 12. Simulated steady-state ground-water levels in (a) the glacial deposits and in (b) the Saginaw aquifer, Vevay Township, Michigan.

discharges to the drain that flows to Mud Creek and onsite discharges to local ponds. Knowledge of the relative timing of quarry dewatering operations and location of discharge areas is necessary for comparing observed local water levels with model-simulation results and for identifying whether trends in water-level measurements could be attributed to quarry operations. Inclusion of quarry discharges to local ponds and determination of seepage rates to or from Mud Creek in the vicinity of the quarry also would improve the reliability of model-simulation results. Collection of additional water levels also would improve model simulations. Simulations investigated possible effects on steady-state water levels because of simulated quarry withdrawals; changes in withdrawal rates, storage, or recharge were not accounted for during these simulations. Possible effects on local domestic wells were not determined during these simulations and would require inclusion of other factors that affect well performance, such as well or pump depth.

In the current 2003 model, all lakes, rivers, and creeks are represented using river cells, which allow water to flow from the river to the glacial deposits or the Saginaw aquifer or from the glacial deposits or the Saginaw aquifer to the river. However, representation as river cells does not account for the actual amount of water that flows into a cell from an upstream cell; thus, a river cell may lose more water than actually is flowing in the river. More realistic representation of Mud Creek than presently done with the 2003 model, including reduction of cell sizes to better represent the actual width of the creek, as well as simulations where the actual amount of water flowing within the creek is accounted for, would improve understanding of the potential effects of quarry dewatering.

Delineation of Contributing Areas

The particle-tracking program MODPATH (Pollock, 1989) can be combined with MODFLOW-calculated flow in each cell to determine the areas contributing water to production wells. These contributing areas are projections up to the land surface of the areas where water enters the ground-water-flow system at the water table and the areas through which water flows from the water table to a simulated pumping well. Particle tracking describes the advective movement of ground water and the effects of diffusion, dispersion, and degradation are not considered. Therefore, particle tracking is not intended as a substitute for simulating the transport of dissolved chemicals in the ground-water-flow system. An estimated porosity of 15 percent was used for the upper and lower model layers in the particle-tracking simulations (Holtschlag and others, 1996).

Ground-water-flow paths, and, thus, particle-tracking results, depend in part on the stresses to the ground-water-flow system. Different pumping rates or locations will change the ground-water-flow patterns in the modeled area and result in different zones of contribution and areas contributing recharge to the pumping wells. A wellhead protection area represents the areal extent of the areas contributing recharge and the zones of contribution to each pumping well. The area contributing recharge to a pumping well is defined as the surface area on the three-dimensional boundary of the ground-water-flow system that delineates the location of the water entering the ground-water-flow system that eventually flows to the well and discharges (Reilly and Pollock, 1993). The zone of contribution to a pumping well is defined as the three-dimensional volumetric part of the aquifer through which ground water flows to a pumping well from the area contributing recharge (Morrissey, 1989). By tracking particles for a specified amount of time, such as 10 years, time-of-travel areas can be determined. Under steady-state conditions, the water discharging from a pumped well is a blend of water of different ages or travel times. In each specified time-of-travel simulation, it is assumed that model pumping rates and locations remain constant indefinitely and that the water withdrawn by each simulated well may represent water that has entered as recharge or that already was in the zone of contribution when the well began pumping.

A total of 825 hypothetical particles were placed on the sides of the cells containing a pumping well. These particles were tracked backward in time through the ground-water-flow field until they reached a top cell face in the upper model layer. The position of the particle at the end of the simulation represented the actual starting position of the particle; that is, the simulated location where water that eventually discharges at the pumped well entered the ground-water-flow system. Ground-water withdrawals representing well capacities totaled 2.8 Mgal/d from the Saginaw aquifer for the city of Mason's production wells (table 2). Ten- and 40-year time-of-travel areas contributing recharge and zones of contribution were determined using the 2003 model (figs. 13 and 14). The areal extent of the 10-year time-of-travel areas contributing recharge and the zones of contribution for city of Mason's production wells encompasses 148 model cells, or a total of about 2.3 mi^2. The areal extent of the 40-year time-of-travel areas contributing recharge and the zones of contribution for city of Mason's production wells encompasses 398 model cells, or a total of about 6.2 mi^2.

Potential Effects of Quarry Dewatering

The quarry, or gravel mine operation, is within an esker deposit that is part of the Mason Esker complex. The sand and gravel deposits are removed down to the level of the water table. The deposits then are mined with a dragline below water level. Once a pit is opened below water, pumping is started to lower the water level to allow access to the deposits that extend to depths of approximately 60 ft (Strata Environmental Services, 2001). Water that is pumped from the active quarry area is discharged to a drain that flows into Mud Creek northwest of the mine (and likely is removed from the ground-water system in the area) or is discharged to an onsite pond from which it evaporates or infiltrates back into the ground-water-flow system. Quarry dewatering typically occurs from spring until late summer or fall; the water level in the mining area reportedly has been lowered approximately 40 ft below natural

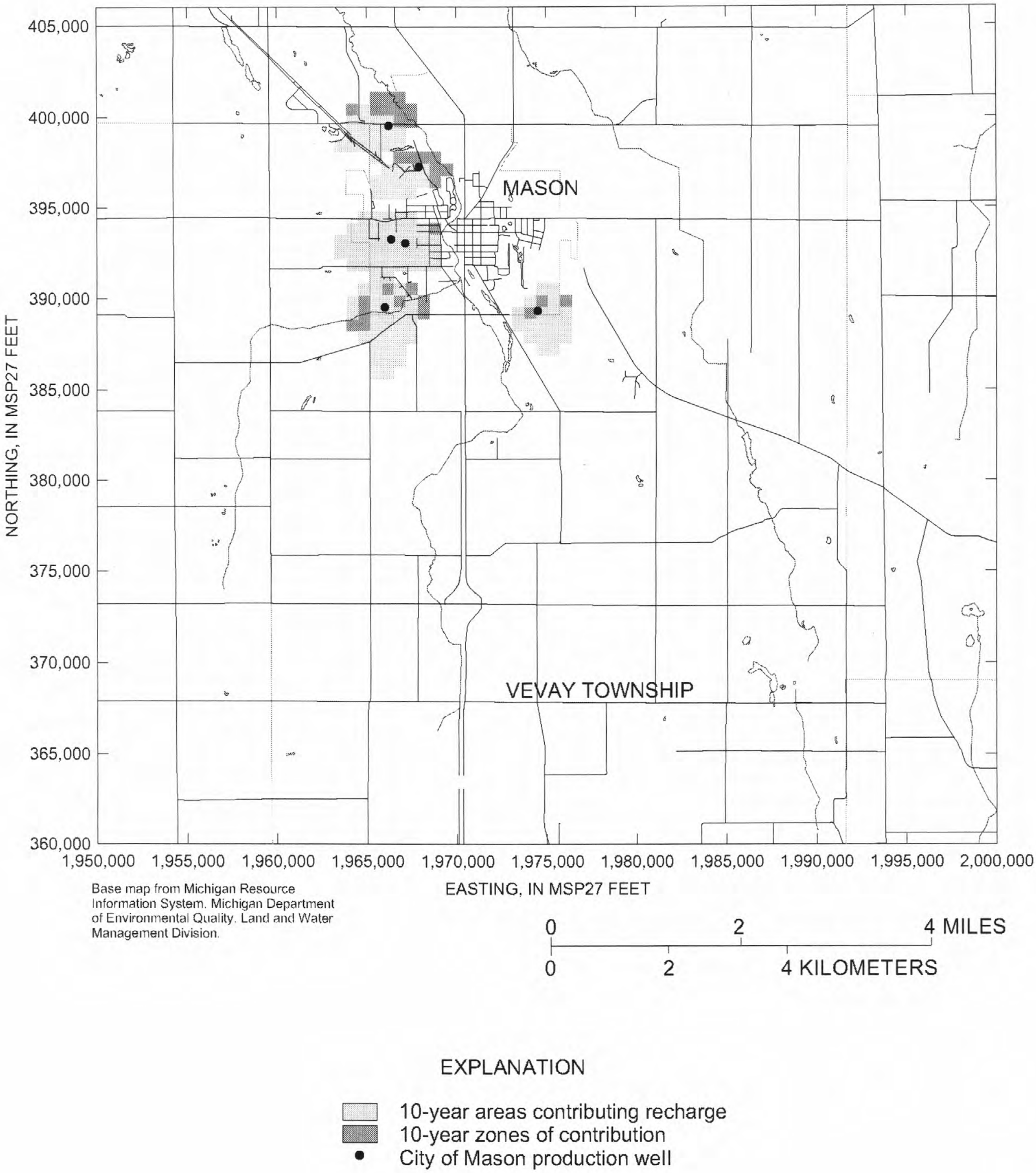


Figure 13. Areal extent of 10-year time-of-travel areas contributing recharge and zones of contribution for city of Mason's production wells, Vevay Township, Michigan.

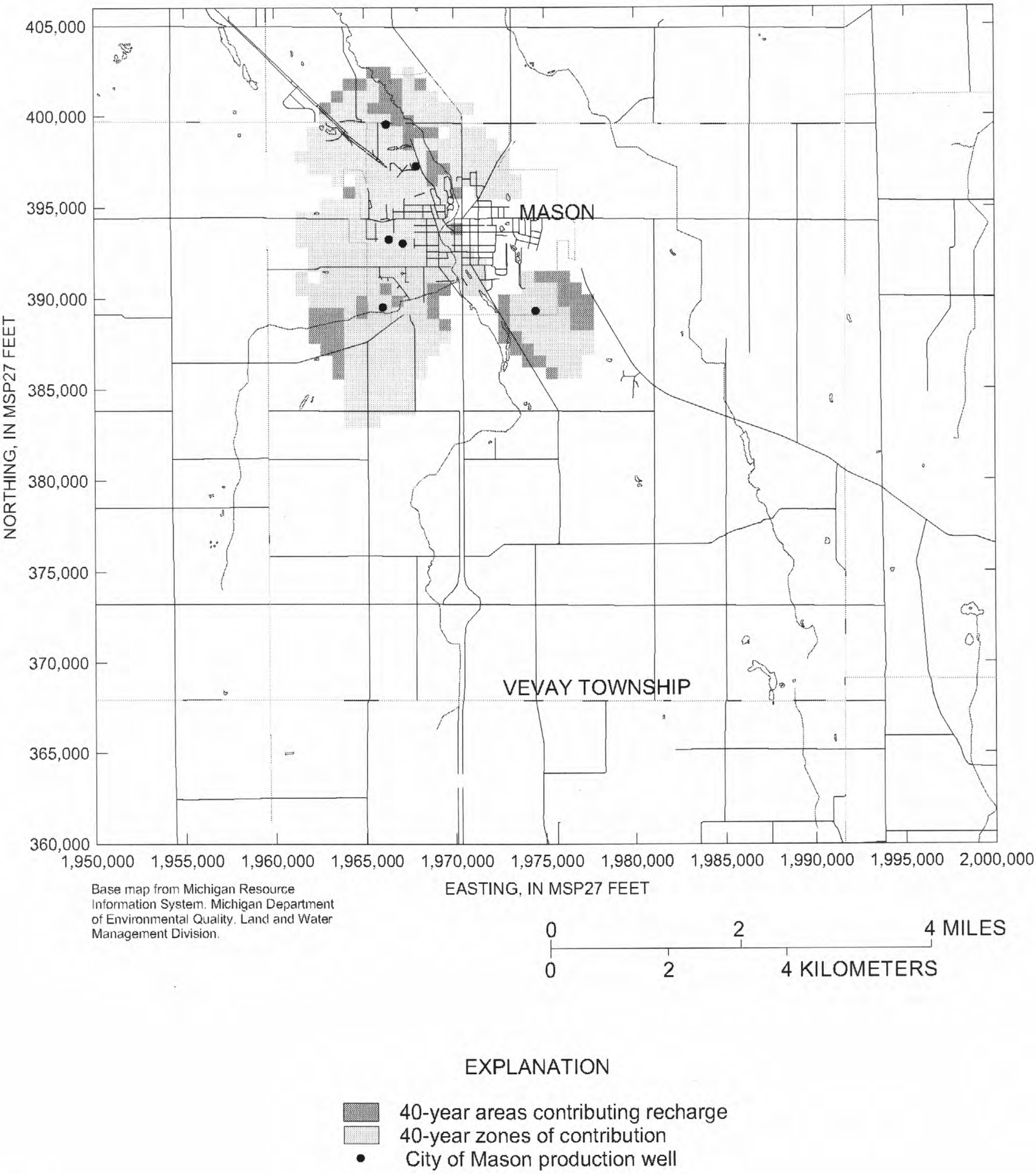


Figure 14. Areal extent of 40-year time-of-travel areas contributing recharge and zones of contribution for the city of Mason's production wells, Vevay Township, Michigan.

(predevelopment) ground-water levels (Strata Environmental Services, 2001). During the past few years, as water that was pumped from the active area was discharged into Mud Creek, area residents have asserted that this pumping has caused problems with domestic water-supply wells and lowered water levels in area ponds (Ronald Weesies, Vevay Township, verbal commun., 2003).

Pumping of water from a ground-water-flow system can affect local water levels; however, water levels also are affected by other factors, such as the horizontal and vertical hydraulic conductivity of the aquifers and confining units, the distance to ground-water-flow system boundaries, and the distribution of recharge. Water levels in wells and ponds can be affected by changes in recharge (that part of precipitation that reaches the water table), by changes in the amount of water stored in the system, by changes in discharge (such as by wells or to rivers), or by a combination of these factors.

Under natural (predevelopment) conditions, the ground-water-flow system was in a state of dynamic equilibrium in which recharge equaled discharge and no long-term changes in storage occurred. With the initiation of pumping, a new discharge was imposed upon a previously stable system. This new discharge must be balanced by an increase in recharge, by removal of water from storage, by a decrease in discharge, or by some combination of these. Eventually, these changes will stabilize. The initial source of water for a new withdrawal primarily comes from storage; the long-term source of water typically is a change in the amount of water entering or leaving the system. Steady-state conditions are simulated with the 2003 regional ground-water-flow model. All stresses within and inputs to the system, including well pumpages and recharge, remain constant throughout the simulation; therefore, changes in storage during a simulation do not occur.

During this study, monthly precipitation from 1995 to 2003 was investigated because part of precipitation eventually seeps beyond the plant root zone and is available to recharge the ground-water system. Thus, water levels may be affected by variations in ground-water-recharge rates. Precipitation generally is lowest from September to April and highest from May to August (fig. 15) (Michigan State Climatologist's Office, 2004, and Midwestern Regional Climate Center, 2004a and 2004b). Precipitation generally was low May to July and October to December 1997 – 1998, and was low July to September during 1996 and 2003. During the time when quarry dewatering operations potentially occur, precipitation has been below average in March, June, July, August, September, and October from 5 to 7 years during the period 1995-2003.

During this study, water levels were collected weekly in four wells because water levels may be affected by quarry dewatering. Three wells (14, 15, and 16; fig. 10) were in the southeastern part of Vevay Township near the quarry and one (17) was in the northwestern part of Vevay Township in the city of Mason (fig. 4). The three wells near the quarry were monitored from late February or early March until the end of October 2003 (fig. 16). Water-level measurements in well 14 indicate a water level of 8.85 ft below land surface on July 31, 2003. At the time this measurement was collected, water was being pumped from the well for use by the well owner; therefore, this drop does not indicate effects of quarry dewatering operations. The observed water levels indicate a trend of higher water levels in the spring (generally April, May, and June) and lower water levels in the summer (July, August, and September). Water levels declined about 2 ft from the spring to the summer levels. In the absence of historical data at these sites, whether the magnitude of water-level declines represents the average seasonal variability is unknown.

Well 17 (USGS site number 423532084274001, Kerns Road Well) in the city of Mason was monitored from early March until September so that water levels near the quarry could be compared to water levels in a well unaffected by quarry withdrawals. The historical data on water levels available from January 1, 1965, to August 29, 1991, for the Kerns Road well can be used for comparison of recent levels to historical levels (fig. 17). Water levels in the Kerns Road well collected during this study indicated the same trend of higher levels in the spring and lower levels in the summer as was observed in wells 14, 15, and 16 and are within the range of measurements collected previously. Water levels declined about 2.5 ft in the Kerns Road well; historical changes in water levels have ranged a total of about 4.5 ft.

Measured water-level fluctuations from wells 14, 15, and 16 do not indicate any obvious effects of quarry operations; however, it is possible that the weekly frequency of measurements might have missed water-level fluctuations caused by quarry withdrawals or that the wells used for water-level observations were too distant from the quarry to indicate effects of dewatering. The frequency of water-level measurements was planned to increase during periods of quarry dewatering operations; however, the relative timing of withdrawals for quarry operations was unavailable until late summer after nearly all data had been collected. More frequent water-level measurements during periods of quarry dewatering operations would have helped determine whether water levels in the monitored wells indicated any declines because of dewatering operations. Additionally, collection of water levels from wells closer to the quarry would be more likely to indicate effects of ground-water withdrawals for dewatering operations.

During the time period that water levels were measured for this study, the amount of water withdrawn for quarry operations that was discharged offsite to Mud Creek ranged from 0 to 1.3 Mgal/d from May 22 to October 31, 2003 (Ronald Weesies, Vevay Township, written commun., 2003) (fig. 18). During the times when no discharge to Mud Creek was recorded, it is likely that either no dewatering was occurring or water was discharged to onsite ponds; however, data on the amount of water withdrawn that was discharged to the onsite pond were unavailable.

Possible effects of quarry dewatering operations also were investigated using the 2003 ground-water-flow model. Model simulations represent the long-term effect of withdrawals and not the transient changes in storage that occur as the system changes in response to new pumping conditions.

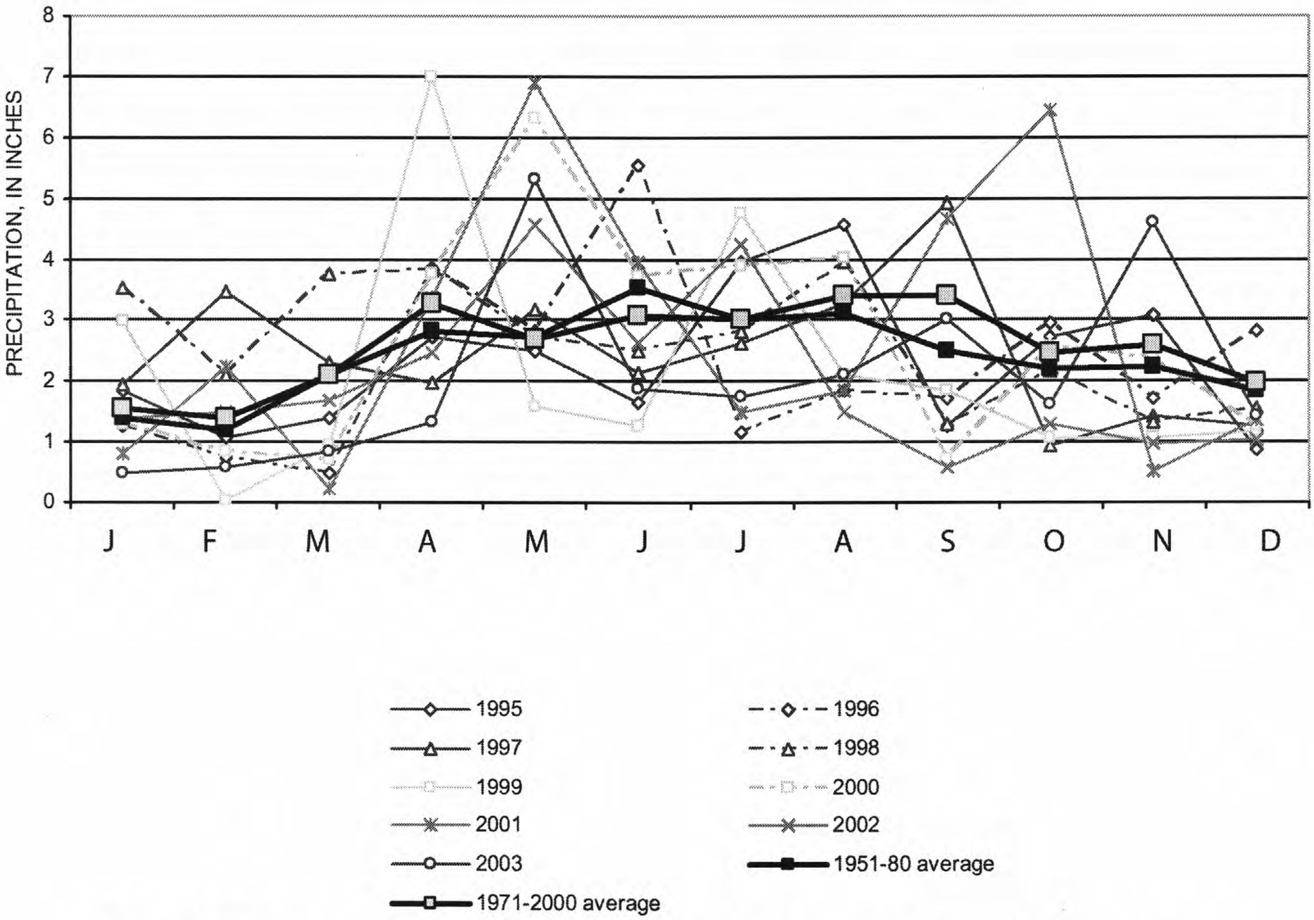


Figure 15. Monthly variation in precipitation recorded at East Lansing, Michigan (Michigan State Climatologist's Office, 2004, and Midwestern Regional Climate Center, 2004a and 2004b).

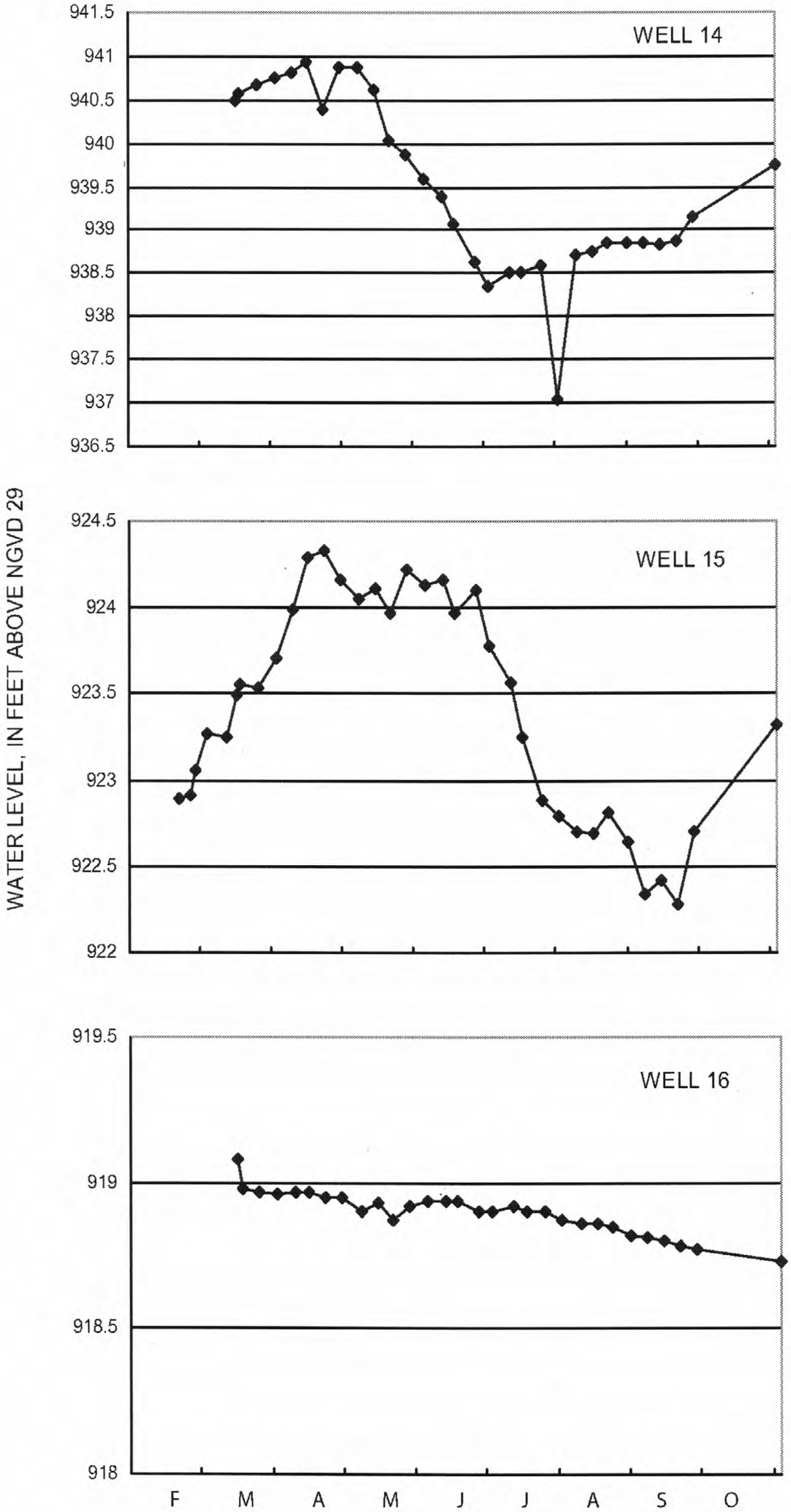
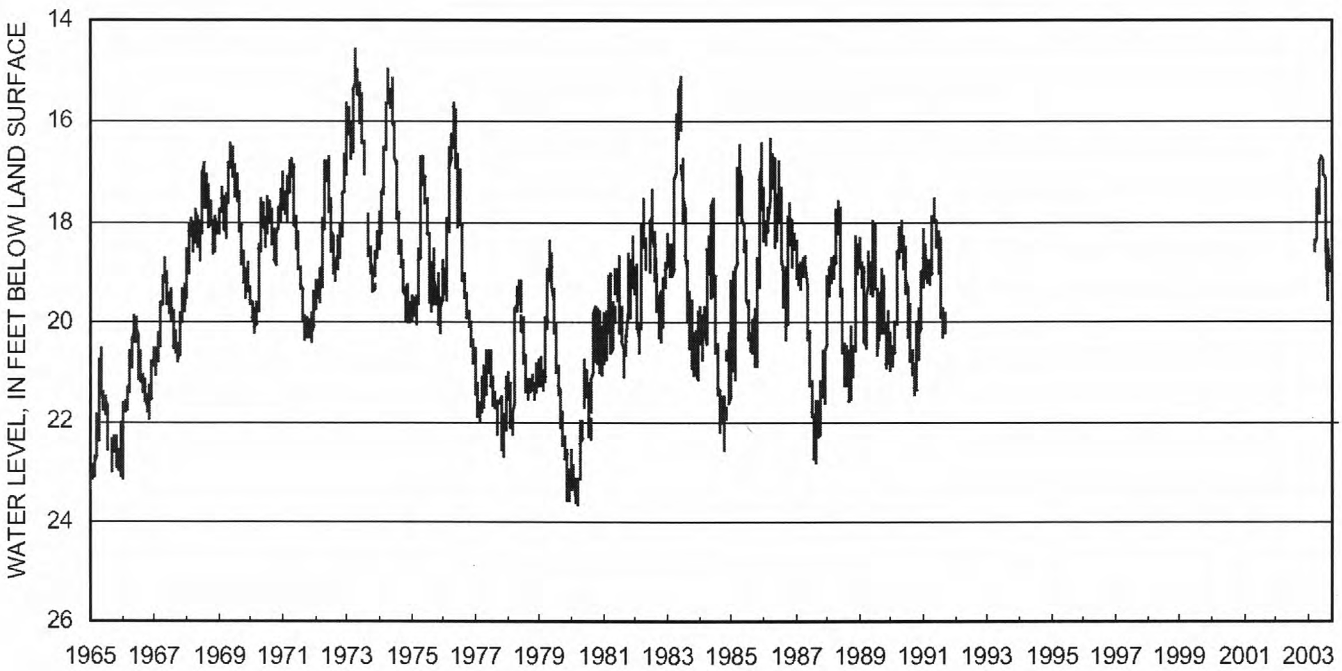


Figure 16. Ground-water levels for selected wells, Vevay Township, Michigan, February - October, 2003. [Note that scale of y-axis varies in these plots].



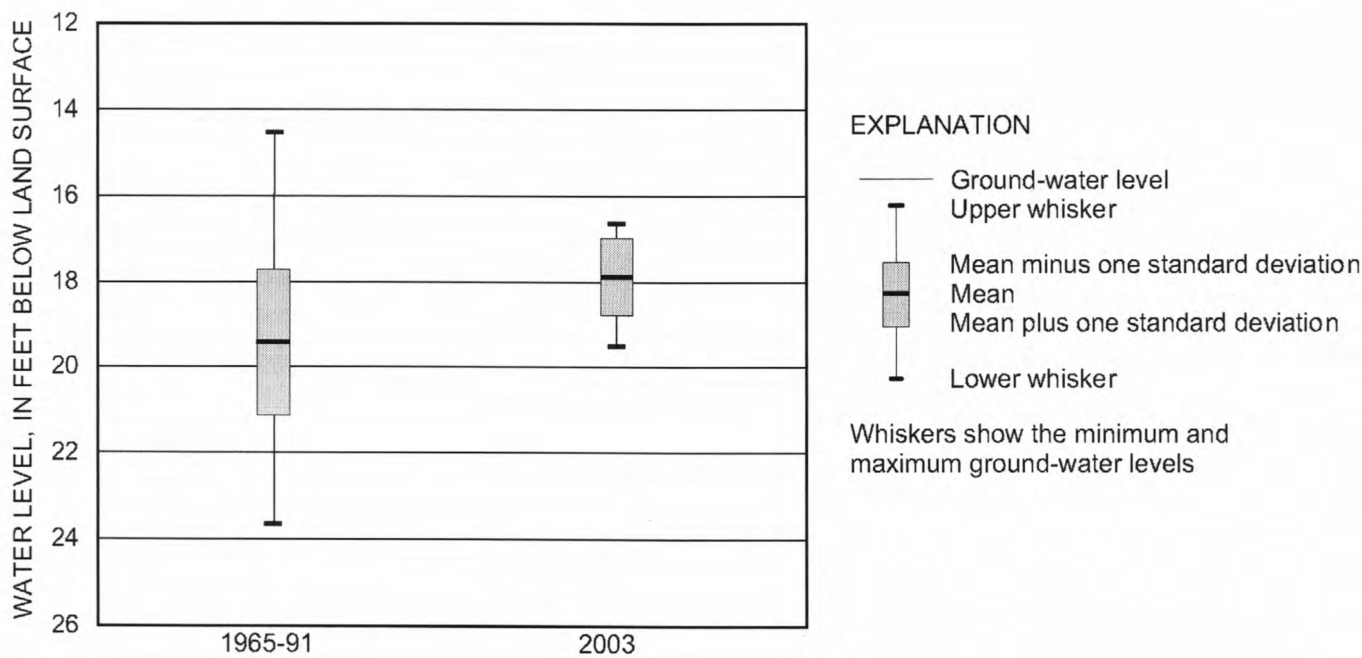


Figure 17. Hydrograph and water-level statistics in the Kerns Road well, city of Mason, Michigan, 1965-2003.

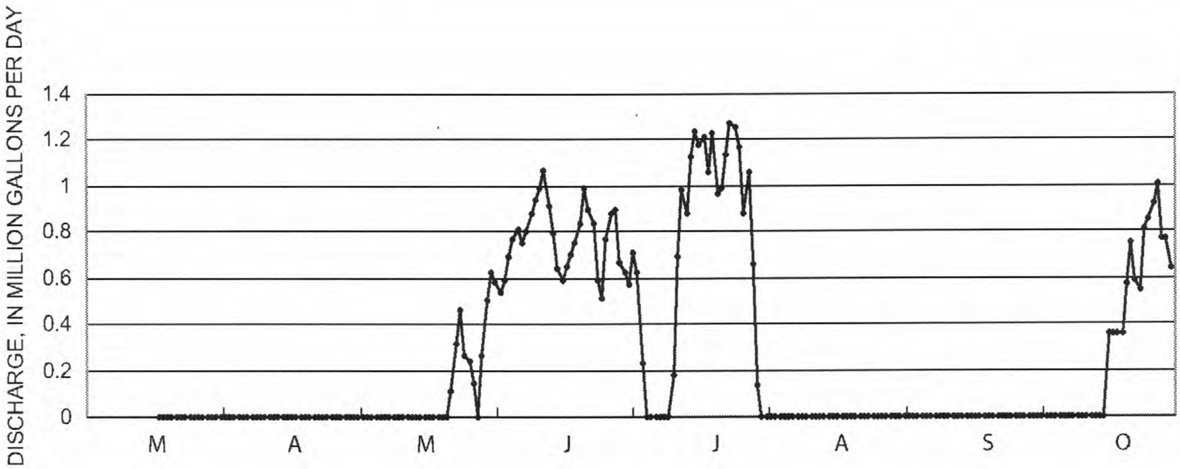


Figure 18. Discharge to Mud Creek from water withdrawals related to quarry operations, Vevay Township, Michigan, March - November 2003.

It also is assumed that recharge is constant during the model simulation; annual or seasonal variations are not incorporated because long-term average conditions are assumed in model simulations. Possible steady-state effects on water levels by simulated quarry withdrawals were simulated. Factors such as well or pump depth that affect well performance are not accounted for in these model simulations.

Withdrawals because of dewatering were simulated in the ground-water-flow model using well or drain cells. If a cell is simulated as a well, it is assumed that water is removed from within the cell at a specified rate. In contrast, water is removed from the bottom of the cells represented as drains at a rate dependent on the difference between water levels in the drain and the adjacent cells. Neither well or drain cells completely simulates the actual method of dewatering where water is removed from all sides of the pit; however, the model simulations provide some indications of the effects of withdrawals for quarry dewatering operations on local water levels.

Model simulations were conducted with one well simulating quarry withdrawals of approximately 1.6 Mgal/d (213,903 ft^3/d) (fig. 6). This value was selected based on the information about discharges to Mud Creek. The measurements of discharge to Mud Creek were reported as daily values; however, no information is available on how the reported value compares to daily operations and no information is available on how much water is discharged to on-site ponds. Thus, simulation results using an estimated withdrawal of 1.6 Mgal/d provide an estimate of the potential effects on local water levels at a rate that is assumed to be representative of quarry operations. Additional simulations were conducted to investigate the sensitivity of the representation of Mud Creek in the vicinity of the quarry. In the model, Mud Creek is represented using river cells that do not account for simulated flow in the creek and that simulate the creek with a width equal to that of the cell. The river cells can contribute as much water as needed to meet nearby withdrawal demands; thus, the amount of water contributed in model simulations could be greater than the amount actually flowing in the creek. Reducing the riverbed conductance or removing the river cells can limit the amount of water that can be removed from the cells represented as rivers. Simulations with withdrawals represented by one well were performed with the riverbed conductance of nearby Mud Creek reduced by 50 percent, by 75 percent, or with local river cells removed entirely.

Simulation results where quarry withdrawals were represented by one well indicate water-level declines exceeding 1 ft almost 2 mi from the quarry in the glacial deposits and in the Saginaw aquifer (fig. 19). In the glacial deposits, simulated water-level declines primarily are to the north and east of the quarry; water-level declines were minimal west of Mud Creek. With the riverbed conductance reduced by half, simulated water-level declines in the glacial deposits extend approximately 4,300 ft to the west in the direction of Mud Creek (table 5). With riverbed conductance reduced by 75 percent, simulated water-level declines extend approximately 5,900 ft to the west in the glacial deposits and approximately 6,600 ft west of the quarry in the Saginaw aquifer. When local river cells representing Mud Creek are removed from the model, simulated water-level declines in the glacial deposits and the Saginaw aquifer extend slightly further (when compared to the 75 percent reduction) from the quarry in all directions.

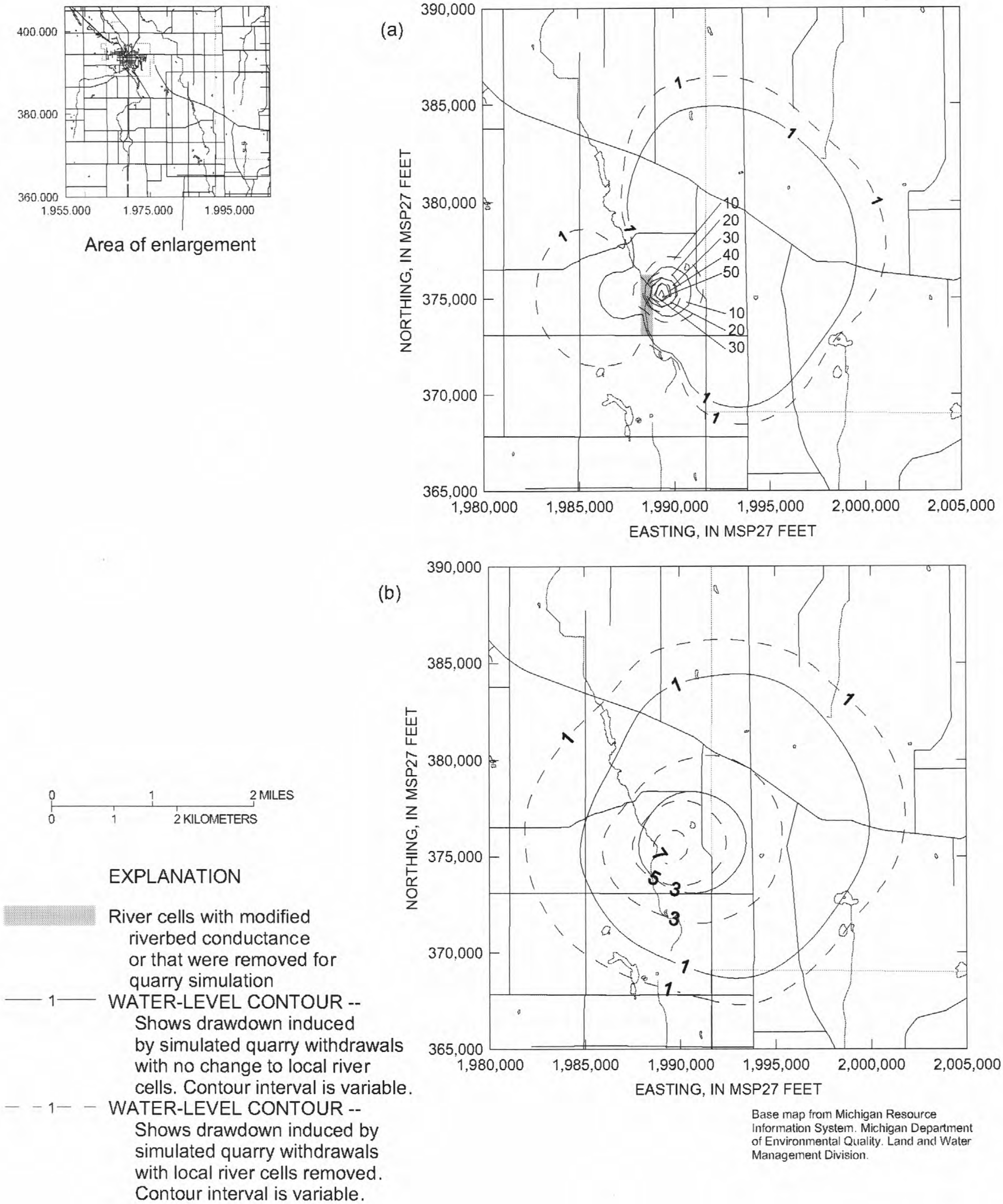


Figure 19. Difference in ground-water levels in (a) the glacial deposits and (b) the Saginaw aquifer with quarry withdrawals represented by one well, Vevay Township, Michigan.

Additional simulations were conducted to investigate the sensitivity of model results where the water withdrawals for quarry operations are represented by four wells or by four drains. With withdrawals for quarry operations represented by four wells, the total amount of water withdrawn from each cell is reduced to 25 percent of 1.6 Mgal/d (53,476 ft^3/d each). Simulations with withdrawals represented by four drains have water removed from the bottom of the drains, which were placed 40 ft below the estimated water table. The simulated hydraulic conductivity of the bottom of the drain cells was modified until the model-simulated amount of water removed was approximately 1.6 Mgal/d. Simulation results indicate water-level declines that exceeded 1 ft greater than 2 mi from the quarry in the glacial deposits and in the Saginaw aquifer (table 5). Declines are greatest to the east and north of the quarry; declines are lowest to the west. Model results with quarry withdrawals represented by four drains indicate similar water-level declines compared to the model results with quarry withdrawals represented by four wells. Model-simulation results where quarry withdrawals are represented by four wells or four drains indicate similar water-level declines to the simulations where quarry withdrawals are represented by one well.

With a reduction of local riverbed conductance or with local river cells removed, water-level declines extend further west of Mud Creek compared to the model-simulation results using unmodified river cells. Comparison of river cell flows indicates little difference between model scenarios (table 6). It is likely as local river cells have reduced riverbed conductances or are removed entirely, some water withdrawn for quarry operations is from the unmodified river cells that are more distant from the quarry. Simulation results indicate that a portion of the water withdrawn for quarry dewatering operations is from Mud Creek and that withdrawals for dewatering operations capture water that would have discharged into Mud Creek. Simulation results also indicate local drawdowns of 40 ft or more and water-level declines in the glacial deposits and the Saginaw aquifer. Collection of additional information on the quarry dewatering activities; and additional hydrologic data on aquifer characteristics and degree of connection, ground-water levels in wells in the vicinity of the quarry, and seepage data from Mud Creek would help to determine which scenario or whether another scenario would most accurately describe the response of the ground-water-flow system in Vevay Township to quarry-dewatering operations. Inclusion of observed temporal changes in recharge rates, as well as allowing the amount of water in storage to change, would improve understanding of dewatering effects on water levels, streamflow, and water-level declines observed in wells near the quarry.

Summary and Conclusions

In 2003, the U.S. Geological Survey, in cooperation with the Tri-County Regional Planning Commission, began a study of the ground-water-flow system in the Vevay Township, Michigan, area. Primary study objectives included describing and understanding regional ground-water flow, delineating contributing areas to production wells, and determining potential effects of quarry dewatering on the ground-water-flow system. A previously developed regional ground-water-flow model of the Tri-County region was refined and updated to better represent ground-water flow in the Vevay Township area.

The 1996 Tri-County regional ground-water-flow model, developed for Clinton, Eaton, and Ingham Counties, has been used in the past by local water managers to answer questions about protection and availability of their ground-water resources and to delineate contributing areas for local Wellhead Protection Programs. In 1997, the uniform grid spacing of the regional model was refined to a variably spaced grid to represent smaller scale flow systems (than represented in the 1996 regional model) in the central part of the model area. However, local variations in the hydraulic characteristics of the glacial deposits and the Saginaw aquifer and in the degree of connection between the aquifers, as well as the grid spacing of the regional model, prevented using the regional model to represent local flow systems in the Vevay Township area. Additional details on the spatial distribution of the hydraulic conductivity of the glacial deposits, the vertical conductance between the glacial deposits and the Saginaw aquifer, the transmissivity of the Saginaw aquifer, and the altitude of the top of the Saginaw Formation were determined from historical information and from analysis of well drillers' logs. This new information was used to refine the hydraulic characteristics, model layer surfaces, and cell size of the 1997 Tri-County regional model, so that the updated 2003 model could better represent the local flow system in the Vevay Township area.

Areas contributing recharge and the zones through which this water moves to the city of Mason wells within 10 and 40 years were determined using the 2003 model. The areal extent of the 10-year areas contributing recharge and the zones of contribution for the city of Mason production wells encompasses about 2.3 mi^2. The areal extent of the 40-year areas contributing recharge and the zones of contribution for the city of Mason production wells encompasses about 6.2 mi^2.

Potential effects of ground-water withdrawals for quarry dewatering operations were simulated using one well, four wells, or four drains at the quarry. Simulations where one well represented quarry withdrawals also were conducted with reduced riverbed conductance in the cells representing Mud Creek nearest the quarry or with local river cells removed entirely. It was assumed in these simulations that the water was discharged offsite, and, therefore, was removed from the ground-water-flow system in the vicinity of the quarry. Measured water levels in nearby wells do not indicate obvious effects of quarry operations; however, it is possible that the

Table 5. Extent of simulated water-level declines in the glacial and Saginaw aquifers exceeding 1 foot from simulated quarry dewatering, Vevay Township, Michigan. [Distances shown are measured from the quarry.]

Simulation of quarry dewatering	Aquifer	Distance to the east (feet)	Distance to the north (feet)	Distance to the south (feet)	Distance to the west (feet)
As one well	glacial	10,200	9,700	5,900	3,300
	Saginaw	10,300	9,200	6,500	4,800
As one well with riverbed conductance reduced by 50 percent	glacial	10,600	9,900	6,000	4,300
	Saginaw	10,600	9,600	6,700	5,400
As one well with riverbed conductance reduced by 75 percent	glacial	11,100	10,600	6,300	5,900
	Saginaw	11,200	10,200	7,200	6,600
As one well with river cells near quarry removed	glacial	11,700	11,300	6,700	6,600
	Saginaw	12,200	11,100	7,900	7,800
As four wells or as four drains	glacial	11,900	11,400	7,000	3,100
	Saginaw	12,500	10,900	7,600	5,100

Table 6. Difference in flow to and from river cells in the 2003 regional model for selected quarry dewatering scenarios, Vevay Township, Michigan. [Flows are in cubic feet per day; Because only pumping rates for the quarry and river cells in the vicinity of the quarry were changed, the budgets presented in the table indicate changes due to the various quarry scenarios.]

Scenario	Simulated flow out of river cells	Simulated flow into river cells	Net difference in flow from scenario with no quarry withdrawals
No simulated quarry withdrawals	14,681,533	87,983,984	0
Quarry withdrawals represented by:			
- one well	14,748,601	87,838,528	212,524
- one well with riverbed conductance reduced by 50 percent	14,727,762	87,827,624	202,589
- one well with riverbed conductance reduced by 75 percent	14,709,875	87,803,880	208,446
- one well with river cells near quarry removed	14,692,098	87,781,816	212,733
- four wells	14,730,936	87,822,072	211,315
- four drains	14,736,405	87,809,424	229,432

weekly measurement frequency might have missed fluctuations in water levels caused by quarry withdrawals or that the measured wells were too distant from the quarry operations to reflect dewatering effects.

Simulation results where quarry withdrawals are represented by one well indicate water-level declines exceeding 1 ft about 2 mi from the quarry in the glacial deposits and in the Saginaw aquifer. Reduction of local riverbed conductance by 50 percent, by 75 percent, or with local river cells removed further extends the area affected by quarry dewatering and water-level declines extend west of Mud Creek. These simulation results indicate that water withdrawn for quarry dewatering operations is from nearby Mud Creek or likely would have discharged into Mud Creek. Simulation results also indicate local drawdowns of 40 ft or more and water-level declines in the glacial deposits and the Saginaw aquifer. Improvement of the simulation of the response of the ground-water-flow system to quarry dewatering would require collection of additional information on sand and gravel mining operations; and additional hydrologic data on aquifer characteristics and degree of connection, water levels in wells in the vicinity of the quarry (generally within about 0.5 mi of the quarry), and seepage rates from nearby surface-water features.

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