Prepared in cooperation with the Lansing Board of Water and Light

Delineation of Contributing Areas for 2017 Pumping Conditions to Selected Wells in Ingham County, Michigan

Open-File Report 2018–1133

U.S. Department of the Interior
U.S. Geological Survey

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Contents

Figures

Tables

Conversion Factors

U.S. customary units to International System of Units

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 foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow and recharge rate	
inch per year (in/yr)	0.3048	millimeter per year (mm/yr)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

Datum

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

Horizontal coordinate information is referenced to the Michigan State Plane Coordinate System, South Zone.

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

Delineation of Contributing Areas for 2017 Pumping Conditions to Selected Wells in Ingham County, Michigan

By Carol L. Luukkonen

Abstract

As part of local wellhead protection area programs, areas contributing water to production wells need to be periodically updated because groundwater-flow paths depend in part on the stresses to the groundwater-flow system. A steady-state groundwater-flow model that was constructed in 2009 was updated to reflect recent (2017) pumping conditions in the Lansing and East Lansing area in the Tri-County region, Michigan. For this current (2017) study, withdrawals from selected production wells were updated, and the existing model calibration under the new pumping conditions was checked. Results of flow simulations indicate that 10-year time-of-travel areas cover approximately 25 square miles and 40-year time-of-travel areas cover approximately 51 square miles.

Introduction

The Tri-County region, which consists of Clinton, Eaton, and Ingham Counties, covers 1,697 square miles (mi^2) in the south-central part of the Lower Peninsula of Michigan (fig. 1). A groundwater-flow model developed in 1996 (Holtschlag and others, 1996) was refined in 2009 (Luukkonen, 2009) in cooperation with the Tri-County Regional Planning Commission and local communities to better represent the groundwater-flow system in the Tri-County region. Participating communities included Alaiedon Township, Bath Township, Delhi Township, Delta Township, city of East Lansing, city of Eaton Rapids, city of Lansing, city of Williamston, Eaton Rapids Township, Lansing Township, Michigan State University, Meridian Township, Oneida Township, Vermontville Township, Village of Dimondale, Watertown Township, Williamstown Township, and Windsor Township. The 2009 study helped to improve understanding of the regional hydrologic system in the Lansing area by means of a model (the "Tri-County model") that continues to be used for planning and protection of the water supplies in the Lansing area. As part of local wellhead protection area programs, areas contributing water to production wells need to be periodically updated because groundwater-flow paths depend in part on the stresses to the groundwater-flow system. Different pumping rates or pumping locations will change the groundwater-flow patterns in the modeled area and result in different zones of contribution and areas contributing recharge to the pumping wells; therefore, for this current (2017) study by the U.S. Geological Survey (USGS), prepared in cooperation with the Lansing Board of Water and Light, withdrawals from selected production wells were updated to reflect 2017 pumping conditions, and the existing model calibration under the new pumping conditions was checked.

Purpose and Scope

The purpose of this report is to describe the updated 2009 Tri-County regional steady-state groundwater-flow model that is currently (2017) used for wellhead protection planning efforts and other water resources issues. Simulated water levels and streamflow under 2017 pumping conditions were compared to observed water levels and estimated streamflow. These updated pumping conditions were used with particle-tracking analysis for delineation of contributing areas to selected production wells for 10- and 40-year times-of-travel. The limitations of the model for assessing groundwater levels and flow and for delineating contributing areas are described in this report.

Previous Studies

Several previous studies contributed to the development of the Tri-County regional model. The development of the 1996 regional groundwater-flow model and simulations used to determine contributing areas for most production wells in the Tri-County region are described in a report by Holtschlag and others (1996). Simulations in the north Lansing area with the original 1996 model and with reduced grid spacing were described by Luukkonen and others (1997a, 1997b). Finally, additional reports describe the refinement of the 1996 model (Luukkonen, 2009) and updated delineations for Lansing area wells under 2011–12 pumping conditions (Luukkonen, 2014).

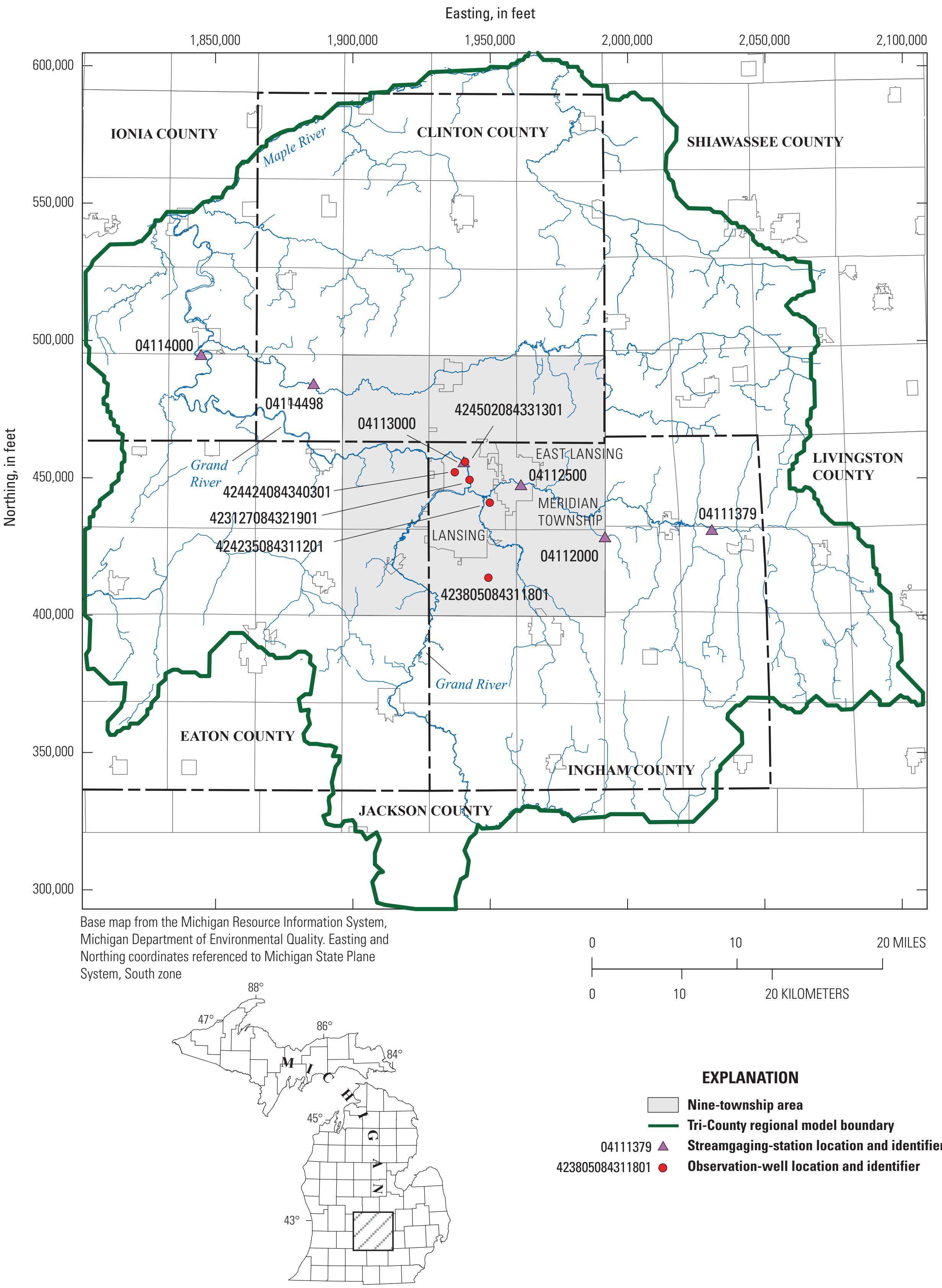

Figure 1. Location of the Lansing, East Lansing, and Meridian Township areas in the Tri-County regional model area, Michigan.

Description of Study Area

Lansing, Michigan, is in the center of the nine-township area, which is the principal area of groundwater withdrawals in the Tri-County region (fig. 1). In the Tri-County region, Jurassic and Pennsylvanian rocks form the uppermost bedrock units; however, the Jurassic rocks are only marginally present in the Tri-County region (Westjohn and others, 1994). Discontinuous lenses of sandstone, shale, coal, and limestone in the Pennsylvanian bedrock units have been formally subdivided into two formations. The uppermost massive, coarse-grained sandstones form the Grand River Formation; all remaining Pennsylvanian rocks are considered part of the underlying Saginaw Formation (Mandle and Westjohn, 1989). Glacial deposits of Pleistocene age overlie Pennsylvanian and Upper Jurassic rocks. The glacial features in Michigan are the result of ice advances during late Wisconsin time (35,000 to 10,000 years before present).

Glacial deposits form the uppermost aquifer in the Tri-County region. Groundwater flow in the glacial deposits is generally from south to north, away from topographic divides and toward surface-water bodies. Aquifers in the glacial deposits are composed primarily of coarse alluvial and outwash materials (Vanlier and others, 1973). The Saginaw aquifer is in the permeable sandstones of the Grand River and Saginaw Formations. The Saginaw aquifer can be thought of as an aquifer system consisting of three sandstone units separated by an upper, interbedded-series unit and a lower shale unit (David Westjohn, U.S. Geological Survey, oral commun., 2005). Most groundwater flow in the Saginaw aquifer is from south to north, although a small amount is toward local pumping centers. Flow between aquifers in the glacial deposits and the Saginaw Formation is small where confining unit(s) consisting of a lower till unit in the glacial deposits and (or) an upper shale unit in the Saginaw Formation are present and is focused in areas where these till and shale units are absent. Groundwater is withdrawn primarily from the Saginaw aquifer, which consists of permeable sandstones within the Grand River and Saginaw Formations of Pennsylvanian age. Aquifers in the glacial deposits and other bedrock units are important groundwater sources in some places. More detailed information is available in Luukkonen (2009).

Groundwater is the principal source of water supply for the Tri-County region, and most communities rely on groundwater from the Saginaw aquifer. Simulated groundwater withdrawals for selected production wells for the cities of Lansing and East Lansing/Meridian Township in the central part of the model area were updated to reflect 2017 pumping conditions; other municipal withdrawals were updated to represent 2015 pumping conditions. Simulated groundwater withdrawals totaled 32.2 million gallons per day (Mgal/d) for the cities of Lansing and East Lansing (Cheryl Louden, Lansing Board of Water and Light, oral commun., 2017 and Clyde Dugan, East Lansing/Meridian Water and Sewer Authority, oral commun., 2017) and 7.7 Mgal/d for other communities (Dieter and Maupin, 2017) in the steady-state model. The total withdrawals are less than those simulated for 2011–12 conditions (Luukkonen, 2009) and are similar to rates determined for 1992 (Holtschlag and others, 1996) (fig. 2).

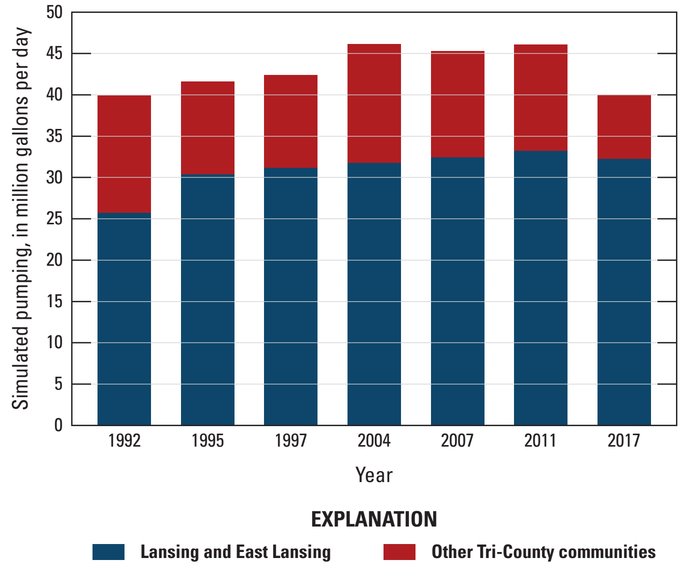

Figure 2. Simulated pumping in the Tri-County regional model for selected years, Michigan.

Groundwater-Flow Simulation

The USGS modular three-dimensional finite-difference numerical groundwater-flow model MODFLOW–2000 (Harbaugh and others, 2000) was used to simulate groundwater flow in the Tri-County region (Luukkonen, 2009). The model in this study is exactly the same as in the previous study except simulated pumping rates for selected wells were updated to reflect more recent (2017) conditions. The steady-state model area consists of Clinton, Eaton, and Ingham Counties along with parts of Ionia, Shiawassee, Jackson, and Livingston Counties (fig. 1). A brief description of the model characteristics and the water-level and streamflow data used to check model calibration under the updated pumping conditions are described in the following sections. A more detailed description of the model construction, boundary conditions, and hydraulic characteristics of the various hydrogeologic units and model layers is available in Luukkonen (2009). Model input and output files are available in a USGS data release (Luukkonen, 2018).

Spatial Discretization

The model area covers about 3,500 mi^2 and consists of 338 rows and 307 columns of grid cells that vary in size. Cell spacing increases from approximately 660 by 660 feet (ft) in the central part of the model area to a maximum grid spacing of about 1,330 by 1,330 ft. Three units were determined to represent the glacial materials. The uppermost glacial unit (layer 1) was thickest for deposits adjacent to rivers to minimize problems associated with model convergence of calculated water levels. The remaining glacial materials were subdivided equally to create layers 2 and 3. The Saginaw Formation materials were divided into an uppermost shale unit overlying three aquifer units that are separated by an interbedded series consisting of shale and sandstone lenses and a lowermost shale unit. Model layers 4, 6, and 8 represent confining unit materials; whereas model layers 5, 7, and 9 represent sandstone aquifer units. The lowermost model layer (layer 10) represents the material underlying the Saginaw aquifer and was included because well logs indicate that some wells may be completed below the bottom of the Saginaw aquifer.

Boundary Conditions

External boundary conditions for the upper layers representing glacial materials are constant head (Grand River in the south, Maple and Grand Rivers in the north) and no flow (surface-water and groundwater divides). No-flow boundaries form the external boundaries of model layer 4. External boundary conditions for the lower six layers include constant heads (Grand River in the south) and no-flow boundaries along the boundaries of the outermost active cells. The upper boundary of the model is the water table receiving recharge from precipitation and the lower boundary is a no-flow boundary. A detailed description of the boundary conditions can be found in Luukkonen (2009).

Water Levels and Streamflow

Water-level and streamflow data were used to determine whether simulation results with the updated pumping rates represented the groundwater-flow system. Water-level data available from well logs in the Michigan Department of Environmental Quality (MDEQ) Wellogic database (https://secure1.state.mi.us/wellogic/Login.aspx?ReturnUrl=%2fwellogic%2fdefault.aspx) from 242 wells installed in 2017 (of these, 214 were completed in the Saginaw aquifer and 28 were completed in the glacial aquifer) were used for calibration of the model. Within the Tri-County region, water-level measurements also were available from five active USGS observation wells completed in the Saginaw aquifer (table 1, fig. 1). Streamflow data used for checking calibration of the model consisted of base flow estimates determined for six active USGS streamgaging stations using the USGS-GW Toolbox program version 1.3.1 (https://water.usgs.gov/ogw/gwtoolbox/) (table 1, fig. 1). Three methods were used for determining the base flow component of streamflow using available flows during 2012–16 for comparison to simulated flows. The use of multiple methods is warranted because all available methods have elements of subjectivity and are not based on mathematical solutions to groundwater- or overland-flow equations (Barlow and others, 2014). The three methods applied in this study include PART (Rutledge, 1998), the base flow index (BFI-standard) (Wahl and Wahl, 1995) using a partition length of 5 days, and HYSEP (fixed interval) (Sloto and Crouse, 1996). Water-level and streamflow data for USGS observation wells and streamgaging stations are available from the USGS National Water Information System (https://dx.doi.org/10.5066/F7P55KJN).

Steady-State Model Fit

Model fit is evaluated by comparing the magnitude and distribution of the differences (residuals) between observed and simulated water levels and flows. Simulated water levels and flows for the Tri-County regional model using 2017 pumping conditions were compared to water-level observations for 2017 from well driller logs, average water levels for 2012–17 from active USGS observation wells, and estimated base flow derived using 2012–16 streamflow observations. The relation between observed and simulated groundwater levels and the relation between estimated and simulated streamflow are shown in figures 3 and 4, respectively. The spatial distribution of water-level residuals is shown in figure 5. The mean absolute error for water level residuals is 14.4 ft, whereas the mean error is -10.4 ft. Because water-level observation locations differed from those used for earlier hydrologic conditions, these errors were not compared to previous simulations. For the flow observations, six USGS streamgaging stations were used in the model simulations representing 2011–12 and 2017 pumping conditions. For these stations, the average ratio between observed and simulated flows was 1.47 under 2011–12 conditions and 1.73 under 2017 conditions. The differences between observed and simulated water levels and flows are similar to the accuracy of the 2009 model; therefore, recalibration of the model is not needed before estimating contributing areas.

In the steady-state model, the amount of water recharging the groundwater system is assumed to equal the amount of water discharging from the groundwater system; changes in storage do not occur. Water may enter the system as recharge from precipitation, seepage from lakes and rivers, and as inflow from outside the study area. Water may leave the groundwater-flow system as seepage into lakes and rivers, outflow from the study area, and as withdrawals by wells. The model budget components for the current (2017) model and budget components for simulations of 2011–12 and 2006–7 pumping conditions are listed in table 2.

Delineation of Contributing Areas

The particle-tracking program MODPATH (version 4, release 3) (Pollock, 1989) can be combined with MODFLOW–2000-calculated flow in each cell to determine the areas of the water table, projected up to the land surface, where water that is discharged by a well enters the groundwater-flow system. The area contributing recharge to a pumping well is defined as the surface area of the three-dimensional boundary of the groundwater-flow system defining the

Table 1. U.S. Geological Survey streamgaging stations and observation wells in the Tri-County region, Michigan.

[USGS, U.S. Geological Survey; mi^2, square miles; Water-level and streamflow data are available in the USGS National Water Information System database (https://dx.doi.org/10.5066/F7P55KJN)]

Streamgaging stations			
USGS gaging-station number	**Station name**	**Drainage area (mi^2)**	**Period of record**
04111379	Red Cedar River near Williamston, Michigan	163	1975–89, 2001–11, 2013–18
04112000	Sloan Creek near Williamston, Michigan	9.34	1954–2018
04112500	Red Cedar River at East Lansing, Michigan	355	1903, 1931–2018
04113000	Grand River at Lansing, Michigan	1,230	1901–6, 1934–2018
04114000	Grand River at Portland, Michigan	1,385	1952–82, 1988–2018
04114498	Looking Glass River near Eagle, Michigan	280	1944–96, 2001–18
Observation wells			
USGS well number	**Well name**	**Aquifer**	**Period of observations**
423127084321901	04N 02W 16DAAA 01 Ingham Co (Cedar)	Saginaw	1945–54, 1960–2018
424502084331301	04N 02W 09BDAD 01 Ingham Co (Seymour)	Saginaw	1961–80, 1986–2018
424424084340301	04N 02W 17ABAA 01 Ingham Co (Logan)	Saginaw	1960–2018
424235084311201	04N 02W 26BBDB 01 Ingham Co (Fenner Arboretum)	Saginaw	1968–82, 1991–2018
423805084311801	03N 02W 23BCBD 01 Ingham Co (Holt)	Saginaw	1983–2018

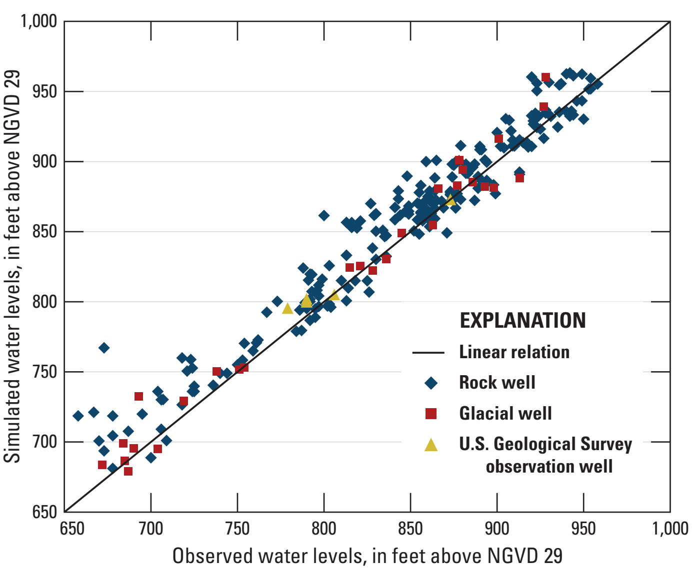

Figure 3. Relation between observed and simulated water levels in the glacial and Saginaw aquifers, Tri-County regional model, Michigan.

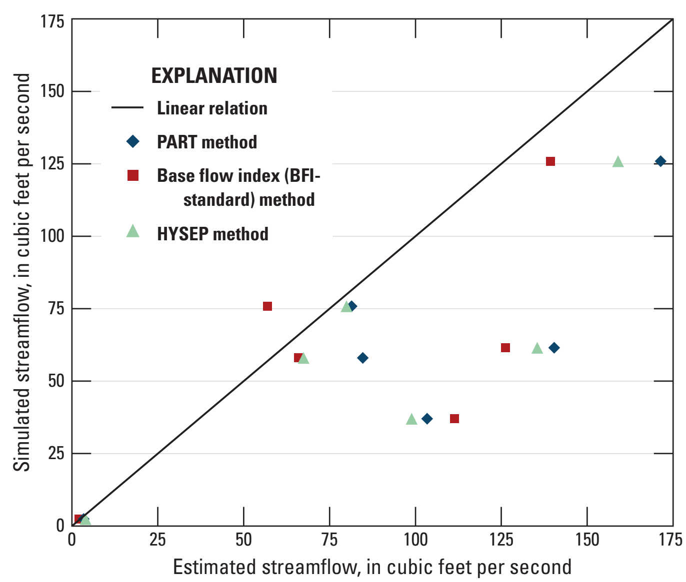

Figure 4. Relation between estimated and simulated streamflow, Tri-County regional model, Michigan.

location where water entering the groundwater-flow system 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 groundwater flows to a pumping well from the area contributing recharge (Morrissey, 1989). A wellhead-contributing area for each pumping well is defined here as the combination of areal extent of the areas contributing recharge and of the zones of contribution projected up to the land surface. Identification of these contributing areas are needed for local wellhead protection plans to guide protection efforts for areas that contribute water to municipal water supply wells. The locations and shapes of these contributing areas are influenced by the hydrologic stresses on the flow system and, therefore, need to be reevaluated as pumping rates and locations change. The flow paths to each well used for

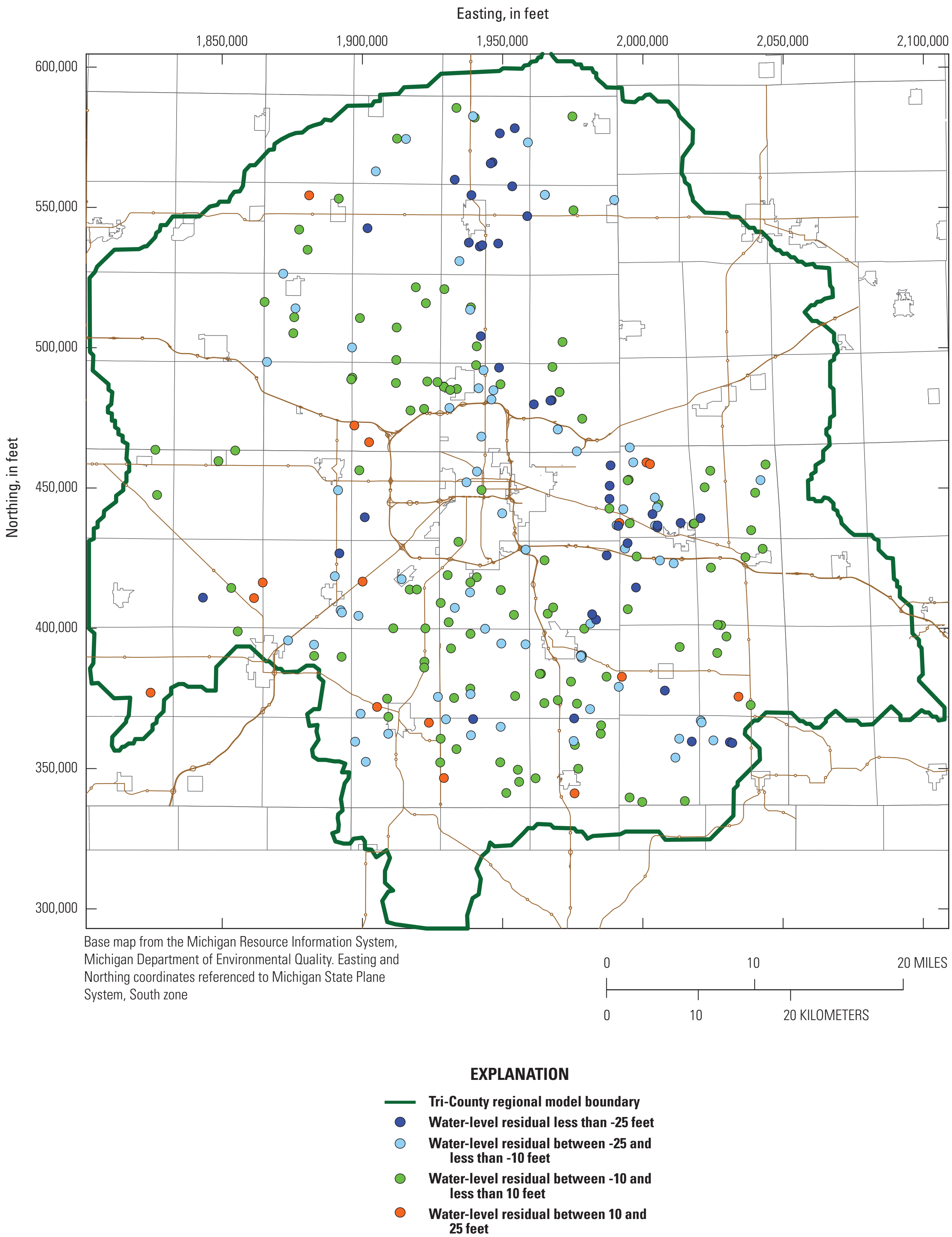

Figure 5. Spatial distribution of water-level residuals for head observations under 2017 pumping conditions in the Tri-County regional model, Michigan.

Table 2. Summary of model budget components for 2006–7, 2011–12, and 2017 pumping conditions, Tri-County regional model, Michigan.

[Volume in million gallons; constant head component represents boundary flow; multi-node well and well components represent pumping]

Budget component	Cumulative simulated volume		
	2006–7 pumping conditions	2011–12 pumping conditions	2017 pumping conditions
Into the model			
Constant head	0.0	0.0	0.0
River	80.2	80.0	78.1
Recharge	689.8	689.8	689.8
Multi-node well	1.5	1.6	0.5
Out of the model			
Constant head	47.1	47.1	47.1
Multi-node well and well	46.8	47.7	40.5
River	677.8	676.8	680.9

Table 3. Summary of wellhead protection area delineations for Lansing and East Lansing/Meridian Township areas, Tri-County region, Michigan.

[NA, not available]

Year	Municipality	10-year contributing areas (square miles)	40-year contributing areas (square miles)
2004	Lansing	16.1	40.4
	East Lansing/Meridian Township	4.8	11.7
2006–7	Lansing	19.2	38.0
	East Lansing/Meridian Township	5.1	11.8
2011–12	Lansing	19.4	38.9
	East Lansing/Meridian Township	NA	NA
2017	Lansing	20.1	39.0
	East Lansing/Meridian Township	5.3	12.0

the delineation of contributing areas also depend on the hydrogeologic framework and hydraulic characteristics of the flow system and the system boundary conditions. Boundary conditions include the actual physical extent of the modeled area, as well as recharge and discharge locations where water enters or leaves the groundwater-flow system. An estimated effective porosity of 15 percent was previously used for particle-tracking simulations (Holtschlag and others, 1996) and, in the absence of any additional information, was also used in the current (2017) study for all model layers.

A total of 34,200 hypothetical particles were placed on the sides of the cells in the Saginaw aquifer layers containing selected Lansing and East Lansing/Meridian Township-area production wells. Traveltimes from the center of each cell where a well is simulated to the sides of the cell are neglected because these times are assumed to be very short. The particles were tracked backward using the steady-state model along flow paths through the groundwater-flow field until the particles reached a top cell face in the upper model layer or until a specified amount of time elapsed. The position of the particle at the end of the simulation represents the location at the water table where the particle enters the groundwater-flow system or the location where water would flow to the well in the specified amount of time. Groundwater withdrawals of 40 Mgal/d representing 2017 conditions were specified for this simulation. Areas contributing recharge as well as zones of contribution were determined for 10- and 40-years using the Tri-County regional model to represent wellhead protection areas. The areal extent of the 10-year time-of-travel wellhead-contributing areas for selected wells encompasses about 25 mi^2 (fig. 6), and the areal extent of the 40-year time-of-travel areas encompasses about 51 mi^2 (fig. 7). Contributing area sizes determined during previous wellhead protection area delineations are similar (table 3).

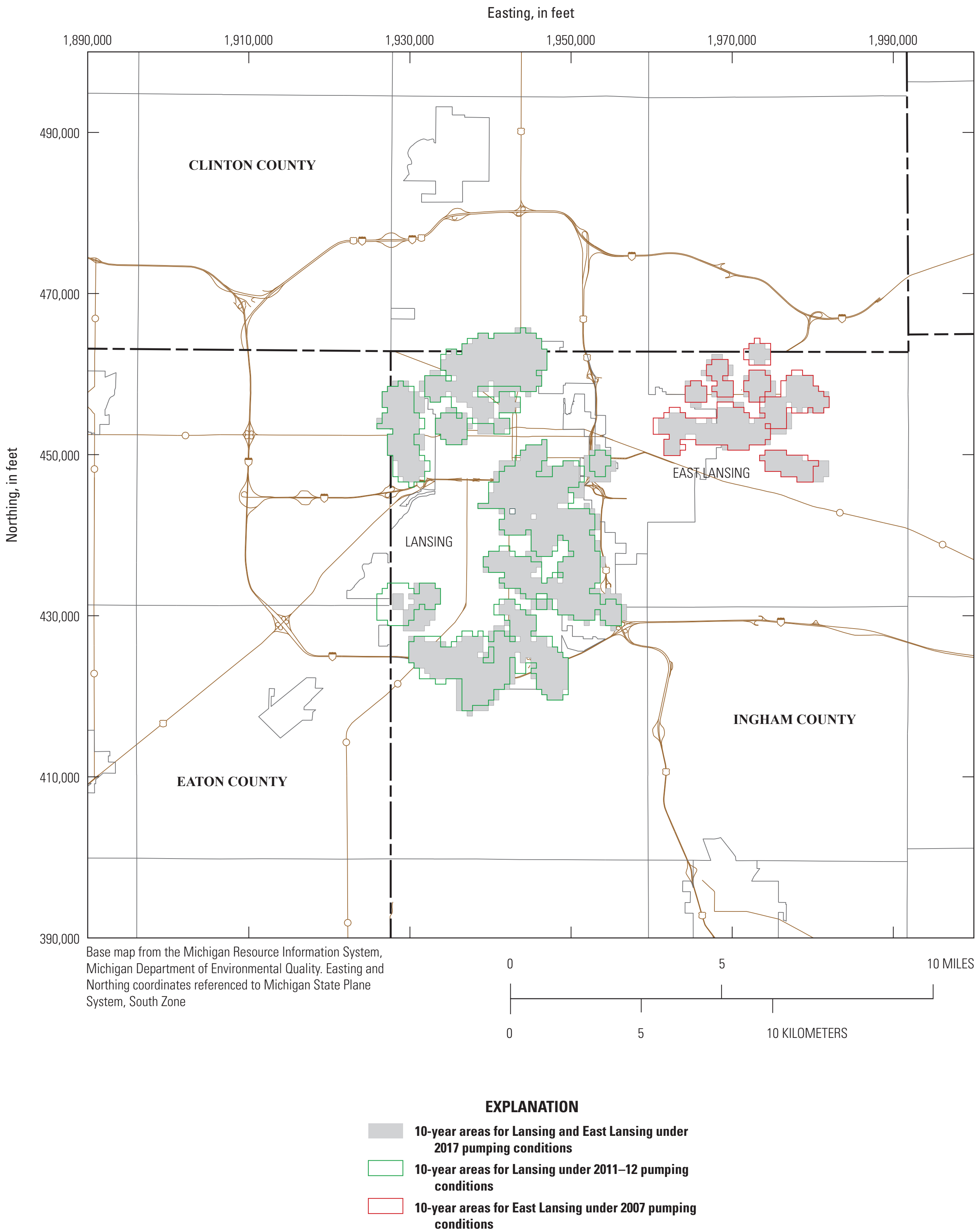

Figure 6. Simulated 10-year time-of-travel contributing areas for selected production wells in the Tri-County region, Michigan.

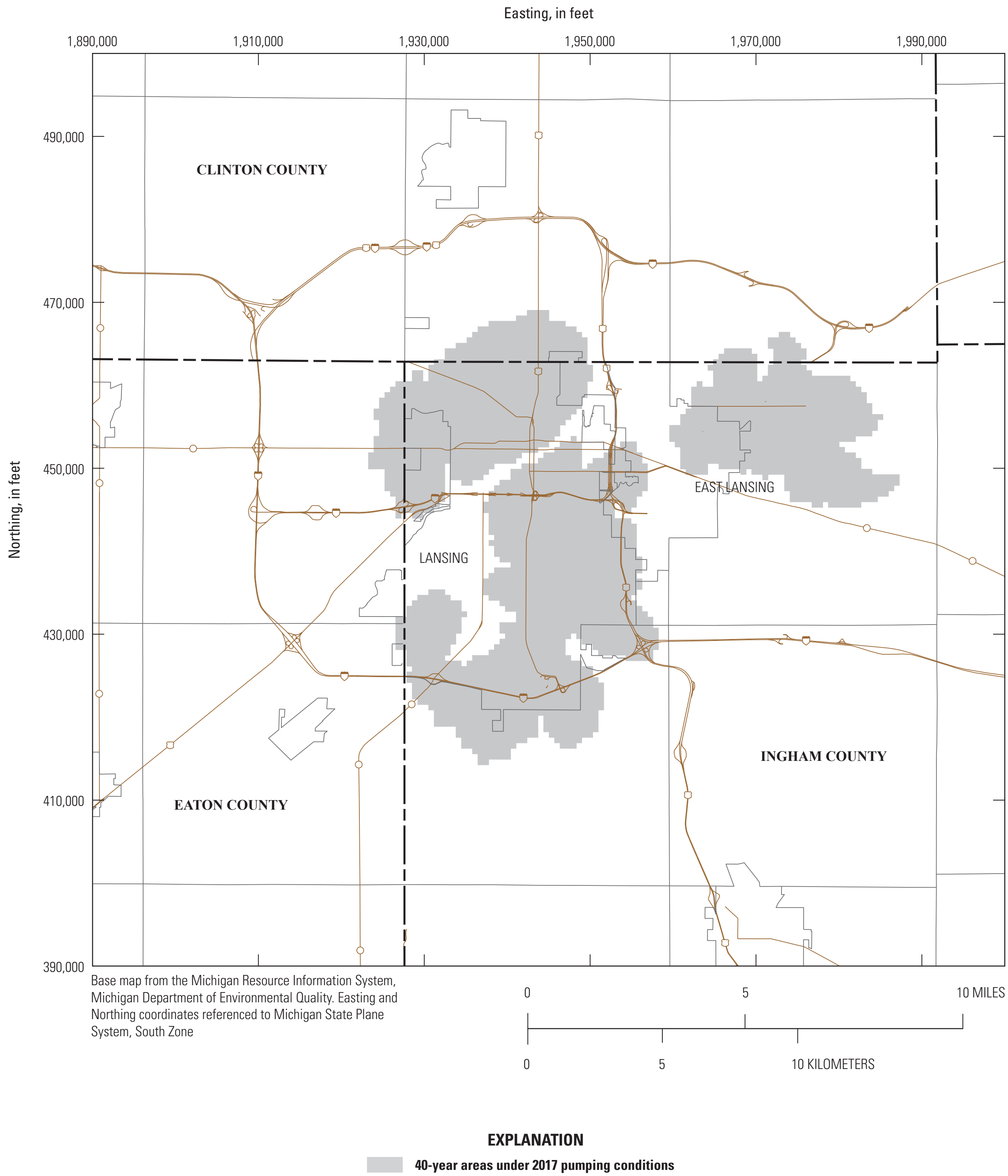

Figure 7. Simulated 40-year time-of-travel contributing areas for selected production wells in the Tri-County region, Michigan.

Model Assumptions and Limitations

The groundwater-flow model was developed to simulate the regional groundwater-flow system in the Tri-County region. Hydraulic properties represented in each layer were assumed to be horizontally isotropic; that is, within a cell, hydraulic properties are the same in the north-south direction as in the east-west direction. Hydraulic properties do vary from location to location; however, each grid cell represents the average hydraulic properties in the volume of aquifer represented by the cell. Vertical variations in aquifer properties within layers and any variations in head or flow within each layer are not simulated in the model. Local flows over distances smaller than the dimensions of the grid cell also cannot be accurately simulated. Additional geologic and hydrologic data, as well as finer discretization of the model, would be needed to simulate flow systems in smaller areas. The accuracy of layer surfaces and hydraulic conductivity estimates are limited by the available data at well and boring locations. Additional control and accuracy could be achieved by inclusion of more data points.

In steady-state model simulations, all stresses to the system, including well withdrawals and recharge rates, are assumed to remain constant throughout the simulation. No net gain or loss of flow is simulated in the system; that is, in the model budget, water entering the model approximately equals water leaving the model. No changes in groundwater storage result.

Small withdrawals from domestic wells were not included because of the difficulty in obtaining reliable data and the limitations in representing small-scale flow systems (systems considerably smaller than simulated as part of this study). However, domestic groundwater withdrawals probably are small at the scale of the model.

The base of the model is assumed to be impermeable. Model results could be misrepresenting flows and contributing area extents in areas where this assumption is not valid. External boundary conditions, which are based on natural hydrologic conditions and are distant from the Tri-County region well fields, are assumed to have minimal effect on water levels and flow in the interior of the model. The model may not accurately represent the groundwater-flow system for any predictive simulations involving groundwater withdrawals near the model boundaries.

The location and size of the areas contributing recharge to wells are affected by the hydrogeologic characteristics and boundary conditions of the groundwater-flow system, as well as the location, depth, and discharge rate of each simulated well. Thus, the simulated areal extent of the areas contributing recharge and zones of contribution is dependent on the estimated values for the hydraulic characteristics, such as transmissivity and riverbed conductance, and on the pumping rates of the individual wells. With annual or seasonal variations in pumping rates or pumping locations and depths, 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 the way the groundwater-flow system is 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 the accuracy of the cell flow velocities in approximating the local groundwater-flow velocities. Actual effective porosity may differ from location to location and from layer to layer. Particle tracking simulates the advective movement of groundwater, so the effects of diffusion, dispersion, and chemical reactions are not considered. Therefore, particle tracking is not intended as a substitute for simulating the transport of dissolved chemicals in the groundwater-flow system. Under steady-state conditions, the water discharging from a pumped well is a blend of water of different ages or traveltimes. In each specified time-of-travel simulation, the model pumping rates and pumping locations remain constant indefinitely. Also, the water withdrawn by each simulated well may represent water that has entered as recharge or could include water that was already in the zone of contribution when the well began pumping.

Summary and Conclusions

A groundwater-flow model that was constructed in 2009 was updated to reflect recent (2017) pumping conditions for selected Lansing and East Lansing/Meridian Township production wells in the Tri-County region, Michigan. The Saginaw aquifer, which is in the Grand River and Saginaw Formations of Pennsylvanian age, is the primary source of groundwater for Tri-County residents. As part of local wellhead protection area programs, areas contributing water to local production wells need to be periodically updated because groundwater-flow paths depend in part on the stresses to the groundwater-flow system. Different pumping rates or pumping locations will change the groundwater-flow patterns in the modeled area and result in different zones of contribution and areas contributing recharge to the pumping wells; therefore, for this current (2017) study, withdrawals from selected production wells were updated to reflect 2017 pumping conditions, and model calibration under the new pumping conditions was checked to verify that model fit was similar to the calibration of the 2009 model.

Wellhead-contributing areas (defined for this study as the combination of the areal extent of the areas contributing recharge and of the zones of contribution projected up to the land surface) were delineated for selected Tri-County-region production wells by using particle-tracking analysis. Groundwater withdrawals for 2017 totaled approximately 40 million gallons per day. Results of flow simulations indicate that 10-year time-of-travel areas cover approximately 25 square miles, and 40-year time-of-travel areas cover approximately 51 square miles.

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