Prepared in cooperation with the Minnesota Department of Health

Evaluation of Methods for Delineating Zones of Transport for Production Wells in Karst and Fractured-Rock Aquifers of Minnesota

Scientific Investigations Report 2010–5005

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

Evaluation of Methods for Delineating Zones of Transport for Production Wells in Karst and Fractured-Rock Aquifers of Minnesota

By Perry M. Jones

Prepared in cooperation with the Minnesota Department of Health

Scientific Investigations Report 2010–5005

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

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2010

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit http://www.usgs.gov or call 1-888-ASK-USGS

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod

To order this and other USGS information products, visit http://store.usgs.gov

Suggested citation:
Jones, Perry M., 2010, Evaluation of methods for delineating zones of transport for production wells in karst and fractured-rock aquifers of Minnesota: U.S. Geological Survey Scientific Investigations Report 2010–5005, 32 p.

Contents

Figures

Tables

Conversion Factors

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

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.

Evaluation of Methods for Delineating Zones of Transport for Production Wells in Karst and Fractured-Rock Aquifers of Minnesota

By Perry M. Jones

Abstract

Assessment of groundwater-flow conditions in the vicinity of production wells in karst and fractured-rock settings commonly is difficult due in part to the lack of detailed hydrogeologic information and the resources needed to collect it. To address this concern and to better understand the hydrogeology and aquifer properties of karst and fractured-rock aquifers in Minnesota, the U.S. Geological Survey, in cooperation with the Minnesota Department of Health, conducted a study to evaluate methods for delineating zones of transport for 24 production wells in karst and fractured-rock aquifers in Minnesota. Two empirical methods for delineating zones of transport around wells were applied to the 24 production wells that extract groundwater from karst and fractured-rock aquifers in nine Minnesota communities. These methods were the truncated-parabola and modified-ellipse methods, and both methods assume porous-media flow conditions. The 24 wells extracted water from a karst aquifer (Prairie du Chien-Jordan aquifer), porous aquifers interspersed with solution-enhanced fractures (Jordan and Hinckley aquifers), or fractured-bedrock aquifers (Biwabik Iron-Formation and Sioux Quartzite aquifers). Zones of transport delineated using these two empirical methods were compared with zones of transport previously delineated by Minnesota Department of Health hydrologists for the wells using the calculated-fixed-radius method and groundwater-flow models.

Large differences were seen in the size and shapes of most zones of transport delineated using the truncated-parabola and modified-ellipse methods compared with the zones of transport delineated by the Minnesota Department of Health. In general, the zones of transport delineated using the truncated-parabola and modified-ellipse methods were smaller in area than those delineated by the Minnesota Department of Health and included only small parts of the Minnesota Department of Health zones of transport. About two-thirds (67 percent) of the individual or composite truncated parabolas and modified ellipses covered less than 50 percent of the area included in zones of transport delineated by the Minnesota Department of Health. The shapes of some of the truncated parabola and modified ellipses did not closely match the zones of transport delineated by the Minnesota Department of Health using the calculated-fixed-radius method and groundwater-flow models. Differences between the zones of transport delineated by the truncated-parabola and modified-ellipse methods and those delineated by the Minnesota Department of Health can be explained by variations inherent to the methods and by the amount of complexity taken into account by different groundwater-flow models. Additional field hydrogeologic studies would be needed at specific sites to support the use of these zone-of-transport delineation methods. Application of the truncated-parabola and modified-ellipse methods to sites for which existing hydrogeologic information is limited can produce questionable results in karst and fractured-rock settings, particularly in areas where many high-capacity wells or active mining operations are nearby.

Introduction

About 78 percent of Minnesotans use groundwater extracted from bedrock and glacial aquifers for their drinking water (Kenny and others, 2009). Approximately one-half of the 970 community water supply systems in Minnesota are potentially vulnerable to contamination mainly due to local hydrogeology and type of well construction (Minnesota Department of Health, 2009a).

Communities in northern, southeastern, and southwestern Minnesota use production wells to extract water from bedrock aquifers in which groundwater flows mainly through karst features (solution openings and solution channels or conduits) and fractures (fig. 1). Source waters for these wells are particularly vulnerable to contamination due to short residence times in the karst features and fracture zones. Groundwater flow to wells in these aquifers commonly is complex, occurring as regional flow along bedding planes and large fracture networks, as localized flow in discrete fractures near the wells, or as a combination of both. Temporal flow conditions in karst and fractured-rock aquifers commonly are difficult to characterize or predict.

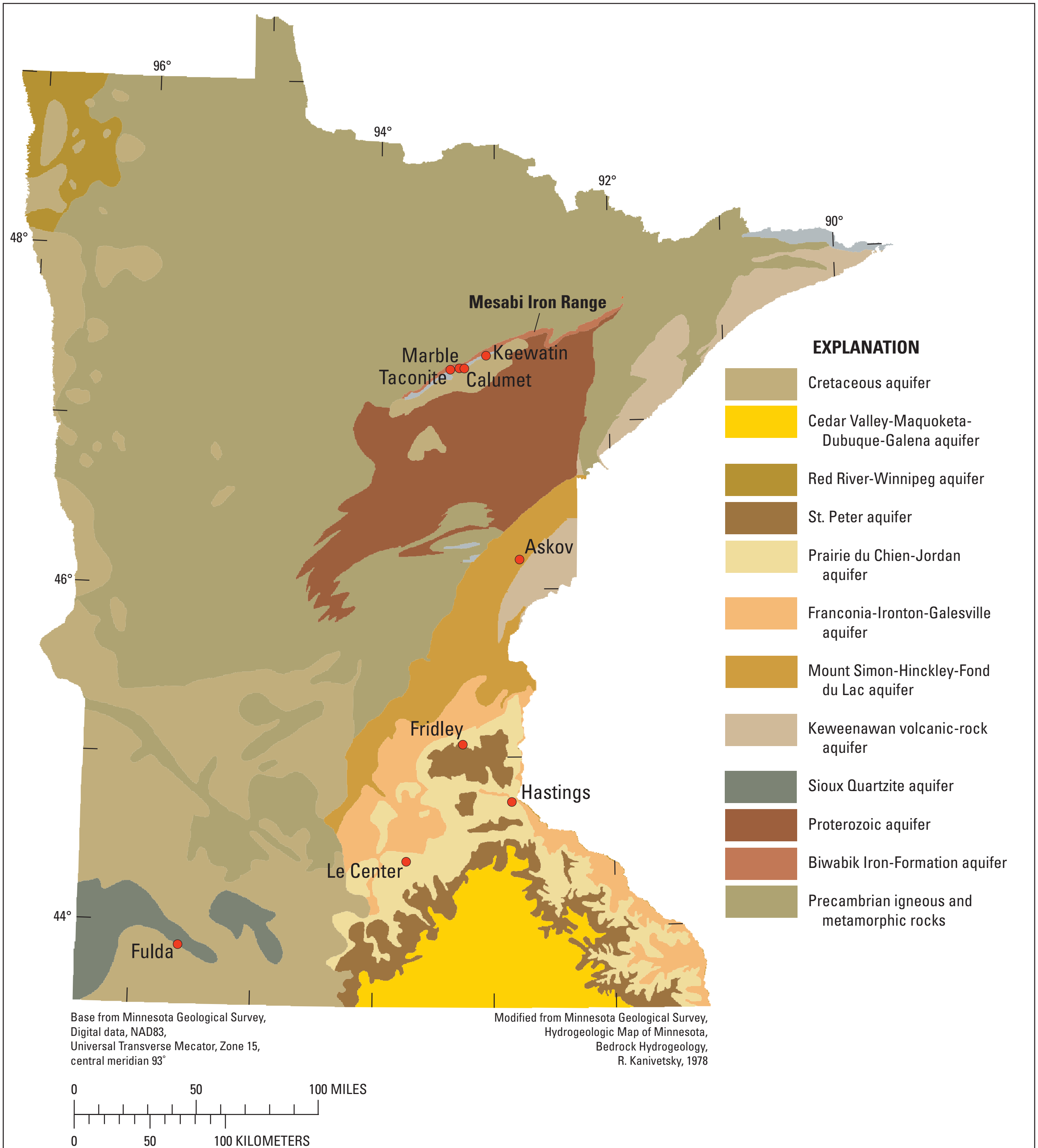

Figure 1. Bedrock hydrogeology and communities for which zone-of-transport analyses were applied to fractured or karst bedrock aquifers, Minnesota.

Communities in Minnesota and throughout the United States are being required to develop and implement wellhead protection plans that safeguard their water sources from contamination (Minnesota Department of Health, 2005a). The Minnesota Department of Health (MDH) is assisting Minnesota communities in delineating management (or protection) areas around production wells to protect groundwater sources for these supplies. Hydrologists from MDH are developing tools and techniques for determining zones of transport around production wells (Minnesota Department of Health, 2005b). A zone of transport is the volume of an aquifer supplying water to a discharging well within a specified period of time. Any sources of contamination within the zone of transport may eventually be captured by the production well. Thus, it is important for water-resources managers to minimize potential sources of contamination within the zone of transport.

Several approaches have been applied to delineate zones of transport around wells obtaining groundwater from karst and fractured-rock aquifers to account for flow through solution channels or fractures. Expensive and more detailed approaches to zone-of-transport delineation involve use of one or both of two approaches: (1) borehole geophysical and hydrologic techniques, and hydrogeologic mapping techniques to identify the physical and hydraulic properties of solution channels and fractures near production wells; and (2) groundwater-flow models to delineate zones of transport for the wells (Bair and Roadcap, 1992; Podgorney and Ritzi, 1997; Knochenmus and Robinson, 1996; Barton and others, 1999, 2003). The application of borehole geophysics and groundwater-flow models is too expensive and impractical for many Minnesota communities using groundwater from karst and fractured-rock aquifers.

Communities with limited resources to expend on hydrogeologic studies commonly chose between either (1) making broad assumptions in the application of fracture-flow/dual-permeability equations and groundwater-flow models that cannot be validated by use of existing data or (2) applying hydrogeologic mapping techniques and porous media equations that use data that are more readily available. Typically, small communities use existing hydrogeologic data and empirical methods to delineate zones of transport (Delin and Almendinger, 1991; Bradbury and others, 1991). However, the accuracy of zones of transport delineated by using simple empirical methods may be questionable for complex karst and fractured-rock settings. The main assumption involved in using these less-expensive methods is that non-Darcian flow (that is conduit or fracture flow) conditions occur in only a small portion of the zone of transport (Long and others, 1982). Demonstration of this type of flow commonly requires conducting aquifer, water-quality, and other hydrogeologic testing.

The lack of effective zone-of-transport delineation methods for wells completed in karst or fractured-rock aquifers may have a substantial effect on the ability of wellhead protection plans to effectively protect the water supplies. The MDH cannot approve wellhead protection area (WHPA) delineations that do not adequately address the delineation criteria specified under current State regulations (Minnesota Department of Health, 2005a). The MDH uses empirical methods, analytical element methods, numerical modeling methods, and dual-porosity methods, incorporating karst and fracture-rock flow features, to delineate zones of transport needed to determine wellhead protection areas around wells in karst and fractured-rock settings. Many of these methods assume Darcian flow conditions. Simple empirical methods proposed for delineating wellhead protection areas in karst and fractured-rock aquifers may not be technically defensible under the criteria if non-Darcian flow conditions govern groundwater flow in a large portion of the zone of transport. In addition, few cost-effective tools are available to assist communities in delineating WHPAs for wells completed in karst or fractured-rock aquifers. To address this concern and to better understand the hydrogeology and aquifer properties of karst and fractured-rock aquifers in Minnesota, the U.S. Geological Survey, in cooperation with the Minnesota Department of Health, conducted a study to apply and evaluate methods for delineating zones of transport for 24 production wells in karst and fractured-rock aquifers in Minnesota.

Purpose and Scope

This report presents the results from the application of two empirical methods for delineating zones of transport around 24 production wells in karst and fractured-rock aquifers in the vicinity of nine communities in Minnesota (fig. 1). The two empirical methods are the truncated-parabola and modified-ellipse methods, and both methods assume porous-media flow conditions. Existing hydrologic data from MDH records and reports and other scientific literature were used to delineate the zones of transport. The MDH delineation methods and the empirical delineation methods are described in some detail in the “Methods of Investigation” section of this report. Zones of transport determined from application of these methods were compared with zones of transport that were from application of the calculated-fixed-radius method and groundwater-flow models by MDH hydrologists for the same 24 wells.

Acknowledgments

The author thanks the staff of the Minnesota Department of Health Drinking Water Protection Program, in particular Bruce Olsen, Sheila Grow, James Walsh, Justin Blum, Stephen Robertson, and Gail Haglund for providing information on the MDH delineated zones of transport and assistance in the collection of hydrologic data used in the empirical methods zone-of-transport analyses. The author also thanks Alan Epp (MDH) for his development of geographic information system (GIS) extensions for the truncated-parabola method. The author thanks Robert Borgstede and Chris Sanocki (USGS) for their work on the figures for this report.

Methods of Investigation

Two empirical methods, the truncated-parabola and modified-ellipse methods, were applied in this study to delineate zones of transport for production wells for which MDH hydrologists had previously applied methods outlined in their guidance document for delineating wellhead protection zones in karst and fractured-rock aquifers in Minnesota (Minnesota Department of Health, 2005c). Zones of transport delineated by using the two empirical methods were compared with zones of transport delineated by MDH to identify and assess differences between the zones of transport using the different methodologies.

The study focused on determining zones of transport using existing data and methods that are practical for most Minnesota communities. Water suppliers and managers commonly do not have the resources to collect the extensive data needed to accurately characterize complex groundwater-flow conditions present in karst and fractured-rock settings. These two empirical methods can be applied to production wells by use of existing data obtained from aquifer tests, modeling studies, and regional hydrogeologic literature. When possible, hydraulic property data used by MDH in their zone-of-transport analyses were incorporated in the empirical methods.

Both empirical methods assume porous-media (Darcian) flow conditions in the aquifer being evaluated. The application of zone-of-transport delineation methods in karst and fractured-rock settings that are based on the assumptions of Darcian flow warrants scrutinization. The assumptions of Darcian flow include laminar flow, in which the Reynolds number is less than 1, as well as homogenous and constant hydrologic conditions, such as hydraulic conductivity, porosity, and uniform hydraulic gradients in an aquifer (Todd, 1980). In karst and fracture-rock settings, these assumptions generally are not valid. A single solution channel/fracture or a set of channels/fractures can be the sole contributor of water to a well. Under these conditions, the hydraulic and physical properties of the channel or fracture will control the orientation, dimensions, and shape of the zone of transport.

Minnesota Department of Health Zone-of-Transport Delineation Methods for Solution-Weathered and Fractured Bedrock Aquifers

Hydrologists from the MDH have developed a guidance document that establishes criteria for determining when secondary porosity conditions need to be considered and that also identifies techniques for delineating WHPAs in Minnesota where bedrock is solution-weathered or fractured (Minnesota Department of Health, 2005c). In general, these techniques are modifications of techniques applied in porous media. The techniques include the calculated-fixed-radius method that uses several types of upgradient extensions and extensions along fracture orientation, analytical element methods, numerical modeling methods, and dual-porosity methods (Minnesota Department of Health, 2005c). These techniques can be applied to (1) wells open to a fractured or solution-weathered bedrock aquifer, (2) both a porous media and a solution-weathered or fractured bedrock aquifer, (3) a porous media aquifer that is hydraulically connected to a solution-weathered or fractured bedrock aquifer, and (4) an aquifer that exhibits dual-porosity conditions (Minnesota Department of Health, 2005c). The calculated-fixed-radius method applies the following equation (U.S. Environmental Protection Agency, 1987) to determine the radius of a cylinder (R) that represents the volume of the aquifer needed to supply the well discharge (Q) (Minnesota Department of Health, 2005c):

$$R = (Q/nL\pi)^{0.5}$$

where

R is the radius of the cylinder [length (L)],
Q is the well discharge [L^3] = (well pumping rate [L^3/time (t)])(pumping time period [t]),
n is the effective porosity [dimensionless],
L is the thickness of the saturated portion of the aquifer [L], and
π is 3.1416 [dimensionless].

The MDH has determined that either a 10-year or 20-year zone of transport be calculated for production wells by using either 10 or 20 years for the pumping time period, respectively, depending on the local hydraulic gradient and the ratio of well discharge to the absolute groundwater flow through an aquifer (Minnesota Department of Health, 2005c). A 10-year zone of transport is used for wells that are not part of the supply system but that are within the supply's zone of transport. Methods for overlapping zones of transport also were established in the MDH guidance document (Minnesota Department of Health, 2005c).

Empirical Zone-of-Transport Delineation Methods

The truncated-parabola and modified-ellipse methods are calculated-variable-shape methods that delineate zones of transport on the basis of superposition of the effects of uniform flow gradients on the effects of the pumping well (U.S. Environmental Protection Agency, 1987, 1993; Delin and Almendinger, 1991). Both methods use hydrogeologic properties for which values often are available to water suppliers and managers or that can be estimated from literature values. More detailed descriptions of the two methods are provided in Delin and Almendinger (1991) and U.S. Environmental Protection Agency (1993).

Truncated-Parabola Method

The truncated-parabola method involves a two-step process: (1) calculation of a zone of contribution (fig. 2*A*) based on simple assumptions of steady-state flow conditions in a

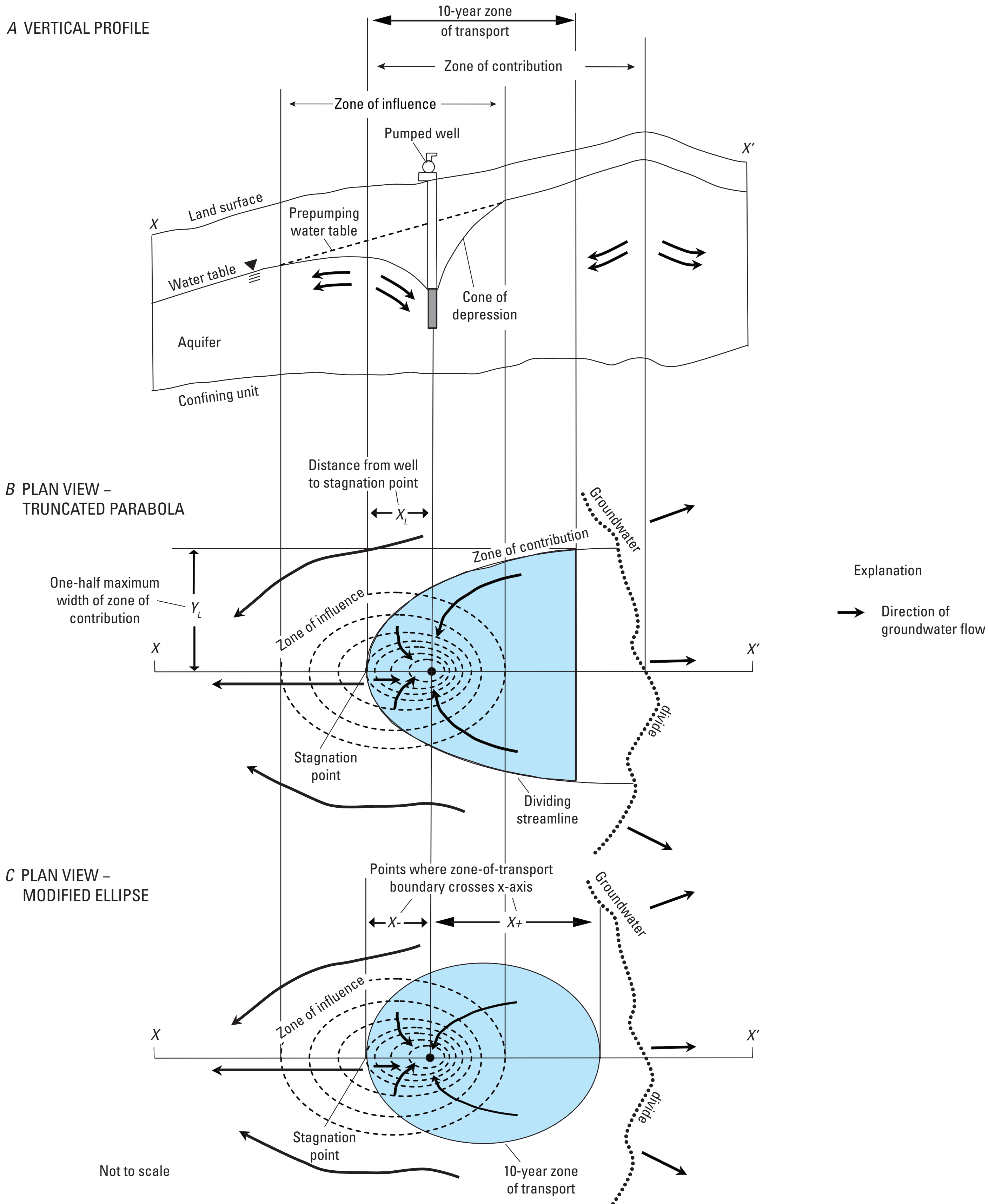

Figure 2. Schematic diagrams showing *A*, areas of potential recharge (zone of contribution) to a well and examples of *B*, the truncated-parabola and *C*, modified-elipse methods (modified from the U.S. Environmental Protection Agency, 1987, figure 2-7; and Delin and Almendinger, 1991, figure 1).

confined or unconfined aquifer and (2) application of travel-time of water particles to the calculation of the particle travel distance, which is used to define the upgradient boundary of the zone of transport (Delin and Almendinger, 1991). The zone of contribution is determined by using a set of standard groundwater-flow equations (Todd, 1980, p. 121) to establish the locations of a stagnation point and asymptotes ($\pm Y_L$) of a parabola along a coordinate system (fig. 2). A stagnation point is a point in a groundwater-flow field at which groundwater is not moving in any direction (Fetter, 2001). The coordinate system for the zone of contribution is oriented so that the x-axis is parallel to the uniform groundwater-flow direction, and the well is placed at the origin of the coordinate system (Delin and Almendinger, 1991). The stagnation point is located X_L distance downgradient from the well, and the asymptotes are located $\pm Y_L$ distance along dividing streamlines that form a parabola (fig. 2*B*). These dividing streamlines meet at the stagnation point and become parallel to the x-axis upgradient from the well as they approach the asymptotes. The stagnation point (X_L) and the asymptotes ($\pm Y_L$) locations are computed using the following equations (U.S. Environmental Protection Agency, 1987):

$$X_L = w/(2\pi), \text{ and}$$
$$Y_L = w/2$$

where

$w = Q/(-Kbi) = Q/Q_x$ is the limiting width of aquifer from which the well captures flow [L],
Q is the well discharge [L^3/t],
K is the horizontal hydraulic conductivity [L/t],
b is the aquifer thickness [L],
i is the hydraulic gradient of uniform field [dimensionless], and
$Q_x = -Kbi$ is the “strength” of the uniform flow field [L^2/t].

The following equation (U.S. Environmental Protection Agency, 1987) is used to produce the dividing streamlines:

$$X = y/[\tan(y/X_L)].$$

Truncation of the parabola assumes that (1) the distance that a particle of water travels over a given period of time is primarily a function of the hydraulic gradient, (2) the hydraulic effects of pumping on this distance are negligible, and (3) the hydraulic gradient is constant near the well (Delin and Almendinger, 1991). When these assumptions are applied, the following equation (U.S. Environmental Protection Agency, 1987) can be used to determine the distance traveled for a water particle over a specified time period:

$$X = -t_t Ki/n$$

where

X is the distance traveled for a water particle [L],
t_t is the time of travel [t],
K is the horizontal hydraulic conductivity [L/t],
i is the hydraulic gradient of uniform field [dimensionless], and
n is the porosity [dimensionless].

The distance traveled for a water particle for the specified time of travel is measured upgradient from the well along the x-axis of the coordinate system. The parabola is truncated at this distance. For this study, both 10 and 20 years were used for time of travel.

The well discharge rates and hydraulic properties used to compute the zones of transport for the 24 production wells are listed in table 1. Well discharge rates were based on the maximum volume of water pumped annually during the previous 5 years from water-use records managed by the Minnesota Department of Natural Resources (Minnesota Department of Natural Resources, 2010). When possible, hydraulic properties used by the MDH for their zone-of-transport analyses were used in the empirical methods analyses. These values were obtained from aquifer and other types of pumping tests conducted on the wells, modeling studies, and existing literature. When values for hydraulic properties were not available from the MDH analyses, regional values for the aquifer from existing literature were used.

In this study, when wells were near one another and were extracting water from the same aquifer, the pumping rates from the wells were summed and used with the empirical methods to determine a single zone of transport for multiple wells. This was done for the production wells in Askov, Calumet, Fridley (only done for wells 6, 7, and 8), Fulda, Marble, and Taconite (table 1). This or a similar approach also was used by MDH for delineating zones of transport or the WHPAs for these groups of wells.

Modified-Ellipse Method

The modified-ellipse method is used to compute a zone-of-transport for water particles under the assumptions of steady-state flow conditions in a confined aquifer. In this study, this method was applied to confined and unconfined settings. Application of the method for unconfined conditions produces a computed zone of transport that is a conservative estimate for the actual zone of transport, provided that the hydraulic head at the well is substituted in the equations for the aquifer thickness (Delin and Almendinger, 1991).

This method uses a coordinate system that is similar to the system used in the truncated-parabola method; in both methods, the production well is positioned at the origin and the assumption of uniform flow is parallel to the x-axis (Delin and Almendinger, 1991). The method produces two streamlines that are collinear with the x-axis, so that one of the streamlines approaches the well directly upgradient, and the other starts at the stagnation point and approaches the well directly downgradient. The following equations (U.S. Environmental Protection Agency, 1987) are used to find the distances that two water particles travel along the two streamlines:

$$t_t = B(Axi - \ln(1 + Axi)),$$

where

$B = -n/(AKi^2)$ [t],
$A = Kb2\pi/Q$ [1/L],

Table 1. Hydraulic properties applied to the truncated-parabola and modified-ellipse methods to delineate zones of transport for production wells open to karst and fractured-rock aquifers, Minnesota.

[ft^3/d, cubic foot per day; ft/d, foot per day; ft, feet; MDH, Minnesota Department of Health]

Community	Well number	Well discharge rate (ft^3/d)	Horizontal hydraulic conductivity (ft/d)	Aquifer saturated thickness (ft)	Hydraulic gradient (dimensionless)	Porosity (dimensionless)
Askov	3 and 4	5,100	[1]30	[2]82	[3]0.004	[4]0.21
Calumet	2 and 3	5,600	[4]5.0	[5]200	[3].008	[5].01
Fridley	6, 7 and 8	170,000	[1]39	[1]230	[3].002	[1].15
Fridley	11	97,000	[1]39	[1]230	[3].002	[1].15
Fridley	12	100,000	[1]39	[1]230	[3].002	[1].15
Fulda	1 and 6	15,000	[6]1.0	[5]200	[7].006	[5].01
Hastings	3	68,000	[1]54	[1]100	[1].007	[5].2
Hastings	4	58,000	[1]54	[1]100	[1].007	[5].2
Hastings	5	84,000	[1]54	[1]100	[1].007	[5].2
Hastings	6	100,000	[1]54	[1]100	[1].007	[5].2
Hastings	7	110,000	[1]54	[1]100	[1].007	[5].2
Keewatin	1	11,000	[4]5.0	[5]150	[3].006	[5].1
Keewatin	2	6,000	[4]5.0	[5]120	[3].006	[5].1
Le Center	1 and 3	41,000	[1]77	[1]240	[3].002	[1].2
Marble	1 and 2	15,000	[5]5.0	[5]190	[5].008	[5].1
Taconite	1 and 2	6,300	[5]4.7	[5]94	[5].005	[5].01

[1]Mean value from groundwater-flow model used to delineate MDH zone of transport.

[2]Mean value for the two wells.

[3]Mean value in the vicinity of wells.

[4] Value from MDH zone-of-transport analysis for wells in Marble.

[5]Used in MDH zone-of-transport analysis.

[6]Regional mean value for the Sioux Quartzite.

[7]Mean value in the vicinity of the wells for glacial aquifers.

x = distance traveled for a water particle [L],
n is the porosity [dimensionless],
t_t is the time of travel [t],
K is the horizontal hydraulic conductivity [L/t],
i is the hydraulic gradient of uniform flow [dimensionless],
b is the aquifer thickness [L], and
Q is the well discharge [L^3/t].

For each traveltime, the starting positions (X+ and X-) are the locations at which the ellipse crosses the x-axis (fig. 2*C*). Assuming that groundwater flow is horizontal and the aquifer thickness is constant, the total volume of the aquifer providing water to the well can be represented by its area in the x-y plane. When a uniform-flow field is present, the shape of this area approximates an ellipse, and its boundary is determined from its area and its major axis. The area is determined from the following equation (Delin and Almendinger, 1991):

$$a = (Qt_t)/(bn)$$

where
a = area of the aquifer providing water to well [L^2],
Q is the well discharge [L^3/t],
t_t is the travel time [t],
b is the aquifer thickness [L], and
n is the porosity [dimensionless].

The major axis is simply the distance between X+ and X- (fig. 2*C*). As the uniform flow gradient approaches zero, the modified ellipse approaches the shape of a circle, and when the uniform flow gradient approaches infinity, the ellipse approaches a shape similar to the truncated parabola (Delin and Almendinger, 1991).

As with the truncated-parabola method, the time of travel used in the modified-ellipse analyses was either 10 or 20 years for the production well applications. The hydraulic properties used to compute the zones of transport for the production wells are listed in table 1.

Differences Between Delineation Methods

Differences between the truncated-parabola and modified-ellipse zones of transport and the MDH zones of transport (calculated-fixed-radius method and groundwater-flow models) can be explained by variations inherent to the methods and by the amount of complexity taken into account for groundwater-flow models. The calculated-fixed-radius method combined with an upgradient extension used by MDH to delineate zones of transport for production wells in the communities of Askov, Calumet, Fulda, Marble, and Taconite is more conservative (larger zones of transport) than the truncated-parabola and modified-ellipse methods because the former method uses a total discharge (in cubic feet) over the specified time period (for this application 10 years) for the amount of flow through the well. In contrast, the truncated-parabola and modified-ellipse methods use only a well discharge rate (in cubic feet per day for this study) from which times of travel are determined. Groundwater-flow models used to delineate the MDH zones of transport for production wells in the communities of Fridley, Hastings, and Le Center accounted for the influence of groundwater extraction from nearby multiple large-capacity wells. Pumping from nearby wells can reduce the amount of groundwater available to the production wells, resulting in larger zones of transport.

Physical Description of Aquifers and Study Communities in Minnesota

The zones of transport for 24 production wells in nine communities located in northeastern, southwestern, or southeastern Minnesota were evaluated in this study (fig. 1). These wells extracted water from a karst aquifer (Prairie du Chien aquifer), porous aquifers interspersed with solution-enhanced fractures (Jordan and Hinckley aquifers), or fractured-bedrock aquifers (Biwabik Iron-Formation and Sioux Quartzite aquifers). Depending on location, these aquifers can be confined or unconfined.

Two of the 24 production wells evaluated in this study (Hastings wells 4 and 5) extract water from the Cambrian-age Jordan Sandstone and Cambrian-age St. Lawrence Formation, and one production well (Fridley well 11) extracts water from the Ordovician-age Prairie du Chien Group, the Jordan Sandstone, St. Lawrence Formation, and the Cambrian-age Franconia Sandstone (table 2). The St. Lawrence Formation was not included in zone-of-transport delineations done in this study because the MDH did not include the formation in groundwater-flow models used in delineating zones of transport around the Hastings wells 4 and 5 (Barr Engineering, 2003) and Fridley well 11 (Robertson, 2002). The Franconia Sandstone also was not included in zone-of-transport delineations done in this study because the top of the Franconia Sandstone was 490 feet below the land surface at Fridley well 11 and, at that depth, groundwater flow through the sandstone is considered mainly intergranular (Runkel and others, 2003).

Aquifers

The Prairie du Chien aquifer consists of the Ordovician-age Prairie du Chien Group. This group consists of two formations: the Shakopee Formation and the Oneota Dolomite. The overlying Shakopee Formation consists of thin to medium beds of dolostone, shale, and minor amounts of siliciclastic sandstone (table 2; Runkel and others, 2003). The Oneota Dolomite is primarily thick beds of very fine-grained dolostone, and fine and coarse clastic interbeds are common in the lower part of the formation (Runkel and others, 2003). Solution-enhanced cavities along bedding planes and fractures are pronounced in the Shakopee Formation and along its contact with the Oneota Dolomite (Runkel and others, 2003). Where karst features are present, the Prairie du Chien-Jordan aquifer is sensitive to contamination.

The Jordan aquifer consists of the Cambrian-age Jordan Sandstone, which is composed of coarse to fine clastic sediments, with fractures present at various depths below the land surface (Runkel and others, 2003). Hydraulic conductivity values for the Jordan aquifer generally are higher and more variable at shallow depths, indicating that groundwater flow through these fractures is more prevalent at shallow depths (Runkel and others, 2003).

The Hinkley aquifer contains the Proterozoic-age Hinckley Sandstone of the Keweenawan Superpgroup, which is fine- to medium-grained and has solution-enhanced fractures (Berg, 2004). The Hinckley Sandstone and overlying Cambrian-age Mount Simon Sandstone and Proterozoic-age Fond du Lac Formation commonly are difficult to distinguish from one another, and therefore they commonly are grouped as a single aquifer (Mount Simon-Hinckley-Fond du Lac aquifer). Shade and others (2001, 2002) mapped many sinkholes, springs, and caves associated with fractures and bedding planes in the Hinckley Sandstone in the Askov area of Pine County, Minn., where the sandstone is the upper bedrock unit.

The Proterozoic-age Biwabik Iron Formation of the Animikie Group consists of chert and iron minerals (Morey, 1972). The formation contains the main aquifer (Biwabik Iron Formation aquifer) used by water supplies along the Mesabi Iron Range (Kanivetsky, 1978). Water in the Biwabik Iron Formation aquifer flows mainly along a combination of fractures, joints, and solution-weathered channels in the cherty layers of the formation (Walsh, 2004). This aquifer is particularly susceptible to contamination along the Mesabi Iron Range at natural outcrops and mine pits or where it may be covered by only a few feet of overlying sediments.

The Sioux Quartzite aquifer consists of the Proterozoic-age Sioux Quartzite, which consists dominantly of red, tightly cemented quartzite, but it contains some intercalated beds of mudstone and conglomerate (Austin, 1972). The Sioux Quartzite is used by water supplies in southwestern Minnesota and southeastern South Dakota where there are limited sources of water. Water in the aquifer moves through vertical fractures and bedding planes along bedrock highlands (Olsen, 2004).

Table 2. Geologic units and general information on production wells in Minnesota for which zones of transport were determined for karst or fractured-rock aquifers by using empirical methods.

[Aquifer nomenclature follows the geologic nomenclature of the U.S. Geological Survey. ft BLS, feet below land surface]

Community	Well number	System	Series	Geologic unit/aquifer	Lithology	Well depth (ft BLS)	Depth to aquifer (ft BLS)
Askov	3	Precambrian	Proterozoic Era (Middle)	Hinckley Sandstone of the Keweenawan Supergroup (Hinckley aquifer)	Fine- to medium-grained sandstone	193	23
Askov	4	Precambrian	Proterozoic Era (Middle)	Hinckley Sandstone of the Keweenawan Supergroup (Hinckley aquifer)	Fine- to medium-grained sandstone	200	23
Calumet	2	Precambrian	Proterozoic Era (Middle)	Biwabik Iron Formation of the Animikie Group (Biwabik Iron-Formation aquifer)	Ferruginous chert, shale, and iron minerals, also called taconite	495	311
Calumet	3	Precambrian	Proterozoic Era (Middle)	Biwabik Iron Formation of the Animikie Group (Biwabik Iron-Formation aquifer)	Ferruginous chert, shale, and iron minerals, also called taconite	500	378
Fridley	6	Paleozoic	Cambrian and Ordovician	Prairie du Chien Group/ Jordan Sandstone (Prairie du Chien-Jordan aquifer)	Dolostone and shale with fine and coarse clastic interbeds (Prairie du Chien Group); coarse and fine clastic sandstone (Jordan Sandstone)	255	130
Fridley	7	Paleozoic	Ordovician	Prairie du Chien Group (Prairie du Chien aquifer)	Dolostone and shale with fine and coarse clastic interbeds	262	128
Fridley	8	Paleozoic	Ordovician	Prairie du Chien Group (Prairie du Chien aquifer)	Dolostone and shale with fine and coarse clastic interbeds	265	186
Fridley	11	Paleozoic	Cambrian and Ordovician	Prairie du Chien Group, Jordan Sandstone (Prairie du Chien-Jordan aquifer), St. Lawrence Formation, and Franconia Sandstone (Franconia aquifer)	Dolostone and shale with fine and coarse clastic interbeds (Prairie du Chien Group); coarse and fine clastic sandstone (Jordan Sandstone); interbeds of fine clastic and carbonate rock (St. Lawrence and Franconia Formations)	669	225
Fridley	12	Paleozoic	Cambrian	Jordan Sandstone (Jordan aquifer)	Coarse and fine clastic sandstone	276	225
Fulda	1	Precambrian	Proterozoic Era (Middle)	Sioux Quartzite (Sioux Quartzite aquifer)	Red, tightly cemented quartzite, some intercalated beds of mudstone and conglomerate	1,400	235
Fulda	6	Precambrian	Proterozoic Era (Middle)	Sioux Quartzite (Sioux Quartzite aquifer)	Red, tightly cemented quartzite, some intercalated beds of mudstone and conglomerate	550	237
Hastings	3	Paleozoic	Cambrian	Jordan Sandstone (Jordan aquifer)	Coarse and fine clastic sandstone	299	197

Table 2. Geologic units and general information on production wells in Minnesota for which zones of transport were determined for karst or fractured-rock aquifers by using empirical methods.—Continued

[Aquifer nomenclature follows the geologic nomenclature of the U.S. Geological Survey. ft BLS, feet below land surface]

Community	Well number	System	Series	Geologic unit/aquifer	Lithology	Well depth (ft BLS)	Depth to aquifer (ft BLS)
Hastings	4	Paleozoic	Cambrian	Jordan Sandstone (Jordan aquifer) and St. Lawrence Formation	Coarse and fine clastic sandstone (Jordan Sandstone) and interbeds of fine clastic and carbonate rock (St. Lawrence Formation)	400	290
Hastings	5	Paleozoic	Cambrian	Jordan Sandstone (Jordan aquifer) and St. Lawrence Formation	Coarse and fine clastic sandstone (Jordan Sandstone) and interbeds of fine clastic and carbonate rock (St. Lawrence Formation)	355	264
Hastings	6	Paleozoic	Cambrian	Jordan Sandstone (Jordan aquifer)	Coarse and fine clastic sandstone	332	229
Hastings	7	Paleozoic	Cambrian	Jordan Sandstone (Jordan aquifer)	Coarse and fine clastic sandstone	285	195
Keewatin	1	Precambrian	Proterozoic Era (Middle)	Biwabik Iron Formation of the Animikie Group (Biwabik Iron-Formation aquifer)	Ferruginous chert, shale, and iron minerals, also called taconite	606	211
Keewatin	2	Precambrian	Proterozoic Era (Middle)	Biwabik Iron Formation of the Animikie Group (Biwabik Iron-Formation aquifer)	Ferruginous chert, shale, and iron minerals, also called taconite	473	124
Le Center	1	Paleozoic	Cambrian and Ordovician	Prairie du Chien Group/ Jordan Sandstone (Prairie du Chien-Jordan aquifer)	Dolostone and shale with fine and coarse clastic interbeds (Prairie du Chien Group) coarse and fine clastic sandstone (Jordan Sandstone)	543	280
Le Center	3	Paleozoic	Cambrian and Ordovician	Prairie du Chien Group/ Jordan Sandstone (Prairie du Chien-Jordan aquifer)	Dolostone and shale with fine and coarse clastic interbeds (Prairie du Chien Group), coarse and fine clastic sandstone (Jordan Sandstone)	520	200
Marble	1	Precambrian	Proterozoic Era (Middle)	Biwabik Iron Formation of the Animikie Group (Biwabik Iron-Formation aquifer)	Ferruginous chert, shale, and iron minerals, also called taconite	402	132
Marble	2	Precambrian	Proterozoic Era (Middle)	Biwabik Iron Formation of the Animikie Group (Biwabik Iron-Formation aquifer)	Ferruginous chert, shale, and iron minerals, also called taconite	503	135
Taconite	1	Precambrian	Proterozoic Era (Middle)	Biwabik Iron Formation of the Animikie Group (Biwabik Iron-Formation aquifer)	Ferruginous chert, shale, and iron minerals, also called taconite	384	unknown
Taconite	2	Precambrian	Proterozoic Era (Middle)	Biwabik Iron Formation of the Animikie Group (Biwabik Iron-Formation aquifer)	Ferruginous chert, shale, and iron minerals, also called taconite	394	185

Communities

Zones of transport for 24 production wells in nine communities (Calumet, Keewatin, Marble, Taconite, Askov, Fridley, Hastings, Le Center, and Fulda) were evaluated in this study. Physical descriptions of the nine communities are presented in this section.

Calumet

The city of Calumet is on the Mesabi Iron Range of northeastern Minnesota (fig. 1), and its population is approximately 362 (U.S. Census Bureau, 2005). Zones of transport for two production wells in Calumet (wells 2 and 3; table 2) were evaluated. The wells are less than 120 feet apart, and both wells are completed in the Biwabik Iron-Formation aquifer, which is a confined aquifer in the Calumet area. The Biwabik Iron Formation is the upper bedrock unit in the northern part of the city. At the production wells in Calumet, the Biwabik Iron Formation is more than 300 feet below the land surface, covered by Pleistocene-age glacial deposits and the Proterozoic-age Virginia Formation of the Animikie Group, which is composed of argillites and slates. Glacial deposits in the Calumet area consist mainly of a mix of bouldery tills, lake and stream sediments, and some ice-contact sand and gravel deposits were formed near local natural lakes (Jennings and Reynolds, 2005). The Hill Annex iron ore mine pit is located approximately 0.5 mile north of the production wells (fig. 3). This mine pit is connected to the abandoned Gross Marble, Arcturus, and Hill Trumbull mine pits (fig. 3). A series of large lakes covering an area of more than 800 acres has formed in the pits. High-angle faults generally striking to the northeast/southwest are prevalent in the Calumet area (Jirsa and others, 2005). Aquifer tests have not been conducted on the wells. Data from the Minnesota Department of Natural Resources State Water Use Database (SWUDS) indicates that the production wells in Marble are the only other high-capacity wells near the Calumet area (Walsh, 2007a). Pumping from the production wells in Marble was not included in the zone of transport delineations done in this study and by the MDH for the production wells in Calumet. A zone of transport was delineated by MDH for the two production wells in Marble by using the calculated-fixed-radius method combined with an upgradient extension (James F. Walsh, Minnesota Department of Health, written commun., April 10, 2007).

Keewatin

The city of Keewatin is on the Mesabi Iron Range of northeastern Minnesota (fig. 1), and its population is approximately 1,105 (U.S. Census Bureau, 2005). Zones of transport for two production wells in Keewatin were evaluated (wells 1 and 2; table 2). Both wells are completed in the Biwabik Iron Formation aquifer, which is a confined aquifer in the Keewatin area. In both wells, the Biwabik Iron Formation is more than 100 feet below the land surface, covered by Pleistocene-age glacial deposits and slates of the Proterozoic-age Virginia Formation of the Animikie Group. The glacial deposits consist mainly of clayey and bouldery till, and some buried drumlins are present south of Keewatin (Jennings and Reynolds, 2005). A series of abandoned and active mine pits (Carlz, Mississippi No. 1, St. Paul, Mesabi Chief, Bennett, National Steel, and Russell), mine tailings, and mine stockpiles are north, east, and west of the production wells (fig. 4). Data from SWUDS indicates that the Mississippi No. 1, Mesabi Chief, Russell, National Steel, and Bennett Pits are being dewatered (Walsh, 2003). Lakes are present in the other mine pits (Walsh, 2003). Faulting is common in the area (Jirsa and others, 2005). Aquifer tests were not conducted at the two wells in Keewatin. Walsh (2003) characterized the chemistry and isotopic signatures of mine-pit waters, well waters, and local groundwater in the Keewatin area to assess potential sources of water to the two production wells. Oxygen-18 and chloride data indicated that at least one of the production wells was affected by mine dewatering, most likely from the Carlz mine pit. This effect may change depending on future dewatering scenarios (Walsh, 2003). Data from SWUDS indicates that two mine company wells are the only other high-capacity wells in the Keewatin area (Walsh, 2003). Walsh (2003) used a 10-year calculated-radius equation to determine that the two mine company wells would not affect the zones of transport for the two production wells, so the influence of pumping from these wells was not included in the truncated-parabola and modified-ellipse analyses.

A delineation technique developed by the MDH for confined solution-weathered or fractured-rock aquifers was used to calculate 10-year zones of transport for the two production wells (Minnesota Department of Health, 2005c) (fig. 4). This technique applied calculated-fixed-radius equations and existing water-level and water-quality data to determine zones of transport for the wells (Walsh, 2003). The surface-water drainage area for the Carlz mine pit was included in the MDH zone of transport for the production wells in Keewatin because water-quality and isotopic data indicated that the Carlz Pit is a source of water to the two production wells. When delineating the orientations of the truncated parabolas and modified ellipses, it was assumed that the Carlz pit was the only pit contributing water to the wells. This assumption also was made when the MDH zones of transport were delineated (Walsh, 2003).

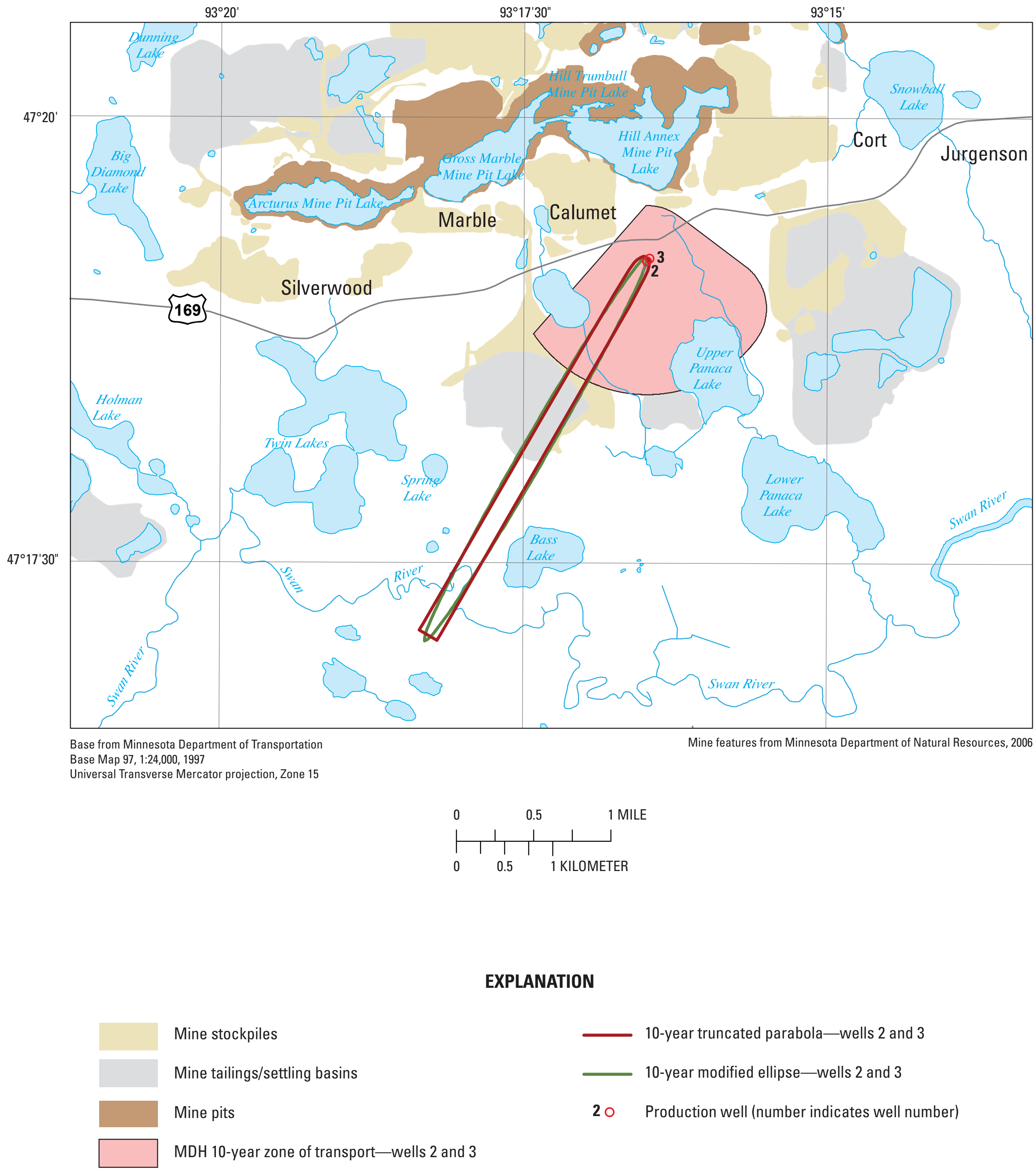

Figure 3. Zones of transport delineated using the truncated-parabola and modified-ellipse methods and existing zone of transport delineated by the Minnesota Department of Health (MDH) for production wells in Calumet, Minnesota.

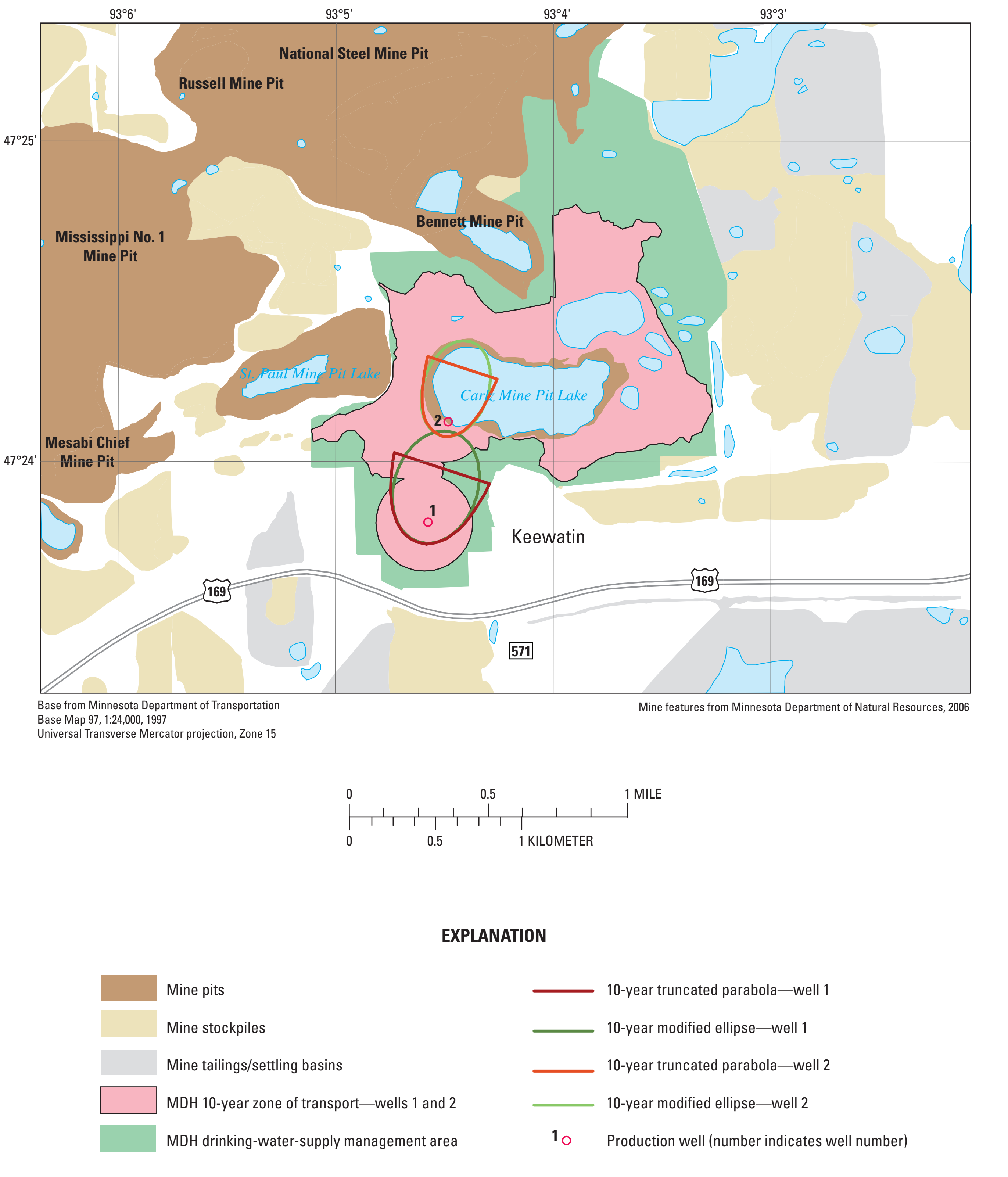

Figure 4. Zones of transport delineated using the truncated-parabola and modified-ellipse methods and existing zone of transport delineated by the Minnesota Department of Health (MDH) for production wells in Keewatin, Minnesota.

Marble

The city of Marble is just west of the city of Calumet on the Mesabi Iron Range of northeastern Minnesota (figs. 1 and 5), and its population is approximately 678 (U.S. Census Bureau, 2005). Zones of transport for two production wells in Marble (wells 1 and 2; table 2) were evaluated. Both wells are completed in the Biwabik Iron-Formation aquifer, which is a confined aquifer in the Marble area. At both wells, the Biwabik Iron Formation is approximately 135 feet below the land surface, covered by Pleistocene-age glacial deposits. Similar to the Calumet area, glacial deposits in the Marble area consist mainly of a mix of bouldery tills, lake and stream sediments, and some ice-contact sand and gravel deposits formed near local natural lakes (Jennings and Reynolds, 2005). Similar to many production wells on the Mesabi Iron Range, abandoned mine pits (Gross Marble, Hill Trumbull, Hill Annex, and Arcturus), mine stockpiles, and tailings/settling basins lie in the vicinity of the production wells (fig. 5). Lakes have formed in the abandoned mine pits. Aquifer tests were not conducted at the production wells. Data from SWUDS indicates that the production wells in Calumet are the only other high-capacity wells near the Marble area (Walsh, 2007a). Pumping from the production wells in Calumet was not included in the zone of transport delineations done in this study or for delineations by the MDH for the production wells in Marble. A MDH delineation technique for unconfined solution-weathered or fractured-rock aquifers that applied the calculated-fixed-radius method combined with an upgradient extension was used to calculate a 10-year zone of transport for the two production wells (Walsh, 2007a) (fig. 5). This technique is applied to wells where the local horizontal hydraulic gradient is greater than 0.001 and the ratio of well discharge to the absolute groundwater flow through an aquifer is less than 3,000 (Minnesota Department of Health, 2005c).

Taconite

The city of Taconite is on the Mesabi Iron Range of northeastern Minnesota (fig. 1), and its population is approximately 285 (U.S. Census Bureau, 2005). Zones of transport for two production wells in Taconite (wells 1 and 2; table 2) were evaluated. Both wells are completed in the Biwabik Iron Formation aquifer, which is a confined aquifer in the Taconite area. Approximately 178 feet of glacial clay, boulders, and sand, and approximately 100 feet of Proterozoic-age Virginia Formation and Cretaceous-age bedrock overlie the Biwabik Iron Formation in Taconite. Faulting is present near Taconite, and the major faults strike northwest/southeast (Jirsa and others, 2005). The city and the production wells are southeast of the Canisteo Mine Pit (fig. 6), a flooded mine pit in which water levels have been rising since the cessation of mine dewatering activities in 1984 (Jones, 2002). Future plans for the mine may include dewatering for power production. Aquifer tests were not conducted at the two production wells in Taconite. Data from SWUDS indicates that a production well in Bovey is the only other high-capacity well in the Taconite area (Walsh, 2007b). The production well in Bovey is completed in a glacial aquifer, and it is unlikely to affect the zone-of-transport shape and size for the wells in Taconite. Therefore, pumping from the production well in Bovey was not included in the MDH zone of transport delineation. Similar to the production wells in Marble, a MDH delineation technique for unconfined solution-weathered and fractured-rock aquifers that applied the calculated-fixed-radius method combined with an upgradient extension was used to calculate a 10-year zone of transport for the two production wells in Taconite (Walsh, 2007b) (fig. 6).

Askov

The city of Askov is in northeastern Minnesota (fig. 1), and its population is approximately 368 (U.S. Census Bureau, 2005). Zones of transport for two production wells in Askov (wells 3 and 4; table 2) were evaluated. Both wells are completed in the Hinckley aquifer, which is an unconfined aquifer in the Askov area. The Hinckley aquifer is covered by sandy and silty glacial sediments deposited as Superior moraine ridges, meltwater stream deposits, and ice margin deposits in the Askov area (Patterson and Knaeble, 2001). Glacial deposit thicknesses generally are less than 50 feet in the Askov area. Both production wells in Askov were determined by MDH hydrologists to be vulnerable to contamination due to the lack of geologic material between the land surface and the bedrock aquifer and the presence of tritium in water sampled from well 3 (Haglund, 2007). Shade and others (2001, 2002) identified a series of sinkholes within 200 feet of the production wells in Askov and characterized the formation of sinkholes in the Askov area (fig. 7). These sinkholes generally are present where fractures and bedding planes intersect. Results from aquifer tests conducted on production well 3 and a former production well in Askov indicate that dual-porosity flow within enlarged voids occurs in the vicinity of the wells (Haglund, 2007). Data from SWUDS indicates that no other high-capacity wells are in the Askov area (Haglund, 2007). Hydrologists from MDH used two analytical groundwater-flow models and calculated-fixed-radius equations to delineate 10-year zones of transport for both wells (wells 3 and 4) (Haglund, 2007). These zones of transport were used with a combined pumping rate for the two wells, geologic maps, sinkhole maps, and fracture-lineament maps to determine a series of upgradient extensions that were modified to account for upgradient flow, flow direction ambiguity, and the effects of secondary permeability features. The modified zones of transport were used to create a composite area of capture zones defining the boundaries of the WHPA for the wells (light green area in fig. 7) (Haglund, 2007).

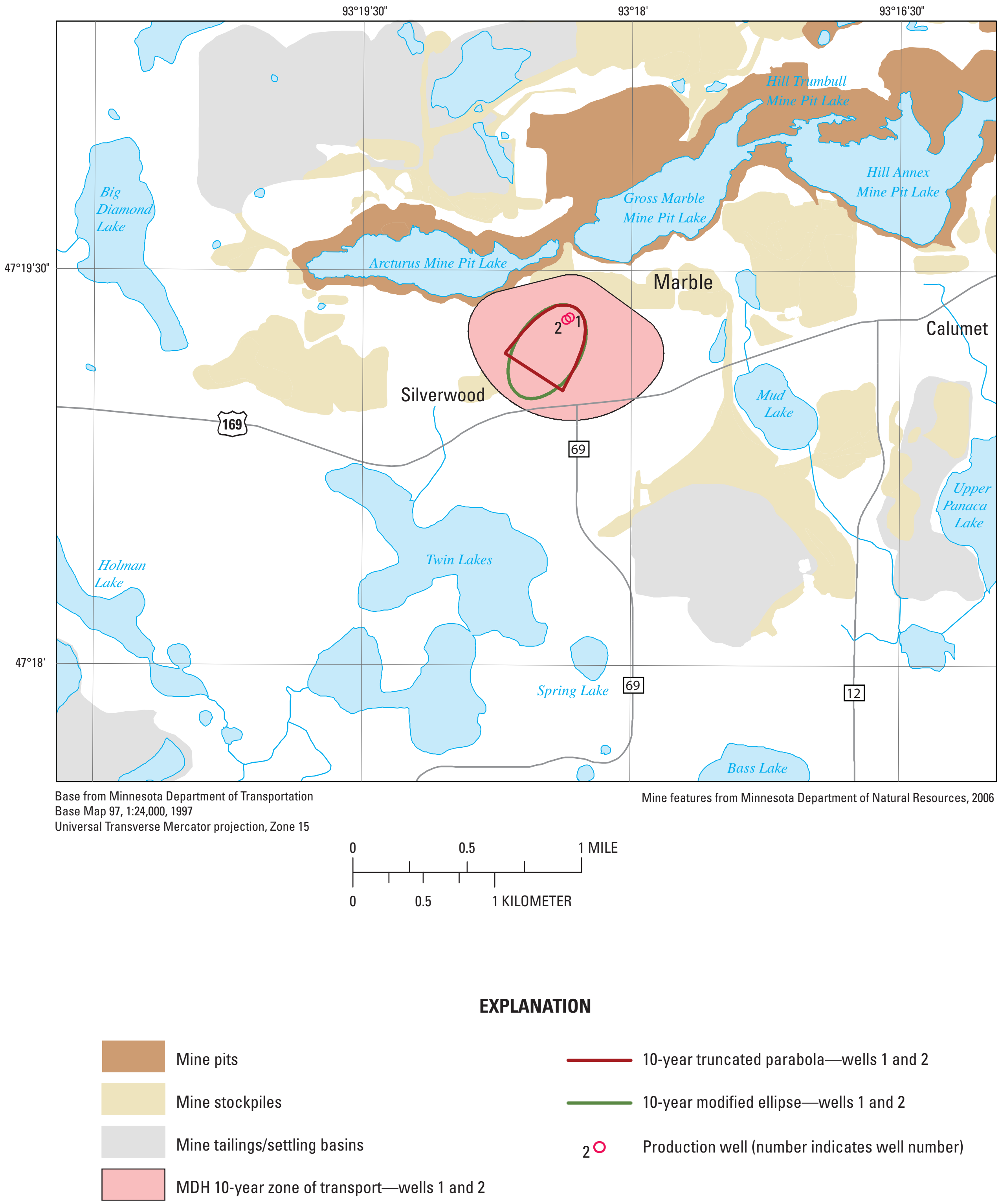

Figure 5. Zones of transport delineated using the truncated-parabola and modified-ellipse methods and existing zone of transport delineated by the Minnesota Department of Health (MDH) for production wells in Marble, Minnesota.

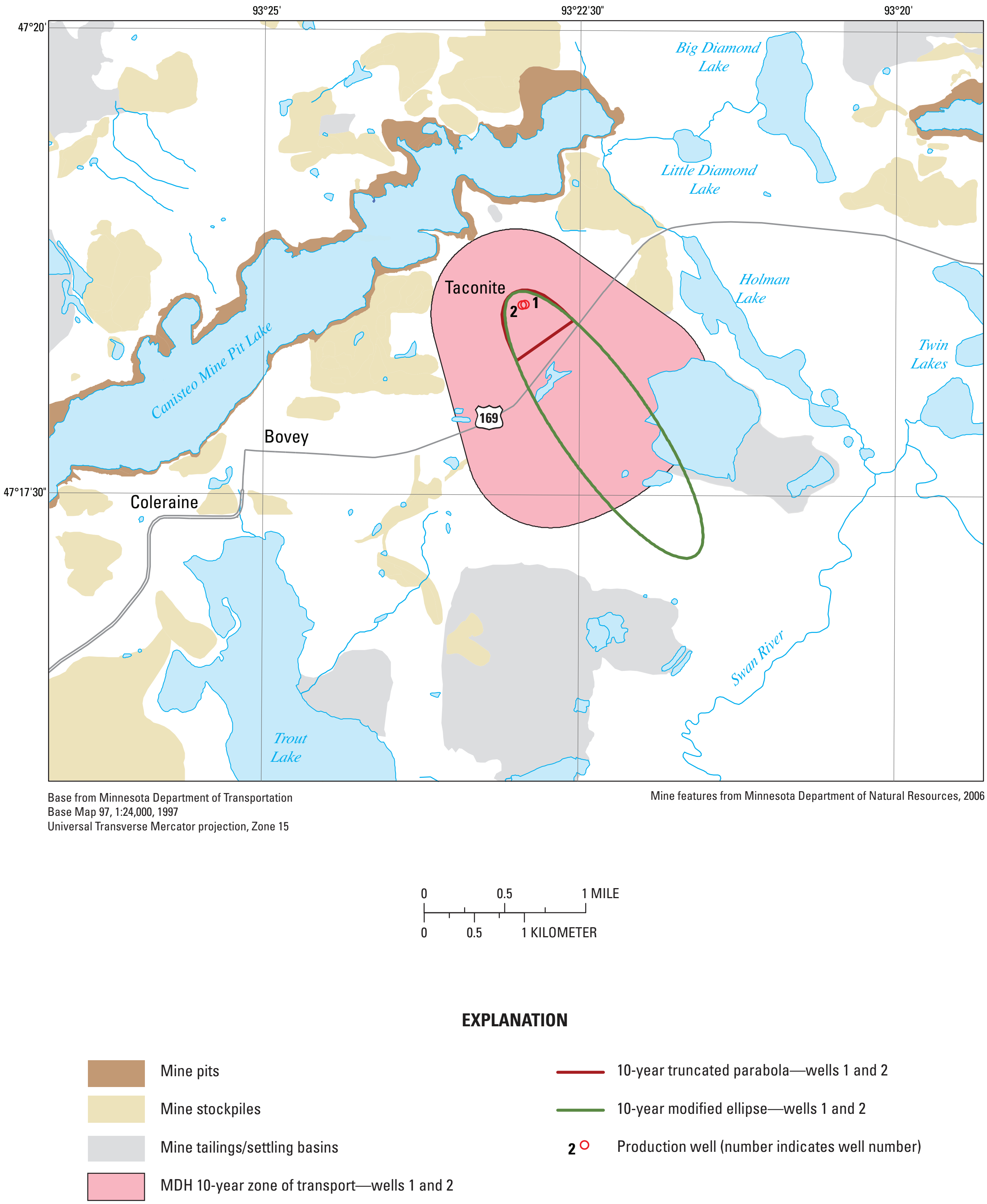

Figure 6. Zones of transport delineated using the truncated-parabola and modified-ellipse methods and existing zone of transport delineated by the Minnesota Department of Health (MDH) for production wells in Taconite, Minnesota.

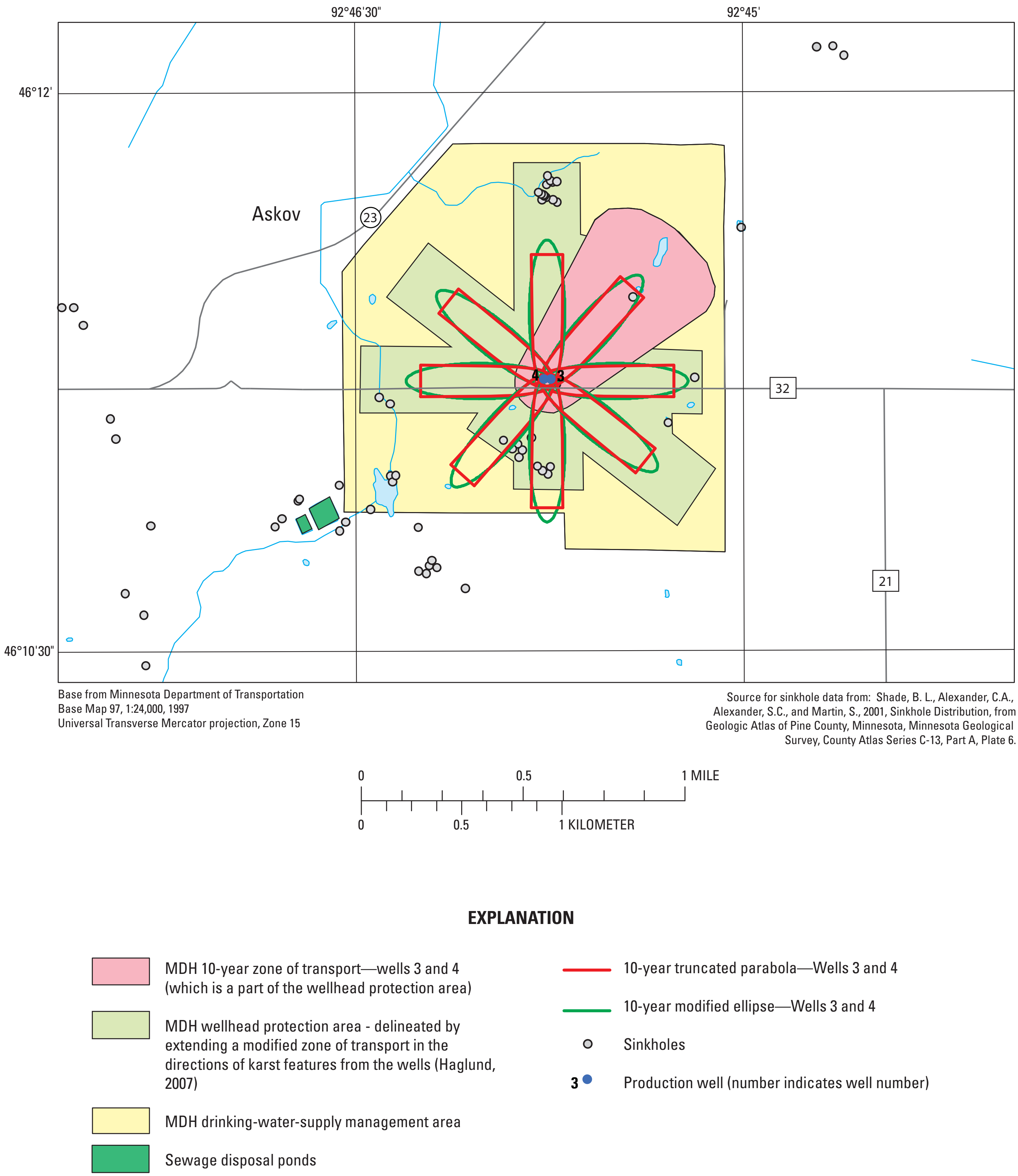

Figure 7. Zones of transport delineated using the truncated-parabola and modified-ellipse methods and existing zone of transport delineated by the Minnesota Department of Health (MDH) for production wells in Askov, Minnesota.

Fridley

The city of Fridley is in east-central Minnesota (fig. 1), and its population is approximately 26,515 (U.S. Census Bureau, 2005). There are 13 production wells in Fridley: one well is completed in Quaternary-age glacial deposits; six wells are completed in either the Prairie du Chien Group, Jordan Sandstone, or both geologic units; four wells are completed in the Mount Simon Sandstone; and two wells are completed in multiple formations. For this study, zones of transport for five wells were evaluated. The five wells withdraw water from the Prairie du Chien aquifer (wells 7 and 8), Jordan aquifer (well 12), or both aquifers (wells 6 and 11) (fig. 8 and table 2). Well 9, withdrawing water from the Prairie du Chien and Jordan aquifers, was not included in the study because it is pumped only for emergencies, and the MDH did not include this well in their wellhead protection planning (Robertson, 2002). The five Fridley wells assessed in this study range in depth from 255 to 669 feet below land surface (table 2). For this study, the Prairie du Chien aquifer and Jordan aquifer were grouped together as a single aquifer because groundwater levels and flow directions are similar in both aquifers (Robertson, 2002). However, the two aquifers were simulated as separate hydrogeologic units in a multi-layered analytical element groundwater-flow model used by MDH to calculate 10-year zones of transport (Robertson, 2002) (fig. 8). The WHPAs for the wells completed in the Prairie du Chien Group and Jordan Sandstone were generated by supplementing the 10-year zones of transport with an upgradient extension using hydrogeologic mapping techniques. An aquifer test conducted at the production wells in Fridley produced transmissivity values for the Shakopee Formation of the Prairie du Chien Group ranging from 42,500 to 73,900 feet squared per day (ft^2/d) (Robertson, 2002). A hydraulic conductivity value of 39 ft/d was used in the groundwater-flow model to delineate the MDH zones of transport (Robertson, 2002). Twenty-two high-capacity wells identified in SWUDS were included in the groundwater-flow model to assess the effect of water extraction from these wells on the shape and size of the zones of transport for the production wells (Robertson, 2002). The influence of these 22 high-capacity wells on the truncated-parabola and modified-ellipse zones of transport was not assessed for this report.

Hastings

The city of Hastings is in southeastern Minnesota (fig. 1), and its population is approximately 20,910 (U.S. Census Bureau, 2005). Six production wells are located in Hastings (wells 1, 3, 4, 5, 6, and 7; table 2). All of the wells are completed in the Jordan Sandstone except for well 1, which is a multi-aquifer well completed in the Jordan Sandstone, St. Lawrence Formation, Franconia Formation, Ironton Sandstone, and Galesville Sandstone (Barr Engineering, 2003). Well 1 was not included in this study because it is pumped only in an emergency, and it was not included in the MDH wellhead protection assessment. The other five wells ranged in depth from 285 to 400 feet below the land surface (table 2). Depth to the Jordan Sandstone in the wells varies from approximately 195 to 290 feet below the land surface (table 2). The Jordan aquifer is confined in the Hastings area but receives water through leakage from upper aquifers and confining layers (Barr Engineering, 2003). Buried bedrock valleys cut through the Hastings area in a north-northwest direction (Barr Engineering, 2003). All of the production wells in Hastings are susceptible to contamination, and nitrates, herbicides, and herbicide metabolites were detected in water samples from all five wells. Data analyses of aquifer tests conducted at well 5 produced a mean transmissivity of 5,400 ft^2/d for the Jordan aquifer (Barr Engineering, 2003). A multi-layered, finite-difference, groundwater-flow model was used by MDH to delineate 1-year and 10-year zones of transport around the five wells (Barr Engineering, 2003) (fig. 9). The 10-year zones of transport were supplemented by upgradient extensions using hydrogeologic mapping techniques by MDH to produce the WHPAs for the wells. Other high-capacity wells from a Dakota County database were included in the groundwater-flow model to assess the effect of these wells on the zones of transport (Barr Engineering, 2003). The influence of these other high-capacity wells on the truncated-parabola and modified-ellipse zones of transport for the production wells in Hastings was not assessed in this report.

Le Center

The city of Le Center is in southeastern Minnesota (fig. 1), and its population is approximately 2,308 (U.S. Census Bureau, 2005). There are three production wells in Le Center (wells 1, 2, and 3) (fig. 10); however, well 2 is used only in emergencies, and consequently was not included in the zone-of-transport analyses. Both wells 1 and 3 extract water from the Prairie du Chien and Jordan aquifers (table 2), which is confined in the Le Center area. The Prairie du Chien Group is approximately 280 feet below land surface and 170 feet thick under Le Center, and the Jordan Sandstone is about 80 feet thick under Le Center (Blum, 2003).

Well 1 is 543 feet deep, and it is uncased through the entire aquifer. Analysis of a constant-discharge aquifer test conducted at well 1 produced a transmissivity value of 17,900 ft^2/d (Blum, 2003). A nearly instantaneous water-level decline in the observation well during this aquifer test indicated the presence of conduit flow in the Prairie du Chien and Jordan aquifers between well 1 and the observation well (Blum, 2003). Well 3 is 520 feet deep, and it is uncased to the Oneota Dolomite of the Prairie du Chien Group and the Jordan Sandstone. Approximately 200 to 280 feet of glacial clay-rich till cover the Prairie du Chien-Jordan aquifer in Le Center. Blum (2003) determined that no other high-capacity wells in the Le Center area influence groundwater-flow conditions in the vicinity of the production wells. An analytical-element, groundwater-flow model and a statistical model were used by the MDH to calculate a 10-year composite zone of transport for the two production wells (Blum, 2003) (fig. 10).

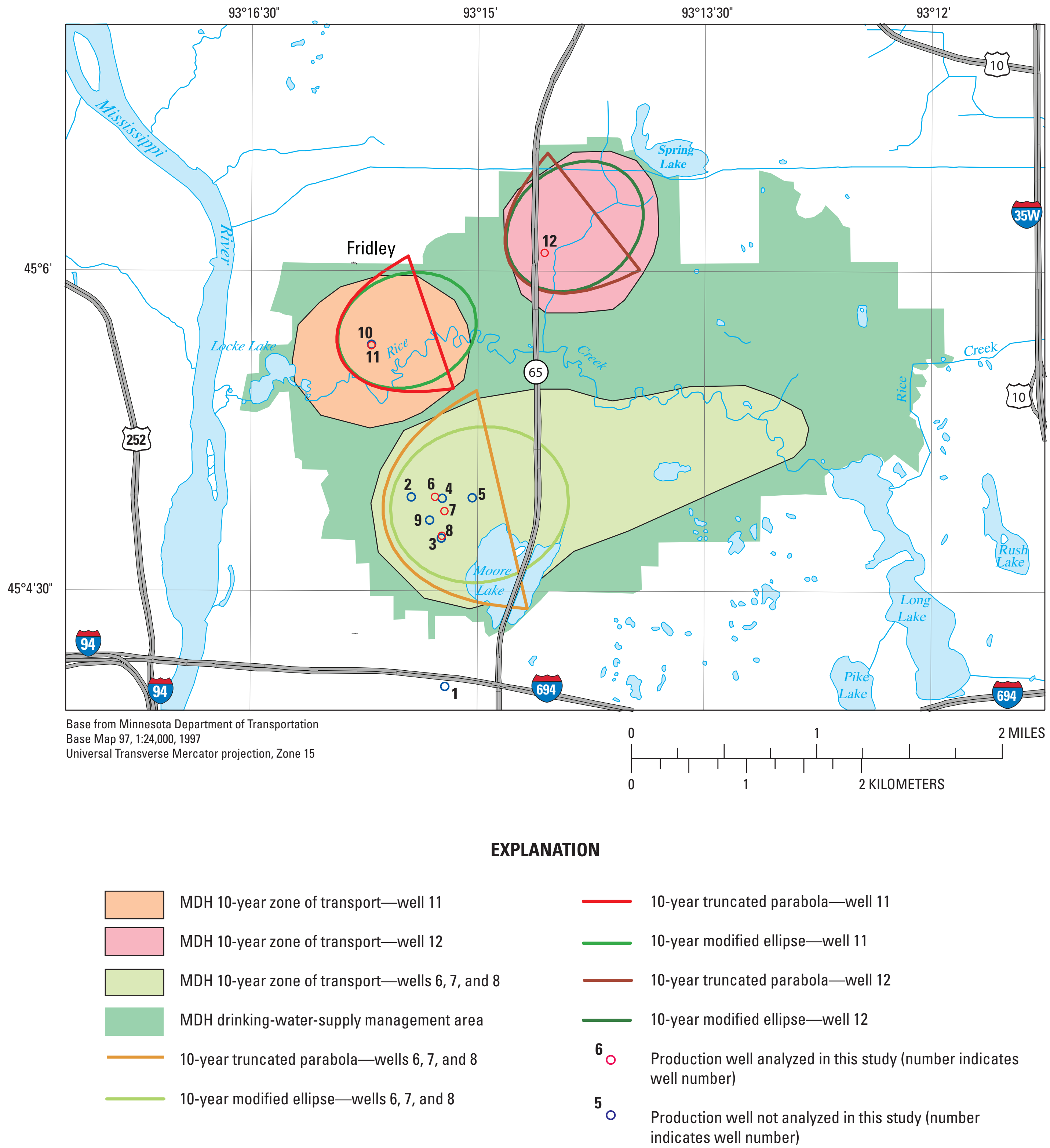

Figure 8. Zones of transport delineated using the truncated-parabola and modified-ellipse methods and existing zone of transport delineated by the Minnesota Department of Health (MDH) for production wells in Fridley, Minnesota.

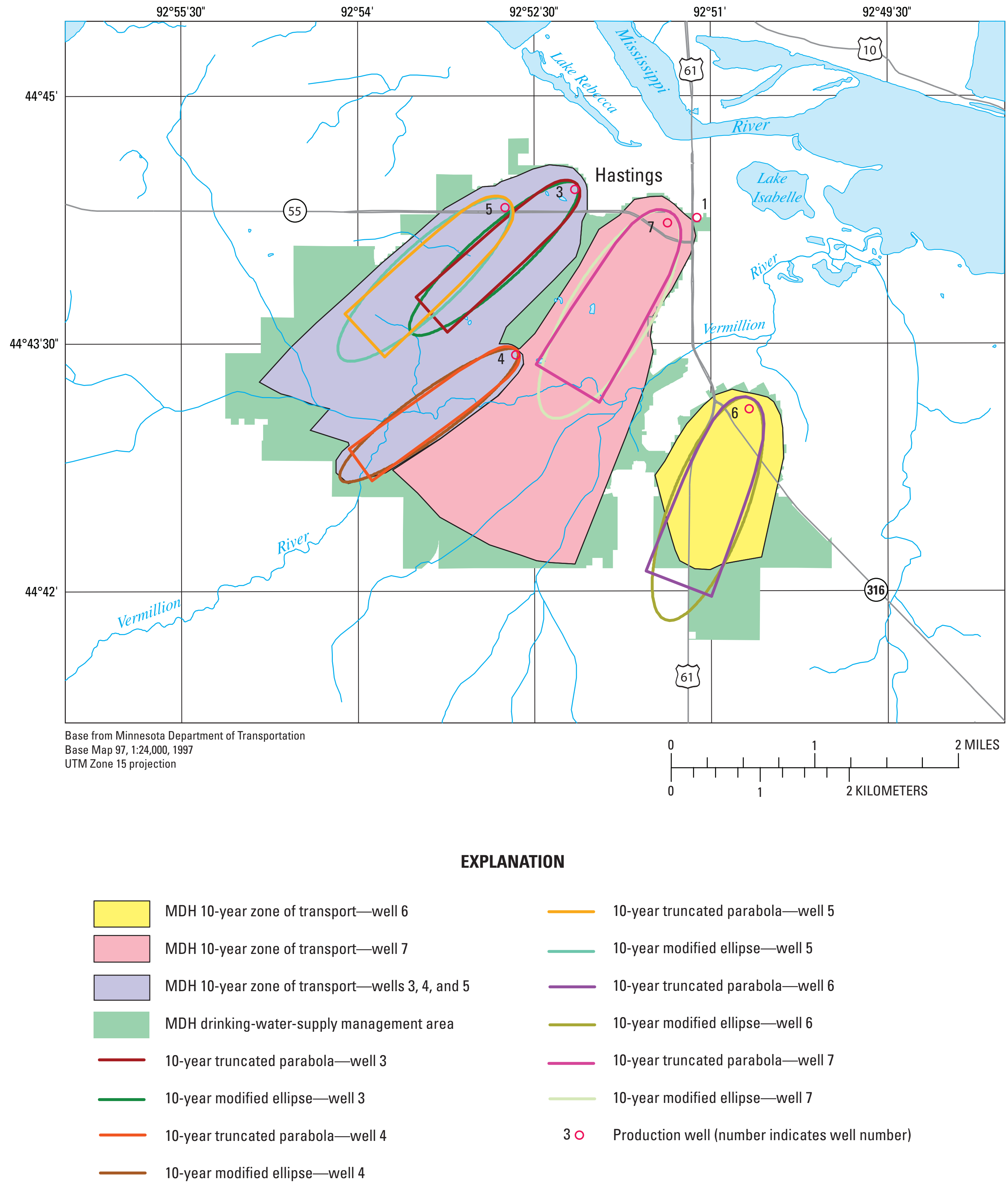

Figure 9. Zones of transport delineated using the truncated-parabola and modified-ellipse methods and existing zone of transport delineated by the Minnesota Department of Health (MDH) for production wells in Hastings, Minnesota.

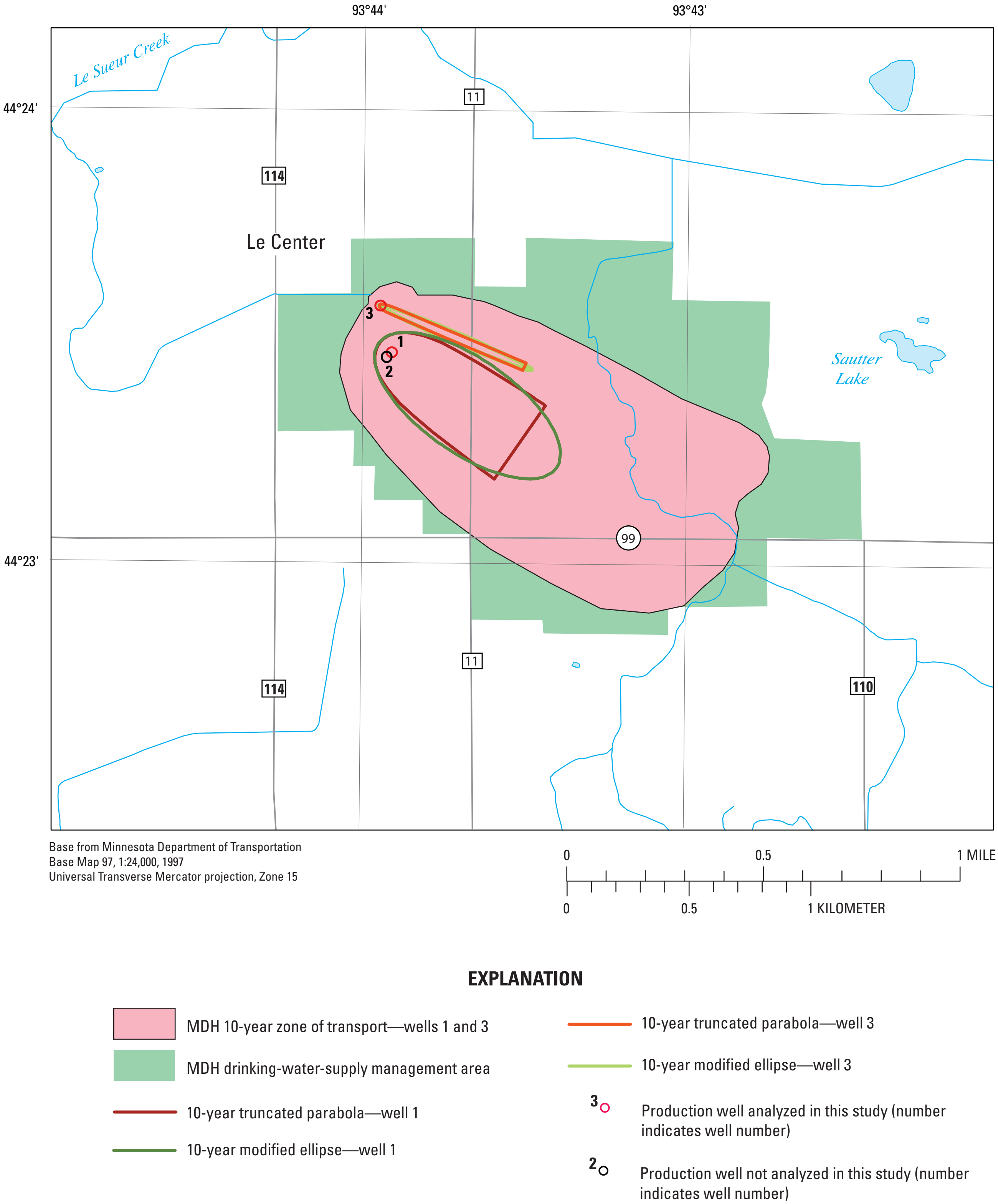

Figure 10. Zones of transport delineated using the truncated-parabola and modified-ellipse methods and existing zone of transport delineated by the Minnesota Department of Health (MDH) for production wells in Le Center, Minnesota.

Fulda

The city of Fulda is in southwestern Minnesota (fig. 1), and its population is approximately 1,272 (U.S. Census Bureau, 2005). There are five production wells in Fulda. Three production wells (wells 4, 5, and 7) extract groundwater from a confined aquifer consisting of glacial outwash sands, deposited by the Des Moines lobe ice sheet, and thus were not included in this study. Zones of transport were evaluated for wells 1 and 6, which extract water from the Sioux Quartzite aquifer (table 2). The Sioux Quartzite is a confined aquifer in the Fulda area, and approximately 60 feet of clay-rich glacial sediments lie between the glacial outwash sands, from which wells 4, 5, and 7 obtain groundwater, and the top of the quartzite. The Sioux Quartzite forms a highland in the Fulda area, and its long axis extends northwest-southeast several miles from the city of Fulda (Olsen, 2004). The highland is buried by approximately 235 feet of glacial deposits in the city of Fulda, but less than 100 feet of deposits overlie it east and southeast of the city (Olsen, 2004). An aquifer test conducted in well 6 produced a transmissivity of 36.7 ft^2/d for the Sioux Quartzite aquifer, and this likely represents the connectivity of the local fracture system around the well. Data from SWUDS indicates that no other high-capacity wells are in the Fulda area (Olsen, 2004). The MDH used a calculated-fixed-radius equation with an upgradient extension and potentiometric and fracture-lineament maps to delineate 10-year zones of transport for the two production wells (Olsen, 2004) (fig. 11).

Evaluation of Delineation Methods

The 10-year zones of transport delineated using the truncated-parabola and modified-ellipse methods, along with the 10-year zones of transport delineated previously by MDH, are shown on figures 3–11 for production wells in each of the nine communities included in this study. An evaluation of delineation methods for zones of transport indicates that the truncated-parabola and modified-ellipse methods can produce questionable results in karst and fractured-rock terranes. Substantial differences were seen in the size and shapes of most zones of transport delineated using these methods compared with the MDH zones of transport (figs. 3–11). Only the 10-year zones of transport for the two empirical methods were plotted on figures 3–11, because only 10-year zones of transport were used by MDH. Calculated parameters for the truncated parabolas and modified ellipses for both the 10-year and 20-year zones of transport are listed in tables 3 and 4, respectively.

Table 3. X-axis coordinates for stagnation points, y-asymptotes, and water particle travel distances for 10-year and 20-year zones of transport obtained using the truncated-parabola method for production wells open to karst or fractured-rock aquifers, Minnesota.

[ft^3/d, cubic foot per day]

Community	Well number	Well discharge rate (ft^3/d)	X-axis coordinates for stagnation point (ft)	Y-axis asymptotes (±ft)	Water particle travel distance (ft)	
			X_L	Y_L	10-year	20-year
Askov	3 and 4	5,100	-84	270	2,050	4,100
Calumet	2 and 3	5,600	-110	350	14,600	29,200
Fridley	6, 7, and 8	170,000	-1,500	4,800	1,900	3,800
Fridley	11	97,000	-860	2,700	1,900	3,800
Fridley	12	100,000	-910	2,900	1,900	3,800
Fulda	1 and 6	15,000	-2,000	6,300	2,200	4,400
Hastings	3	68,000	-290	900	7,000	14,000
Hastings	4	58,000	-240	760	7,000	14,000
Hastings	5	84,000	-350	1,100	7,000	14,000
Hastings	6	100,000	-440	1,400	7,000	14,000
Hastings	7	110,000	-470	1,500	7,000	14,000
Keewatin	1	11,000	-380	1,200	1,100	2,200
Keewatin	2	6,000	-270	840	1,100	2,200
Le Center	1	38,000	-210	670	2,100	4,200
Le Center	3	3,000	-17	53	2,100	4,200
Marble	1 and 2	14,000	-300	950	1,460	2,920
Taconite	1 and 2	6,300	-450	1,400	8,600	17,200

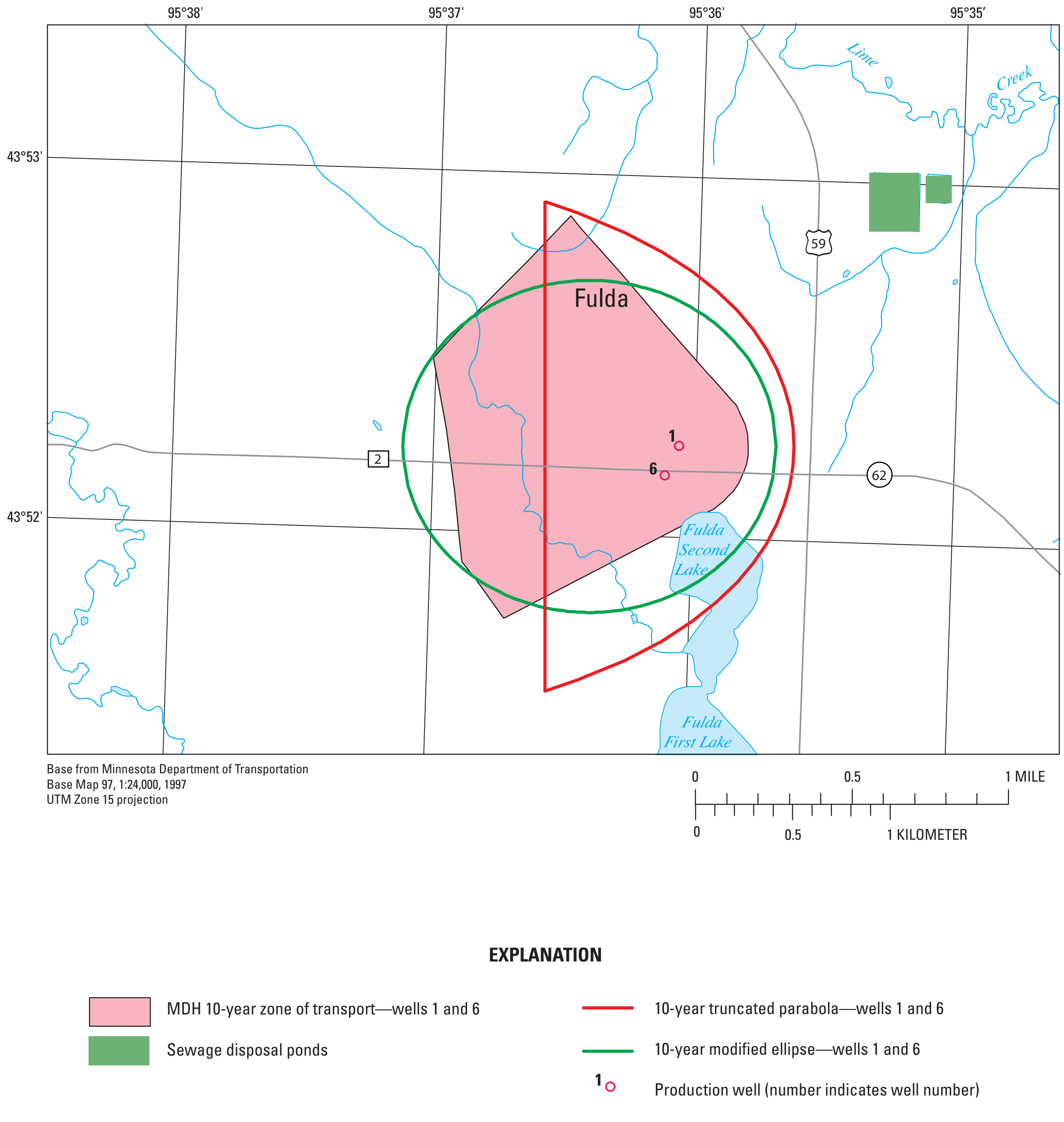

Figure 11. Zones of transport delineated using the truncated-parabola and modified-ellipse methods and existing zone of transport delineated by the Minnesota Department of Health (MDH) for production wells in Fulda, Minnesota.

Table 4. X-axis coordinates, y-axis distances, and areas of ellipses for 10-year and 20-year zones of transport obtained using the modified-ellipse method for production wells open to karst or fractured-rock aquifers, Minnesota.

[ft^3/d, cubic foot per day; mi^2, square mile; ft, foot]

				Hydraulic parameters for 10-year zones of transport			Hydraulic parameters for 20-year zones of transport		
				X-axis coordinates (ft)		Y-axis coordinates (±ft)	X-axis coordinates (ft)		Y-axis coordinates (±ft)
Community	Well number	Well discharge rate (ft^3/d)	Area of ellipse (mi^2)	X+	X-		X+	X-	
Askov	3 and 4	5,100	0.04	2,300	-84	290	4,400	-84	150
Calumet	2 and 3	5,600	.36	15,000	-110	420	30,000	-110	220
Fridley	6, 7, and 8	170,000	.63	3,800	-1,300	2,200	6,300	-1,500	1,500
Fridley	11	97,000	.36	3,200	-820	1,600	5,500	-860	2,900
Fridley	12	100,000	.40	3,300	-870	1,700	5,600	-900	4,400
Fulda	1 and 6	15,000	.99	4,600	-1,700	2,800	7,500	-1,900	1,900
Hastings	3	68,000	.43	7,900	-290	970	15,000	-290	1,800
Hastings	4	58,000	.39	7,800	-240	830	15,000	-240	2,300
Hastings	5	84,000	.54	8,100	-350	1,200	15,000	-350	2,100
Hastings	6	100,000	.68	8,300	-440	1,400	15,000	-440	2,200
Hastings	7	110,000	.74	8,300	-470	1,500	16,000	-470	2,700
Keewatin	1	11,000	.09	1,800	-380	790	3,000	-380	490
Keewatin	2	6,000	.06	1,600	-270	620	2,800	-270	380
Le Center	1	38,000	.10	2,700	-210	630	4,900	-210	350
Le Center	3	3,000	.01	2,200	-17	64	4,300	-17	33
Marble	1 and 2	14,000	.10	2,100	-300	740	3,700	-300	440
Taconite	1 and 2	6,300	.86	10,000	-450	1,500	19,000	-450	810

All zones of transport delineated using the truncated-parabola and modified-ellipse methods were smaller in area than the MDH zones of transport, and most incorporated only a small portion of the MDH zone of transport (table 5). Notable exceptions to this were zones of transport delineated for the wells in Fulda, well 12 in Fridley, well 6 in Hastings, and well 1 in Keewatin. About two-thirds (67 percent) of the individual or composite truncated parabolas and modified ellipses covered less than 50 percent of the area incorporated by the MDH zones of transport (table 5). The shapes of some of the truncated parabolas and modified ellipses did not closely match the zones of transport delineated by the MDH using the calculated-fixed-radius methods and groundwater-flow models. This was particularly true for the zones of transport for the production wells in Calumet (fig. 3), Taconite (fig. 6), and Fridley (wells 6, 7, and 8) (fig. 9).

Calumet

The size and the shape of the truncated parabola and modified ellipse delineated for wells in Calumet are much different from the MDH 10-year zone of transport (fig. 3), although key hydraulic properties were the same (table 1). The truncated parabola and modified ellipse are more elongated than the MDH zone of transport, stretching to the Swan River approximately 3 miles southwest of the production wells (fig. 3). The truncated parabola and modified ellipse covered 9 percent and 8 percent, respectively, of the MDH zone of transport (table 5). The low porosity (0.01) used to delineate the truncated parabola and modified ellipse resulted in long, 10-year travel distances for both methods (tables 3 and 4), resulting in the elongated zones. In comparison, the higher porosity (0.1) used for the truncated parabola and modified ellipse for the production wells in Marble resulted in shorter, 10-year travel distances than in Calumet (table 3 and 4) and shorter, wider zones (fig. 5).

Keewatin

The truncated parabolas and modified ellipses for the production wells in Keewatin were much smaller than the MDH zone of transport (fig. 4). The truncated parabola and modified ellipse for well 1 each covered 56 percent of the MDH calculated-fixed radii delineated for the well (table 5). The truncated parabola and modified ellipse for well 2 each covered 43 percent of the MDH calculated-fixed radii delineated for the well (table 5). For well 1, the truncated parabola and modified ellipse cover more of the upgradient watershed than the MDH zone of transport (fig. 4). Like the zones of transport for most production wells in the Mesabi Iron Range, the orientation, shape, and size of these zones of transport likely will change as dewatering activities change when local mine pits are developed or closed.

Table 5. Areas of empirical-method 10-year zones of transport within Minnesota Department of Health (MDH) delineated 10-year zones of transport for production wells open to karst or fractured-rock aquifers, Minnesota.

[Values in parentheses are the percentage of the area of empirical-method zones of transport that is within MDH zones of transport; mi^2, square mile]

		Area of zone of transport (mi^2)			Area of empirical-method zones of transport within MDH zones of transport (mi^2)	
Community	Well number	MDH delineation	Truncated parabola method	Modified ellipse method	Truncated parabola method	Modified ellipse method
Askov	3 and 4	[1]0.22	0.04	0.04	0.04 (18)	0.04 (18)
		[2].69	[3].25	[3].28	.23 (33)	.26 (38)
Calumet	2 and 3	[4]1.18	.36	.36	.11 (9)	.09 (8)
Fridley	6, 7, and 8	[5]1.77	[6].56	[6].63	.55 (31)	.63 (36)
Fridley	11	[5].61	.29	.36	.28 (46)	.33 (54)
Fridley	12	[5].58	.32	.40	.31 (53)	.40 (69)
Fulda	1 and 6	[4].78	.89	.99	.49 (63)	.73 (94)
Hastings	3, 4, and 5	[5]2.45	[7]1.13	[7]1.25	1.13 (46)	1.25 (51)
Hastings	6	[5].83	.59	.68	.49 (59)	.52 (63)
Hastings	7	[5]2.32	.62	.74	.62 (27)	.74 (32)
Keewatin	1	[8,9].09	.08	.09	.05 (56)	.05 (56)
Keewatin	2	[8,9].07	.05	.06	.03 (43)	.03 (43)
Le Center	1 and 3	[5].55	[10].09	[10].11	.09 (16)	.11 (20)
Marble	1 and 2	[4].40	.08	.10	.08 (20)	.10 (25)
Taconite	1 and 2	[4]2.28	.11	.86	.11 (5)	.70 (31)

[1]Zone of transport delineated using calculated-fixed-radius equations, geologic maps, sinkhole maps, and fracture-lineament maps.

[2]Area of MDH wellhead protection area.

[3]Total area covered by eight zones of transport oriented at different groundwater-flow directions.

[4]Zone of transport delineated using calculated-fixed-radius method with an upgradient extension.

[5]Zone of transport delineated using a groundwater-flow model.

[6]Area is the sum of zones of transport for wells 6, 7, and 8.

[7]Area is the sum of zones of transport for wells 3, 4, and 5.

[8]Zone of transport delineated using calculated-fixed-radius method with an upgradient extension.

[9]Area of calculated-fixed-radius zone around well.

[10]Area is the sum of zones of transport for wells 1 and 3.

Marble

The truncated parabola and modified ellipse delineated for the production wells in Marble are smaller than the MDH 10-year zone of transport delineated using the calculated-fixed-radius method combined with an upgradient extension (fig. 5). The zones of transport delineated using empirical methods for wells 1 and 2 covered 20 percent (truncated parabola) and 25 percent (modified ellipse) of the MDH zone of transport (table 5).

Taconite

The truncated parabola and modified ellipse delineated for the production wells in Taconite are shorter and more elongated, respectively, than the MDH 10-year zone of transport for the wells (fig. 6). The truncated parabola and modified ellipse covered 5 percent and 31 percent, respectively, of the MDH zone of transport (table 5). The smaller aquifer saturated thickness (94 feet) for the Taconite wells compared with those of other communities on the Mesabi Iron Range (Calumet, Keewatin, and Marble) and low porosity (0.01) (table 1) resulted in a larger area difference between the truncated parabola and the modified ellipse. Similar to the wells in Calumet, the low porosity (0.01) used to delineate the modified ellipse resulted in long, 10-year travel distances for both methods (tables 3 and 4), and elongated zones resulted. However, the small aquifer thickness (94 feet) compared with the aquifer thickness at the Calumet wells (200 feet) resulted in larger X_L and Y_L values for the truncated parabola for the production wells in Taconite (table 3), thus resulting in more groundwater obtained downgradient and nearer to the well (fig. 6) than for the production wells in Calumet (fig. 3).

Askov

In general, the MDH zone of transport and WHPA for wells 3 and 4 in Askov are more conservative (larger) than the truncated parabolas and modified ellipses, even when truncated parabolas and modified ellipses in multiple directions are considered. Both the truncated parabola and modified ellipse delineated for the production wells in Askov were smaller in area and in upgradient extent when compared to the MDH zone of transport delineated using calculated-fixed-radius methods combined with an upgradient extension (fig. 7). Both the truncated parabola and modified ellipse covered only 18 percent of the MDH zone of transport (fig. 7 and table 5). The truncated parabolas and modified ellipses were smaller than the MDH zone of transport because a well discharge rate (in cubic feet per day) was used for these methods rather than a total well discharge (cubic feet) over the 10-year time period that was used for the calculated-fixed-radius method (See Differences Between Delineation Methods Section). As a result, a larger zone of transport was delineated using the calculated-fixed-radius method when compared to the two empirical methods used for this study.

The truncated parabola and modified ellipse were extended from the wells in eight different potential groundwater-flow directions identified in the MDH zone-of-transport analysis (fig. 7). This was done to create a composite truncated parabola and a composite modified ellipse to compare to the WHPA (fig. 7), which was delineated by MDH by calculating a fixed radius and extending it in eight directions to the location of sinkholes, wetlands, and a buried bedrock valley (Haglund, 2007). The composite truncated parabola covered 33 percent of the WHPA, and the composite modified ellipse covered 38 percent of the WHPA (table 5). The larger WHPA includes many of the sinkholes near the production wells, but the composite truncated parabola and composite modified ellipse do not include sinkholes north, east, west, and southwest of the production wells. Extension of the truncated parabolas and modified ellipses that extend to the north, west, and east to the hydrogeologic features used to delineate the WHPA in those directions would incorporate more of the sinkholes (fig. 7).

Fridley

All of the truncated parabolas and modified ellipses for the five production wells evaluated in Fridley and that are open to the Prairie du Chien-Jordan aquifer are smaller but similar in shape to the MDH 10-year zones of transport (fig. 8). The composite truncated parabola and composite modified ellipse for wells 6, 7, and 8 covered only 31 percent and 36 percent, respectively, of the MDH zone of transport for the wells (table 5). The truncated parabola and modified ellipse for well 11 covered 46 percent and 54 percent, respectively, of the MDH composite zone of transport delineated for the well (fig. 8 and table 5). The truncated parabola and modified ellipse for well 12 were the best fit to the MDH zones of transport for any of the production wells in Fridley. The truncated parabola and modified ellipse covered 53 percent and 69 percent, respectively, of the MDH zone of transport delineated for the well (table 5). Groundwater extraction from 22 other high-capacity wells near the Fridley production wells was taken into account in the groundwater-flow model used to delineate the MDH zones of transport, but it was not taken into account in the delineation of the truncated parabolas and modified ellipses. This water extraction could explain the larger MDH zones of transport compared with those delineated by the truncated-parabola and modified-ellipse methods.

Hastings

All of the truncated parabolas and modified ellipses for the five production wells in Hastings that are open to the Jordan aquifer are smaller than the MDH 10-year zones of transport (fig. 9). The total area for the composite truncated parabola and composite modified ellipse for wells 3, 4, and 5 covered 46 percent and 51 percent, respectively, of the MDH composite zone of transport for the wells (table 5). The truncated parabola and modified ellipse for well 4 seem to be good fits to the portion of the MDH composite zone of transport (for wells 3, 4, and 5) that is upgradient from the well (fig. 9).

The truncated parabola and modified ellipse for well 6 covered 59 percent and 63 percent, respectively, of the MDH zone of transport delineated for the well (table 5). Both the truncated parabola and modified ellipse for the well extend farther upgradient than the MDH zone of transport, but they are smaller in the direction perpendicular to flow (fig. 9). A larger hydraulic gradient used in the empirical methods than that determined by the groundwater-flow model in the vicinity of well 6 may explain these differences. The truncated parabola and modified ellipse for well 7 covered only 27 percent and 32 percent, respectively, of the MDH zone of transport delineated for the well (table 5).

Groundwater extraction from other high-capacity wells near the production wells in Hastings was taken into account in the groundwater-flow model used to delineate the MDH zones of transport, but it was not taken into account in delineation of the truncated parabolas and modified ellipses. Similar to the zone-of-transport analyses in Fridley, this water extraction could result in larger MDH zones of transport compared with the zones of transport delineated by the truncated-parabola and modified-ellipse methods. This is particularly true for the composite MDH zone of transport for wells 3, 4, and 5 and the MDH zone of transport for well 7 (fig. 9).

Le Center

The truncated parabolas and modified ellipses for the production wells in Le Center were much smaller than the MDH composite zone of transport for the wells (fig. 10).

The sum of the truncated parabolas and modified ellipses for wells 1 and 3 covered only 16 percent and 20 percent, respectively, of the MDH composite zone of transport delineated for the wells (table 5). No high-capacity wells extract groundwater from the Prairie du Chien and Jordan aquifers near the production wells in Le Center (Blum, 2003); therefore, additional groundwater extraction not taken into account in the truncated-parabola and modified-ellipse methods is an unlikely cause for the difference between the empirically derived zones of transport and the MDH zone of transport. In the groundwater-flow model used to delineate the MDH zone of transport, the Prairie du Chien aquifer and the Jordan aquifer were simulated as separate aquifers with separate sets of hydraulic parameters (Blum, 2003). The two aquifers were combined in the truncated-parabola and modified-ellipse analyses, which used weighted-mean values of the hydraulic conductivities and porosities used in the groundwater-flow model for the two hydrogeologic units. The combining of the hydrogeologic units for the empirical methods rather than separate simulations of the units may explain the differences in the areas covered by the empirically derived zones of transport and MDH zone of transport.

Fulda

Of the nine communities for which zones of transport were delineated, the truncated parabola and modified ellipse for the two production wells in Fulda best fit the MDH zones of transport (fig. 11). The areas of the truncated parabola and modified ellipse only covered 63 percent and 94 percent, respectively, of the MDH zone of transport delineated for the wells (table 5), but are larger than the MDH zone of transport (fig. 11). Both the truncated parabola and modified ellipse cover more of the aquifer downgradient from the well than the MDH zone of transport (fig. 11).

The better fit between the MDH and empirical-methods zones of transport for the Fulda wells compared with results for other study communities where the calculated-fixed-radius method combined with an upgradient extension was used to delineate the MDH zones of transport (Askov, Calumet, Marble, and Taconite) may be explained by the method used to composite multiple well zones of transport. The MDH zone of transport was delineated based on a composite calculated-fixed radius determined from two overlapping, separate zones of transport delineated for wells 1 and 6 (Olsen, 2004). The composite calculated-fixed radius was extended upgradient (west) in the direction of preferential fracturing in the aquifer to a buried bedrock valley (Olsen, 2004). The truncated parabola and modified ellipse for the production wells in Fulda were delineated on the basis of a single well representation of the two wells that combined the total pumping rates for the two wells in the calculation of a single truncated parabola and modified ellipse for the wells. This approach was used to delineate truncated parabolas, modified ellipses, and MDH zones of transport for the other communities for which the calculated-fixed-radius method combined with an upgradient extension was used. This combination of the discharge rates of the two wells prior to zone-of-transport delineation, rather than a composite of the two separate zones of transport for the two wells, may have resulted in the truncated parabola and modified ellipse being larger than the MDH zone of transport.

Implications of Zone-of-Transport Delineations

The large variability in size and shape of the zones of transport using the truncated-parabola and modified-ellipse methods delineated for the nine communities raises questions about the validity of using these methods in karst and fractured-rock settings. The variations often were largest when local hydrogeologic data were not available and regional values for hydraulic properties were used in the equations. For example, a lack of site-specific values of permeability, aquifer thicknesses, and porosity for the Biwabik Iron Formation resulted in various shapes and sizes for the wells in Calumet, Keewatin, Marble, and Taconite. These large variations had less effect on the final drinking-water-supply management area (DWSMAs) delineations where hydrologic boundaries were close to the production wells; for example, where the mine pits are near the production wells in Keewatin. The DWSMAs are surface and subsurface management and protection areas delineated around production wells using identifiable geographical landmarks that reflect as closely as possible the scientifically calculated zones of transport boundaries (Minnesota Department of Health, 2009b).The DWSMAs delineated by MDH typically were much larger than the zones of transport delineated for the communities.

Results from the empirical methods are particularly questionable under complex flow settings where many high-capacity wells or active mining operations are located in the vicinity of the production wells. These empirical methods did not take this additional water extraction into account. The methods tend to underestimate the extent of the zones of transport, particularly upgradient from the well, and this was true for the communities of Fridley and Hastings, where MDH zones of transport account for the additional water extraction in their groundwater-flow models. If this additional water extraction could be accounted for in the empirical methods, then the areas of the zones of transport may be similar to the zones of transport delineated by groundwater-flow models for some of the wells. Mining operations in the Mesabi Iron Range of Minnesota change their dewatering operations over time on the basis of mine expansion, closure, and local community water-use needs. Changes in dewatering activities can result in substantial changes in hydraulic gradients and groundwater-flow directions. As the water level rises in an abandoned mine pit following cessation of dewatering, the mine pits may become incorporated into a zone of transport and provide water to the well. Mine dewatering activities and any changes to them, therefore, need to be addressed in any zone-of-transport analyses for local production wells.

The application of the truncated-parabola method for the production wells in Askov demonstrated that if the truncated-parabola method is applied in karst and fractured-rock settings, the parabola needs to be extended at least to local hydrogeologic boundaries to include possible identified or unidentified upgradient karst features and fractures near the wells. This is similar to the approach used for the MDH calculated-fixed-radius method combined with upgradient extensions. The WHPA for the production wells in Askov, which was delineated by MDH by using extensions, included many sinkholes near the municipal wells; however, the composite truncated parabola, which was not extended, excluded many sinkholes near the production wells (fig. 7). Extension of the truncated parabolas to known hydrogeologic boundaries incorporated many, but not all, sinkholes. Hydrogeologic mapping could confirm that all karst features and fractures are included in the final WHPA.

With the exception of Askov, results from the application of the empirical methods to wells in the selected communities indicated that more field characterization at specific sites would be needed to support the use of these empirical zone-of-transport delineation methods. The assumption that Darcian flow governs groundwater flow in the zones of transport would have to be validated before the application of any zone-of-transport delineation methods that do not account for groundwater-flow conditions in solution channels and fractures. Data collection would contribute to the accomplishment of this validation, to the determination of the hydraulic properties needed for the zone-of-transport methods, and to a better understanding of the flow conditions to the well. Data requirements may include solution channel or fracture density, orientations, apertures dimensions, and other factors controlling water flow through the features.

The large scale of zones of transport commonly can make data collection for some detailed information impractical. Many equations and models exist for accounting for non-Darcian, groundwater flow through solution channels and fractures and for assessing dual primary and secondary permeability conditions (Faybishenko and others, 2000; Mackie, 1983). However, the practical application of these equations is lacking due to deficiencies in existing data and lack of detailed knowledge of the physical setting of the flow system; more complete information would improve the application of the equations and enhance understanding of the scale of the zones of transport.

A possible data collection approach to characterizing groundwater-flow conditions in the vicinity of a well in karst and fractured-rock settings could include the following steps: (1) creation of hydrogeologic maps, (2) aquifer/pumping tests, (3) water-quality/age-dating analyses, (4) borehole geophysical logging, hydrologic, and water-quality analyses, (5) surficial geophysical studies, and (6) dye tracing and water-quality tests. This data collection approach can be used to verify the assumption of Darcian flow conditions within a zone of transport, to characterize fracture-flow conditions in the vicinity of the well, and to determine an appropriate zone-of-transport delineation method to be used. For small communities that have limited resources to expend on studies, this approach could be done incrementally, over many years.

The inclusion of any karst and fractured-rock features that are identified through hydrogeologic mapping, near production wells and in any protection area delineated for the wells, would contribute to improved protection of the water supply. Hydrogeologic mapping techniques could include mapping of surficial features, such as sinkholes and springs, outcrop fractures, stream patterns, type of karst aquifer, such as epikarst and paleokarst, and lineaments. The Tennessee Division of Water Supply delineated a protection zone for the water supply of the small town of Orme, Tenn., by surveying the locations and elevations of various karst features in the drainage area for the spring (Schroll and McCormick, 1999). They found this approach to produce an effective protection area for the water supply without the cost and possible water disruptions of tracer tests.

Existing water-level data from aquifer or pumping tests and existing water-quality data from a well can be interpreted to provide an initial indication of the influence of fractures or solution channels on groundwater flow to a well. Aquifer and specific-capacity tests commonly are done on production wells installed in Minnesota as part of an aquifer test plan for delineating a wellhead protection area (Minnesota Department of Health, 2010a). Assessment of the water-level data from an aquifer test may indicate if groundwater flow to the well is diffuse or if it results from a single fracture or set of fractures (Gernand and Heidtman, 1997). Water-quality analyses for bacteria, nitrate, arsenic, and other water-quality constituents are required for public supply wells in Minnesota (Minnesota Department of Health, 2010b). Water-quality analyses and age dating of water, such as analyses for chlorofluorocarbons (CFCs), sulfur hexafluoride (SF_6), or tritium-helium, may indicate if the groundwater is from shallow or deeper solution channels or fractures. Water-quality analyses and isotopic characterization of well water and nearby surface-water bodies can be helpful for identifying groundwater and surface-water interactions and upgradient sources of water to a production well, as was done by Walsh (2004) for the MDH zone-of-transport analysis for the Keewatin wells.

If downhole access to the well is available, then borehole techniques are valuable for determining the location, geologic formations, and flow characteristics of major fractures or zones of fractures contributing water to the well. These techniques may include the application of borehole flow meters, packers, caliper logging tools, gamma logging tools, and water-quality sampling at discrete solution channels or fractures in the well. If the well is only accessible by a small-diameter monitoring pipe within the well, then less pervasive techniques, such as continuous downhole water-temperature and water-quality probes, may provide some insight into where water is entering the well and how it may vary seasonally and over storm events. Once a potential link between surficial and borehole features is suspected, surficial geophysical techniques, dye tracing, and water-quality sampling may be done to verify these linkages.

The cost and long-time period required for conducting a detailed analysis of groundwater-flow conditions in or near production wells may be excessive for small communities. Where this is true, communities may consider taking one of the following approaches: (1) assessment of the vulnerability of the water supply to potential contamination and of the cost of follow-up water treatment or water-supply replacement or (2) delineation of large protection areas incorporating multiple production wells. For example, the Center of Hydrogeology of the University of Neuchâtel, Switzerland, developed and applied a multi-attribute approach to mapping intrinsic vulnerability of a karst catchment area for a well or spring to be used to define protection zones (Doerfliger and others, 1999). Four attributes of a karst aquifer were considered in this approach: (1) level of epikarst development, (2) thickness and hydrogeology of protective cover, (3) type of recharge (diffuse or concentrated) to the karst aquifer, and (4) solution channel network development. These attributes are weighted and subdivided into classes that are mapped over the catchment area of the well or spring.

The costs of water treatment or water-supply replacement can be high, depending upon the treatment needed, the type of replacement water (surface or groundwater), and the water distribution system. Options for replacing a current water supply that is contaminated may include locating new wells outside of the contaminated area or using potential surface-water sources. The cost of additional water treatment for surface waters used for drinking water is a substantial consideration in the cost assessment.

The delineation of large protection areas to protect many water supplies has been applied in karst settings. This approach commonly is used in karst and fractured-rock settings where little is known of groundwater-flow paths. The Ohio Environmental Protection Agency and the Great Lakes Rural Community Assistance Program delineated an entire region where water is contributed to wells by a karst aquifer in northwestern Ohio as a drinking-water source protection area, encompassing 15 water supplies (U.S. Environmental Protection Agency, 2010). Delineation of a large protection area around multiple water supplies requires an inventory and the management of a large number of potential sources of contamination.

Summary

Communities in northern, southeastern, and southwestern Minnesota use production wells to extract groundwater from bedrock aquifers in which groundwater flows through karst features and fractures. Source waters for these wells are particularly vulnerable to contamination mainly due to short residence times for groundwater in these aquifers. Several approaches that account for flow through solution channels or fractures have been used to delineate zones of transport around wells that obtain groundwater from karst and fractured-rock aquifers. However, the more detailed approaches to zone-of-transport delineation commonly are too expensive and impractical for many Minnesota communities using groundwater from karst and fractured-rock aquifers. Simple, less empirical methods that apply porous media equations and existing hydrogeologic data are available; however, the accuracy of zones of transport delineated by using empirical methods may be questionable for complex karst and fractured-rock settings.

The U.S. Geological Survey (USGS) , in cooperation with the Minnesota Department of Health (MDH), applied and evaluated two empirical methods—the truncated-parabola and modified-ellipse methods—to 24 production wells that extract groundwater from karst and fractured-rock aquifers in nine Minnesota communities. These wells extracted water from a karst aquifer (Prairie du Chien and Jordan aquifers), porous aquifers interspersed with solution-enhanced fractures (Jordan and Hinckley aquifers), or fractured-bedrock aquifers (Biwabik Iron Formation and Sioux Quartzite aquifers), which are confined or unconfined depending on location. Two of the production wells evaluated in this study (Hastings wells 4 and 5) also extract water from the St. Lawrence Formation, and one production well (Fridley well 11) also extracts water from the St. Lawrence Formation and Franconia Sandstone. The St. Lawrence Formation and Franconia Sandstone were not included in zone-of-transport delineations done in this study. Results from application of these methods were compared with zones of transport previously delineated by MDH hydrologists for the wells. The study focused on producing zones of transport using existing data and empirical methods.

The truncated-parabola and modified-ellipse methods are calculated-variable-shape methods that delineate zones of transport based on the superposition of the effects of uniform flow gradients on the effects of the pumping well. These methods use hydrogeologic properties for which values typically are available to water suppliers and managers or can be estimated from literature values. Both empirical methods assume porous-media (Darcian) flow conditions in the aquifer. The application of zone-of-transport delineation methods derived under the assumptions of Darcian flow to karst and fractured-rock settings requires scrutinization.

Large differences were seen in the size and shapes of most zones of transport delineated using the truncated-parabola and modified-ellipse methods compared with the MDH zones of transport. In general, the zones of transport delineated using the truncated-parabola and modified-ellipse methods were smaller in area than the MDH zones of transport and incorporated only a small portion of the MDH zone of transport. About two-thirds (67 percent) of the individual or composite truncated parabolas and modified ellipses covered less than 50 percent of the area incorporated by the MDH zones of transport. The shapes of some of the truncated parabola and modified ellipses did not closely match the MDH delineated zones of transport, which were delineated by use of the calculated-fixed-radius methods and groundwater-flow models.

Differences between the truncated-parabola and modified-ellipse zones of transport and MDH zones of transport can be explained by variations inherent to the methods and in the amount of complexity taken into account by groundwater-flow models. The calculated-fixed-radius method combined with an upgradient extension used by MDH to delineate zones of transport for wells in the communities of Askov, Calumet, Fulda, Marble, and Taconite is more conservative and produces larger zones of transport than the zones of transport delineated by the truncated-parabola and modified-ellipse methods. This is because the calculated-fixed-radius method uses a total discharge (in cubic feet) over the specified time period, for this application 10 years, for the amount of flow through the well rather than a well discharge rate (in cubic feet per day). Groundwater-flow models used to delineate some of the MDH zones of transport for wells in Fridley, Hastings, and Le Center accounted for the influence of groundwater extraction from nearby multiple large-capacity wells, which was not taken into account in the two empirical methods. Results from zone-of-transport analyses for the wells in Askov indicated that if the truncated-parabola method is applied in karst and fractured-rock settings, then the parabola needs to be extended at least to local hydrogeologic boundaries to include possible identified or unidentified upgradient karst features or fractures near the wells.

In general, additional field hydrogeologic characterization would be needed at specific sites to support the use of these empirical zone-of-transport delineation methods. Results from the evaluation of the empirical methods indicate that the application of the truncated-parabola and modified-ellipse methods using limited existing hydrogeologic information can produce questionable results in karst and fractured-rock settings, particularly in areas where many high-capacity wells or active mining operations are present in the vicinity of the production well. The assumption that Darcian flow conditions govern groundwater flow in the zones of transport would need to be supported using site-specific hydrogeologic characterization before applying any zone-of-transport delineation methods that do not account for groundwater-flow conditions in solution channels and fractures. Hydrogeologic data collection to support groundwater-flow characterization in the vicinity of a production well may include hydrogeologic mapping, aquifer or pumping tests, water-quality and age-dating analysis of local surface and groundwater, borehole geophysical logging, surficial geophysical analyses, and dye tracing. For communities that have a limited amount of resources to expend on studies, data-collection efforts could be done incrementally over many years.

References Cited

Austin, G.S., 1972, The Sioux Quartzite, southwestern Minnesota, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota—a centennial volume: Minnesota Geological Survey, p. 450–455.

Bair, E.S., and Roadcap, G.S., 1992, Comparison of flow models used to delineate capture zones of wells—1. Leaky-confined fractured-carbonate aquifer: Ground Water, v. 30, no. 2, p. 199–211.

Barr Engineering, 2003, Wellhead protection plan for the city of Hastings, Minnesota, part 1: Minnesota Department of Health, 35 p.

Barton, G.J., Risser, D.W., Galeone, D.G., and Goode, D.J., 1999, Case study for delineating a contributing area to a water-supply well in a fractured crystalline-bedrock aquifer, Stewartstown, Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 99–4047, 38 p.

Barton, G.J., Risser, D.W., Galeone, D.G., and Goode, D.J., 2003, Case study for delineating a contributing area to a well in a fractured siliciclastic-bedrock aquifer near Lansdale, Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 02–4217, 46 p.

Berg, J.A., 2004, Hydrogeology of the unconsolidated and bedrock aquifers, *in* Geologic atlas of Pine County, Minnesota, part B, hydrogeology: Minnesota Department of Natural Resources, County Atlas Series C–13, plate 8.

Blum, J.L., 2003, Wellhead protection plan for the city of Le Center, Minnesota, part 1: Minnesota Department of Health, 28 p.

Bradbury, K.R., Muldoon, M.A., Zaporozec, A., and Levy, J., 1991, Delineation of wellhead protection areas in fractured rocks: Wisconsin Geological and Natural History Survey/U.S. Environmental Protection Agency Report EPA 570/9–91–009, 144 p.

Delin, G.N., and Almendinger, J.E., 1991, Delineation of recharge areas for selected wells in the St. Peter Prairie du Chien-Jordan aquifer, Rochester, Minnesota: U.S. Geological Survey Water-Supply Paper 2397, 39 p.

Doerfliger, N., Jeannin, P.Y., and Zwahlen, F., 1999, Water vulnerability assessment in karst environments—a new method of defining protection areas using a multi-approach and GIS tools (EPIK method): Environmental Geology, v. 39, no. 2, p. 165–176.

Faybishenko, B., Witherspoon, P.A., and Benson, S.M., 2000, Dynamics of fluids in fractured rock: American Geophysical Union, Geophysical Monograph, 122, 400 p.

Fetter, C.W., 2001, Applied hydrogeology: Upper Saddle River, New Jersey, Prentice Hall, Inc., 598 p.

Gernand, J.D., and Heidtman, J.P., 1997, Detailed pumping test to characterize a fractured bedrock aquifer: Ground Water, v. 35, no. 4, p. 632–637.

Haglund, G., 2007, Wellhead protection plan for the city of Askov, Minnesota, part 1: Minnesota Department of Health, 46 p.

Jennings, C.E., and Reynolds, W.K., 2005, Surficial geology of the Mesabi Iron Range, Minnesota: Minnesota Geological Survey, Miscellaneous Map Series, Map M–164.

Jirsa, A., Chandler, V.W., and Lively, R.S., 2005, Bedrock geology of the Mesabi Iron Range, Minnesota, Minnesota Geological Survey, Miscellaneous Map Series, Map M–163.

Jones, P.M., 2002, Characterization of ground-water flow between the Canisteo mine pit and surrounding aquifers, Mesabi Iron Range, Minnesota: U.S. Geological Survey Water-Resources Investigations Report 02–4198, 30 p.

Kanivetsky, R., 1978, Hydrogeologic map of Minnesota, bedrock hydrogeology: Minnesota Geologic Survey, sheet 1 (map), sheet 2 (cross-sections) and accompanying text, scale 1:500,000.

Kenny, J.F., Barber, N.L., Hutson, S.S., Linsey, K.S., Lovelace, J.K., and Maupin, M.A., 2009, Estimated use of water in the United States in 2005: U.S. Geological Survey Circular 1344, 52 p.

Knochenmus, L.A., and Robinson, J.L., 1996, Descriptions of anisotropy and heterogeneity and their effect on ground-water flow and areas of contribution to public supply wells in a karst carbonate aquifer system: U.S. Geological Survey Water-Supply Paper 2475, 47 p.

Long, J.C.S., Remer, J.S., Wilson, C.R., and Witherspoon, P.A., 1982, Porous media equivalents for networks of discontinuous fractures: Water Resources Research, v. 18, no. 3, p. 645–658.

Mackie, C.D., 1983, Determination of non-linear formation losses in pumping wells: Proceedings of the International Conference on Groundwater and Man, Sydney, Australia, p. 199–210.

Minnesota Department of Health, 2005a, Wellhead protection, accessed May 11, 2005, at *http://www.health.state.mn.us/divs/eh/water/swp/whp/index.htm.*

Minnesota Department of Health, 2005b, Tools for wellhead protection teams, accessed May 11, 2005, at *http://www.health.state.mn.us/divs/eh/water/swp/whp/whptools.html.*

Minnesota Department of Health, 2005c, Guidance for delineating wellhead protection areas in fractured and solution-weathered bedrock: Minnesota Department of Health, 87 p.

Minnesota Department of Health, 2009a, Community public water supply general information, accessed October 29, 2009, at *http://www.health.state.mn.us/divs/eh/water/com/index.htm.*

Minnesota Department of Health, 2009b, Wellhead protection area delineation, accessed October 30, 2009, at *http://www.health.state.mn.us/divs/eh/water/swp/whp/fs/swpadfs.htm.*

Minnesota Department of Health, 2010a, Wellhead protection area delineation, accessed January 20, 2010, at *http://www.health.state.mn.us/divs/eh/water/swp/whp/fs/swpadfs.html.*

Minnesota Department of Health, 2010b, Monitoring and testing of drinking water in Minnesota, accessed January 20, 2010, at *http://www.health.state.mn.us/divs/eh/water/factsheet/com/sampling.html.*

Minnesota Department of Natural Resources, 2006, Mesabi iron range mine features, Arc/Info export files and shape files of mine features: CD-ROM data.

Minnesota Department of Natural Resources, 2010, Water use–water appropriations permit program, accessed January 19, 2010, at *http://www.dnr.state.mn.us/waters/watermgmt_section/appropriations/wateruse.html.*

Morey, G.B., 1972, Mesabi Range, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota—a centennial volume: Minnesota Geological Survey, p. 204–217.

Olsen, B., 2004, Wellhead protection plan for the city of Fulda, Minnesota, part 1: Minnesota Department of Health, 37 p.

Patterson, C.J., and Knaeble, A.R., 2001, Surficial geology, *in* Geologic atlas of Pine County, part A, geology Minnesota: Minnesota Geological Survey, County Atlas Series C–13, part A, plate 4.

Podgorney, R.K., and Ritzi, R.W., Jr., 1997, Capture zone geometry in a fractured carbonate aquifer: Ground Water, v. 35, no. 6, p. 1040–1049.

Robertson, S.W., 2002, Wellhead protection plan for the city of Fridley, Minnesota, part 1: Minnesota Department of Health, 59 p.

Runkel, A.C., Tipping, R.G., Alexander, E.C., Jr., Green, J.A., Mossler, J.H., and Alexander, S.C., 2003, Hydrogeology of the Paleozoic bedrock in southeastern Minnesota: Minnesota Geological Survey Report of Investigations 61, 105 p., 2 pls.

Scholl, J.S., and McCormick, J.R., 1999, Delineation of the recharge area for a karst spring serving a small community on the Cumberland Plateau Escarpment: Proceedings of the National Cave and Karst Management Symposium, Chattanooga, Tennessee, p. 178–182.

Shade, B.L., Alexander, C.A., Alexander, S.C., and Martin, S., 2001, Sinkhole distribution, *in* Geologic atlas of Pine County, Minnesota, part A, geology: Minnesota Geological Survey, County Atlas Series C–13, part A, plate 6.

Shade, B.L, Alexander, S.C., and Alexander, E.C., Jr., 2002, Karst features in Pine County, Minnesota, *in* Contributions to the geology of Pine County, Minnesota: Minnesota Geological Survey, Report of Investigations 60, p. 53–70.

Todd, D.K., 1980, Groundwater hydrology: New York, N.Y., John Wiley and Sons, 535 p.

U.S. Census Bureau, 2005, American FactFinder, population finder: Information available on the Web, accessed March 13, 2007, at *http://www.census.gov/.*

U.S. Environmental Protection Agency, 1987, Guidelines for delineation of wellhead protection areas: U.S. Environmental Protection Agency, EPA 440/6–87–010.

U.S. Environmental Protection Agency, 1993, Guidelines for delineation of wellhead protection areas: U.S. Environmental Protection Agency, EPA 440–5–93–001; update of same document produced in 1987 (EPA 440/6–87–010).

U.S. Environmental Protection Agency, 2010, Our goal: all people in Region 5 served by public water supplies will have water that is consistently safe to drink, accessed February 8, 2010, at *http://www.epa.state.oh.us/ddagw/pdu/swap_karst.html*.

Walsh, J.F., 2003, Wellhead protection plan for the city of Keewatin, Minnesota, part 1: Minnesota Department of Health, 33 p.

Walsh, J.F., 2004, Isotopic and chemical characterization of water from mine pits and wells on the Mesabi Iron Range, northeastern Minnesota, as a tool for drinking water protection: 2004 U.S. EPA/NGWA Fractured Rock Conference, Portland, Maine, September 13–15.

Walsh, J.F., 2007a, Wellhead protection plan for the city of Marble, Minnesota, part 1: Minnesota Department of Health, 39 p.

Walsh, J.F., 2007b, Wellhead protection plan for the city of Taconite, Minnesota, part 1: Minnesota Department of Health, 40 p.

USGS

Jones—**Evaluation of Methods for Delineating Zones of Transport for Production Wells in Karst and Fractured-Rock Aquifers of Minnesota**—SIR 2010–5005