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Groundwater Flow Model for the City of West Bend, Washington County, Wisconsin:

Report to the City of West Bend, Wisconsin

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Groundwater flow model for the City of West Bend, Washington County, Wisconsin

Introduction

Purpose

Project setting and scope

This report describes the development, construction, and application of a numerical groundwater flow model for the City of West Bend, Wisconsin and surrounding areas. West Bend, located in Washington County, southeastern Wisconsin, has a population of about 29,600. Groundwater is the sole source of water supply for the City, and is supplied to local residents by the West Bend Municipal Water Utility. In 2005 the utility operated nine high-capacity wells for water supply. Although these wells are adequate for present needs, the City continues to grow, and the Water Utility has supported continuing efforts to determine sites for additional wells for increased future supply.

The model area discussed in this report includes the City of West Bend and nearby areas (figure 1). Project boundaries are based on local hydrology and preliminary modeling using an analytic element screening model (described below).

Objectives

This project developed a detailed groundwater flow model of the West Bend, Wisconsin area. The model is designed to be a groundwater management tool. Specific uses of the model include:

- delineating contributing areas for current and future municipal wells as part of the City's wellhead protection efforts;
- simulating current and future groundwater and well pumping scenarios for support of management decisions;
- investigating groundwater/surface water issues, such as the relationship between the local aquifers and the Milwaukee River, local lakes, and local wetlands;
- evaluation of future water supply options for the City.

The model is designed be updated and used by the City for future groundwater supply planning and management.

Acknowledgments

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Background

Recent groundwater studies in southeastern Wisconsin

The West Bend model is an outgrowth of a series of groundwater studies and groundwater models undertaken by the Southeastern Wisconsin Regional planning Commission (SEWRPC) between 1998 and 2006 in the 7-county region of southeastern Wisconsin bordering Lake Michigan and Illinois (figure 1). A joint report by the Wisconsin Geological and Natural History Survey (WGNHS) and SEWRPC (SEWRPC/WGNHS, 2002) summarizes the groundwater resources of this region. Recently, the WGNHS, in cooperation with the U S Geological Survey (USGS) developed a regional groundwater flow model for the region and with major funding from water utilities in the seven counties. SEWRPC Technical Report 41 (*A Regional Aquifer Simulation Model for Southeastern Wisconsin*, SEWRPC, 2005) contains two reports (Feinstein and others, 2005b, 2005b) documenting model construction, calibration and use. Although the regional model includes all aquifer units in the region, its focus is on groundwater flow in the deep sandstone aquifer, which is the source of water for many deep high-capacity wells in the region. The regional model results demonstrate that these wells have caused significant drawdown in water levels in the deep sandstone aquifer. The regional model also demonstrates that these deep drawdowns induce downward flow from overlying shallow aquifers and surface-water features. The possible impacts of this increased downward flow included lowered water-table and surface-water levels and reduced base flow in streams, but it is difficult to document these impacts without extensive field study.

The regional SEWRPC model is based on a numerical finite-difference grid and uses the MODFLOW groundwater modeling code (McDonald and Harbaugh, 1988). Resolution of the regional model is limited by the grid spacing, which has a minimum size of 2500 feet. This resolution is generally too coarse to include more than very general shallow hydrologic features.

Hydrogeology of the West Bend area

Both groundwater and surface water resources are abundant near West Bend. Numerous rivers, lakes and wetlands occur in and around West Bend (figure 2), and these features are generally well-connected to the local groundwater system. The Milwaukee River flows through downtown West Bend, and is controlled by several dams. West of the city, water from Silver Lake and Lucas Lake flows into Silver Creek and eventually discharges into the Milwaukee River. Several other smaller streams, such as Quaas Creek and Silverbrook Creek, also drain to the Milwaukee River. These streams, and the Milwaukee River, are also natural discharge points for local groundwater flow.

West Bend is located adjacent to the Kettle Moraine area of Wisconsin, where Pleistocene glaciation produced a depositional landscape of rolling hills and numerous glacial landforms such as kettles, eskers, kames, and drumlins. Sand, gravel, and diamicton (poorly-sorted sediment commonly interpreted as till) deposited by glaciers and outwash streams dominate the surficial geology of the West Bend area. Mickelson and Syverson (1997) present maps of these glacial deposits and associated landforms (figure 3). Massie-Ferch and Peters (2004) recently mapped the bedrock geology of Washington County. In the project area, glacial deposits cover dolomite of Silurian age, commonly called the Niagara dolomite (table 1). The Ordovician Maquoketa Formation, an important regional aquitard, lies beneath the dolomite. The dolomite aquifer varies in thickness from absent, in deep preglacial channels just east and west of West Bend, to nearly 300 feet thick (Young and Batten, 1980). Figure 4 shows the Maquoketa exposed in the preglacial valley wrapping around the south side of the city. The Maquoketa Shale forms an important regional aquitard, and is the base unit considered for this study. Beneath the Maquoketa, a series of Cambrian and Ordovician-age sandstone and dolomite formations form a deep regional "sandstone" aquifer over much of the SEWRPC region (SEWRPC/WGNHS, 2002). This deep aquifer is over 1000 feet thick in nearby Waukesha and Milwaukee Counties, where it is used extensively for water supply, but is thinner and less productive near West Bend.

Table 1. Shallow stratigraphy of the West Bend area.

Age	Formation	Lithology	Thickness range (feet)	Hydraulic properties
Quaternary	undifferentiated	sand, silt, and organic sediment	0 - 50	extremely variable
	Kewaunee, Oak Creek, Holy Hill, and New Berlin Formations	interbedded diamicton, stream gravel and sand, and lake silt and sand	0 - 400	continuous sand units form prolific shallow aquifers; silt and clay units form shallow aquitards
Silurian	Niagara dolomite	dolomite, white to grey, abundant but discontinuous fractures and solution channels	0 - 300	variable, forms an important aquifer where formation is thick
Ordovician	Maquoketa shale	dolomitic, blue-grey, interbedded shale and dolomite	100-300	regional aquitard

Methodology

Hydrogeologic framework

Establishing a conceptual hydrogeologic framework is essential for any modeling study. The conceptual model is a simplified version of the complex distribution of geologic materials in the study area. The West Bend study compiled information from published sources (primarily Young and Batten, 1980, Mickelson and Syverson, 1997, and Layne Northwest, 1979, 1999) and unpublished data available in the files of the WGNHS, USGS, and WDNR. Geologic maps previously developed for the SEWRPC region (SEWRPC/WGNHS, 2002; Massie-Ferch and Peters, 2004) provided information on material thicknesses and bedrock morphology. These data were assembled into a geographic information system (GIS) and overlayed with basemaps in the WTM coordinate system.

Estimation of hydrogeologic parameters

Hydrogeologic parameters such as hydraulic conductivity, transmissivity, and porosity are critical information for a groundwater flow model. The complex glacial history of the West Bend area has produced high variability in hydraulic conductivity, ranging from less than 1 ft/day in silt and lacustrine deposits to over 1000 ft/day in well-sorted sands and gravels (Young and Batten, 1980). Hydraulic conductivity data used in this report came primarily from three sources, as follows:

- maps of Quaternary materials and summary grain-size distribution data from Mickelson and Syverson (1997),
- aquifer pumping tests conducted using the West Bend municipal wells, compiled and reanalyzed by Layne Northwest (Dan Peplinski, written communication), and
- specific capacity tests on local domestic and commercial wells, analyzed using the TGUESS routine of Bradbury and Rothschild (1994).

Streamflow measurement

Groundwater discharge is an important component of the groundwater budget and is the source of base flow to streams. During this project WGNHS technicians measured surface-water flows at 13 sites in and around the city (figure 2). Measurements were conducted on 5/12/05, following several days of dry weather when the streams were at a low-flow stage. We used a Marsh-McBirney electronic flowmeter mounted on a wading rod to measure discharge, and integrated the flow across the channel using standard depth-slice methods. In addition, we used historic USGS streamflow data to estimate groundwater discharge to the Milwaukee River (Holmstrom, 1982).

Water sample analysis for environmental isotopes

The West Bend project included analyses of environmental isotopes of hydrogen (^{2}H, deuterium and ^{3}H, tritium) and oxygen (^{18}O, oxygen-18) in water produced by municipal wells. These isotopes, often called environmental isotopes because they occur naturally, can provide important information on groundwater age and source area. For this project, water utility employees collected water samples from the West Bend municipal wells at the wellhead prior to any water treatment. Samples were shipped to the Environmental Isotope Laboratory at the University of Waterloo, Ontario, for analysis. Deuterium was determined by manganese reduction (Drimmie et al. 1991). Oxygen-18 was determined by mass spectrometry on CO_2 gas (Drimmie and Heemskerk, 1993). Tritium was determined by liquid scintillation counting on enriched samples (Drimmie et al 1993). Tritium results are reported in Tritium Units (TU; one TU equals one tritium atom in 10^{18} atoms of hydrogen). Deuterium and oxygen-18 results are reported as $\boldsymbol{\delta}\ {}^{0}/_{00}$ (del per mil) differences from the concentrations in standard mean ocean water (SMOW).

Groundwater flow modeling

Modeling process

Groundwater modeling for the West Bend project followed a two-step process. First, we constructed a simple 2-dimensional screening model using the GFLOW analytic-element code (Haitjema, 1995). This model was used to establish boundary locations and conditions for the final 3-dimensional model (e.g. Hunt and others, 1998). Analytic element models utilize exact analytical solutions to a series of mathematical equations describing groundwater flow. The analytic element method can represent many important hydrologic features, such as wells, streams, or lakes, by a series of analytic equations. The analytic element method is independent of scale, and does not require a mathematical grid. It yields solutions for problems at any scale, from a few square feet to many square miles. Analytic element models require simplification of complex groundwater flow systems, and cannot always accurately simulate details of three-dimensional flow or heterogeneity. However since they are relatively easy to construct, analytic element models are commonly used to test and develop boundaries and other components for detailed finite difference groundwater flow models. Appendix A describes the GFLOW model constructed for West Bend.

MODFLOW modeling code

The final West Bend model uses the MODFLOW finite-difference groundwater modeling code developed by the US Geological Survey (McDonald and Harbaugh, 1988). MODFLOW is a powerful and flexible modeling code that is used throughout the United States and the world. It allows 3-dimensional steady state and transient simulations including variable aquifer property zones and complex boundary conditions such as wells, rivers, lakes, streams, and wetlands. The MODFLOW river package was used to simulate flows to or from most surface streams in the model. The river package simulates surface-water features as head-dependent boundaries; groundwater flow depends on the difference in head between constant head assigned to each river node and the calculated head in adjacent model nodes. The MODFLOW drain package simulates shallow features such as wetlands or smaller streams. The drain package is identical to the river package except that the drain package allows surface water features to become inactive if the water table falls beneath the base of the surface-water feature.

A companion code, MODPATH (Pollock, 1994) performs forward and backward particle tracing in order to delineate groundwater flow paths and rates. In forward tracking, hypothetical particles are placed at the water table and allowed to move forward as advective flow. For reverse tracking we placed a rings of hypothetical particles around each well at appropriate screen depths and exercised the model to track these particles backward against the hydraulic gradient to outline contributing areas for the wells. We used the graphic interface Groundwater Vistas (version 4; ESI, 2004) for model input and output and for data visualization.

Data entry

Model data entry utilized the capabilities of Groundwater Vistas to import and interpolate GIS shapefiles and raster (gridded) datsets.

Model assumptions

The groundwater flow model developed for West Bend uses the following assumptions:

- steady flow - all model parameters, including recharge, discharge, and well pumping, are constant with time;
- three-dimensional flow - aquifer parameters, hydraulic head, and groundwater flow paths are simulated in three dimensions; and
- all flow occurs above the Maquoketa Formation - the model does not simulate the lower sandstone aquifer.

Model calibration

Model calibration is the process of adjusting model parameters (hydraulic conductivity, recharge rates, and streambed properties) within reasonable limits until the output of model simulations (hydraulic heads and fluxes of water) reasonably matches target values observed in the field. Calibration targets for the West Bend model consisted of water levels in local wells and water fluxes (flows) measured at local surface water features. The PEST parameter estimation utility was used to aid model calibration. PEST (Dougherty, 2004) is a model-independent computer code that uses linear and nonlinear regression techniques to seek a best model fit to a given set of calibration targets.

Head targets

Head targets included water levels in 271 local wells (figure 5). Of these wells, 173 were completed in unlithified materials and 98 were completed in dolomite. Head targets were selected from several available sets of data, as follows:

1. Wells identified using well construction reports available in the WGNHS files. Only wells having good construction records were used. These wells were almost exclusively water-supply wells, and so reflect a bias toward more permeable geologic materials. Using modern and historic plat maps, WGNHS workers plotted the location of these wells on 1:24000 scale topographic maps, and estimated the surface elevation of each well from the map contours. Depth to static water in each well was taken from the well construction reports. Subtracting the depth to water from the surface elevation gives the hydraulic head in each well, in feet above sea level.
2. Exploration wells and borings installed by water supply consultants for the City of West Bend (Layne Northwest, 1979, 1980). Only a few of these wells and

borings had sufficient location or water-level records to be useful as model targets.

3. Monitoring wells and piezometers installed by engineering consulting firms during selected groundwater contamination investigations in the city, and monitoring wells near the West Bend landfill. Many of these wells are shallow and completed in lower permeability materials. These data were obtained from WDNR files and from reports to the city.
4. Targets identified by the USGS in a study of groundwater flow near Silver Lake (Dunning and others, 2003). The USGS provided digital files of these targets which were primarily shallow water-supply wells near Silver Lake.

Field measurement of wells and surface water levels was beyond the scope of this project, and the head target data set contains considerable uncertainty. This uncertainty is related to location errors, errors in interpolating from topographic maps, errors in the water levels reported by well drillers, and errors associated with seasonal or longer-term changes in groundwater levels. It is difficult to quantify this uncertainty completely, but in general the target head measurements are expected to have an uncertainty of at least +/- 5 feet.

Flux targets

Flux (flow) targets included baseflow estimates for 13 stream gauging sites (table 2, figure 5). Target flows at 12 of these locations were based on the streamflow survey conducted for this project, and flow at the final reach, the Milwaukee River between West Bend and Newburg, was based on an analysis of published streamflow records for Wisconsin. As with the head targets, the flux targets contain considerable uncertainty. The calibration targets assume base flow conditions and only relate to groundwater discharge, a situation difficult to verify in the field. In addition, as flow rates become lower, potential measurement errors become statistically proportionally higher.

Model predictions

The groundwater flow model simulates the shallow groundwater system. It produces three types of output that are useful in evaluation of the effect of existing and potential new city wells on the system. These three outputs are simulated hydraulic heads, simulated flow rates to surface water features, and simulated groundwater flow paths.

Drawdown

The MODFLOW code calculates simulated hydraulic head throughout the model domain. The model then uses a contour-interpolation routine to produce contour maps of head. The model calculates drawdown caused by the wells by subtracting heads simulated in a run using pumping wells from heads simulated in a base run (no pumping wells).

Surface-water flows

The MODFLOW code computes flows of groundwater into or out of head dependant boundaries such as lakes, streams, or wetlands. Calculation of these boundary flow rates is an important check on model calibration, and also allows evaluation of the impacts of land-use change, such as increased well pumping, on surface-water resources.

Contributing areas for wells and surface water features

A companion particle tracking code, MODPATH (Pollock, 1994), allows determination of simulated groundwater flow paths to wells and surface-water features.

Table 2. Streamflow measurement sites

site name	site number	model reach	observed flow, cfs
Silverbrook Creek at Walnut Street	1	1	0.07
Silver Creek at Regner Park	2	2	0.17
culvert below wetland along Schmidt Road	3	3	0.20
Quaas Creek at E. Decorah Rd	4	4	0.25
unnamed creek at E. Decorah Rd	5	5	1.04
Quaas Creek at Cty Rd G	6	6	1.49
Quaas Creek at Cty Rd P	7	7	1.70
south fork Quaas Creek above Cty Rd P	8	8	1.05
Quaas Creek at culvert along 18th Ave	9	9	0.16
Cedar Creek at Pleasant Valley Rd	10	10	0.41
Silverbrook Creek at 18 Ave	11	11	0.43
Silver Creek at 18th Ave	12	12	2.91
unnamed creek at Cty Hwy H	13	13	0.68
Milwaukee River at Newburg[1]		102	5.40

[1]Milwaukee River not gauged; flow taken from published records.

Simulation of the groundwater system

Conceptual model

The conceptual model is a simplified description of the real-world situation to be simulated. The West Bend model covers the area delineated using the GFLOW simulation (Appendix A) and outlined in figure 1. The model simulates groundwater flow above the Maquoketa shale, which forms the base of the model. The model contains two aquifer units: the upper unlithified Quaternary materials and the lower dolomite. Each of these units is irregular in thickness. Figure 6 shows the configuration of these two hydrogeologic units, and figure 7 shows cross sections across the model area. The water table forms the top of the system.

Water enters the system through recharge at the water table and as downward or lateral flow from streams and wetlands. Water leaves the system as discharge to surface water features and discharge to wells. There is no change in storage for the steady state model, and the model solution maintains a water balance (inflows=outflows).

Finite-difference grid

The finite-difference grid developed for the West Bend model contains 197 rows, 178 columns, and 3 layers, for a total of 105,200 cells, of which 91,400 are active (figure 8). Node spacings range from 200 feet near municipal wells to about 1500 feet along the model boundaries. Figure 8 shows the distribution of boundary conditions. Model layers 1 and 2 simulate the unlithified materials, equally divided into these two layers. Model layer 3 simulates the dolomite aquifer.

Hydraulic properties

Hydraulic conductivities

Measured or estimated hydraulic conductivities in the area range from 0.1 ft/day for silt and lacusterine sediment to 300 ft/day in sand and gravel near existing municipal wells. For comparison, Young and Batten (1980) report a hydraulic conductivity range of 20 to 1,500 ft/day for the sand and gravel aquifer and .01 to 585 ft/day for the dolomite in Washington County. Figure 9 shows the distribution of hydraulic conductivity estimates from specific capacity estimates and pumping tests on wells finished in the sand and gravel aquifer. The mean result for the city well pumping tests (214 ft/day) is significantly larger than the mean result for tests on domestic wells (41 ft/day). This difference is probably due to several factors. The city wells are sited in the most conductive parts of the aquifer, and are designed and constructed to higher standards. In addition, large-scale pumping tests stress a larger volume of material than do single well specific capacity tests and usually return larger values.

The initial spatial zoning of hydraulic conductivity in layers 1 and 2 was based on the distribution of materials shown in maps and cross sections from Mickelson and Syverson (1997). Translation from the Quaternary maps to model units required significant interpretation and generalization. The two model layers were zoned differently, as

Mickelson and Syverson's cross sections show that a region of lacustrine silt and sand of the Waubeka Member of the Holy Hill Formation overlies more conductive sands and gravels north and east of the city. Figure 10 shows the initial zonation in layer 1 and 2, and table 3 summarizes the model units and presents initial estimates of hydraulic conductivity. The hydraulic conductivity of the dolomite in layer 3 was assumed to be constant across the model, although the thickness, and thus the transmissivity, of layer 3 varies. An initial hydraulic conductivity of 4 ft/day assigned to layer 3 was based on calibrated values from the regional SEWRPC model (Feinstein and others, 2005b). The model includes horizontal isotropy (K_x=K_y) in all model units but uses variable horizontal:vertical anisotropy.

Table 3. Zonation and initial hydraulic conductivity estimates for the West Bend model.

model zone	layers	primary map units[1]	lithology	interpretation	K_x, K_z, ft/day
1	1, 2	undifferentiated Holy Hill Fm (Ug), New Berlin Member of Holy Hill Fm (Ngh, Ngp, Ngpp)	coarse stratified sand and gravel, moderately well sorted, extending from surface to bedrock	good to very good aquifer, probably discontinuous	50, 5
2	1, 2	silt and sand of Horicon Member of Holy Hill Fm (Hip, Hsp, Htg)	moderately well sorted silt, sand, and clay; poorly sorted diamicton	fair to good aquifer	10, 0.1
3	1	lacustrine silt and sand of the Waubeka member of the Holy Hill Fm (Wip, Wih).	moderately well sorted silt with some sand and clay	lower-conductivity unit; acts as aquitard where it covers more conductive materials	1, .1
4	2	diamicton, sand, and gravel of the NewBerlin Member of the Holy Hill Fm (Ntg, Ngpp)	moderately well sorted silt, sand, and clay; poorly sorted diamicton	fair to good aquifer; present only in subsurface; distribution interpreted from cross sections	10, 1
5	-	-	-	not used in model	-, -
6	1, 2	lacustrine sand and diamicton of the Waubeka Member of the Holy Hill Fm (Wsh, Wgh, Wtr)	sand, moderately wells sorted to well sorted; stratified to unstratified sandy silt	variable unit, often in areas of shallow bedrock	10, 1

[1] primary units from maps and cross sections in Mickelson and Syverson (1997); abbreviations refer to map units

Porosity

Values of effective porosity (the volume of interconnected pore space in a hydrogeologic material) are needed for particle tracking simulations using MODPATH. Field measurements of effective porosity for the West Bend area are not available, and the porosity values are taken from literature values for similar materials. A porosity of 0.15 was assigned to layers 1 and 2 and a porosity of 0.05 was assigned to the dolomite in layer 3.

Streambed properties

Each head-dependent boundary (river and drain node) in the model requires data on the vertical conductance (vertical hydraulic conductivity divided by thickness) of the sediment layer separating the surface water feature from the aquifer beneath it. Field measurement of these values was beyond the scope of the West Bend project. Measurements of streambed properties in Dane County, WI give a range of 1.6 ft/d/ft to 37 ft/d/ft, with an mean of 8.1 ft/d/ft (Krohelski and others, 2000). Initial values assigned to the model ranged from 0.1 to 5 ft/d/ft depending on the stratigraphy of adjacent glacial sediments. These values were later adjusted during the calibration process.

Recharge

Recharge is the addition of water to the model from infiltrated precipitation - rainfall and snowmelt. Recharge varies spatially in response to differences to topography, soil properties, vegetation, and other parameters. Recharge also varies seasonally. The West Bend model is a steady state model, and uses average recharge that is constant with time but varies spatially.

The model uses a recharge zonation developed by Cherkauer (2001) for the regional SEWRPC model. Cherkauer based his zonation on base flow calculations from surface-water subbasins, and his estimates for the West Bend area range between 2.3 and 13.2 inches per year (in/yr), depending on the basin, with a lumped model average of 4.7 in/yr. Figure 11 shows the recharge zonation. The model calibration process adjusted these recharge rates as shown in Table 4. The final array of recharge rates ranges between 1.9 and 13.2 in/yr, with an overall lumped model average of 4.6 in/yr, almost identical to the initial lumped average.

Table 4. Recharge rates for the West Bend model. Subwatershed abbreviations as follows: Ced: Cedar Creek, Ebm; East Branch Milwaukee River, Nbm; North Branch Milwaukee River. See figure 11 for locations. Bolded values in the "calibrated" column were varied during the calibration process; other values were fixed at initial estimates.

model zone	subwatershed	initial value (in/yr)	calibrated value (in/yr)
1	inactive	0.0	0.0
2	Ced4	2.3	2.3
3	Ced8	2.7	**6.0**
4	Ced1	2.9	**6.0**
5	Ebm3	2.9	2.9
6	Ebm14	3.2	**2.0**
7	Ebm5	3.5	3.5
8	Nbm7	3.5	3.5
9	Ced13	3.6	3.6
10	Ebm15	3.6	**2.0**
11	Ebm10	3.7	**2.0**
12	Ced7	3.8	1.9
13	Nbm8	3.8	3.8
14	Ced3	4.1	**6.1**
15	Ebm16	4.1	4.1
16	Ebm9	4.3	4.3
17	Ebm12	4.3	4.3
18	Ebm13	4.6	**3.0**
19	Nbm9	4.8	**3.0**
20	Ced11	5.1	**7.1**
21	Ebm11	5.3	**5.3**
22	Nbm10	8.3	**10.0**
23	Nbm5	8.5	8.5
24	Ced9	8.5	8.5
25	Ced12	13.2	13.2

Pumping rates

Pumping rates in the model reflect actual pumping rates in the wells, averaged over one year. These rates are significantly less than the pump capacity of the wells, because the wells do not run continuously. Instead they each run for only a few hours each day in response to demand from the city water system.

Table 5 shows pumping rates for the West Bend wells. Reported rates are available from a 2004 summary maintained by the Wisconsin Public Service Commission. For purposes of simulating municipal pumping for wellhead protection, the Wisconsin source water protection program (SWAP) recommends using pumping rates calculated as the past year of record plus a 15 percent safety factor to account for future pumping increases as well as being conservative in case of model inaccuracy. In order to be consistent with other simulations done for Wisconsin's SWAP program the West Bend model uses these SWAP pumping rates (table 5).

Table 5. Information about the West Bend municipal wells.

City Well ID	WUWN[1]	WGNHS ID	Depth, feet	Casing depth, feet	Aquifer[2]	2004 pumping rate		ZOC pumping rate	
						GPD	Ft^3/day	GPD	Ft^3/Day
4	BH265	Wn-022	275	89	d	591700	79100	680400	91200
5	BH266	Wn-023	380	230	d	124100	16600	142700	19100
7	BH268	Wn-082	84	64	s&g	363200	48600	417700	56000
8	BH269	Wn-089	88	73	s&g	257200	34400	295800	39600
9	BH270	Wn-070	91	76	s&g	615900	82300	708300	94900
10	GM798	Wn-424	70	61	s&g	281100	37600	323300	43300
11	BH271	Wn-699	77	62.5	s&g	201600	27000	231900	31100
12	BH272	Wn-700	100	80	s&g	327700	43800	376800	50500
13	BH273	Wn-072	100.6	85.5	s&g	352900	47200	405800	54400
				Totals:		3115400	416500	3582700	480100

[1]WUWN = Wisconsin Unique Well Number
[2]d = dolomite; s&g = sand and gravel

Model calibration

Calibration process

Model calibration utilized the PEST universal parameter estimation software developed by Doherty (2004). The Groundwater Vistas interface used with the West Bend model interfaces directly with PEST. The PEST utility runs "outside" the groundwater flow model to achieve automatic model calibration by repeatedly executing the flow model, computing the model "fit" to observed head and flux targets, and adjusting and updating model parameters according to various statistical methods until the desired model "fit" is obtained. For the hydraulic conductivity parameters the model used the "pilot point" method (Doherty, 2004). The pilot point method avoids the use of fixed zones of hydraulic conductivity, and instead treats hydraulic conductivity (or any appropriate parameter) as a spatially varying parameter within limits established by the user. In essence each pilot point, or point estimate of hydraulic conductivity, becomes an additional parameter in the PEST solution, and the algorithm adjusts the model solution to honor these pilot points as well as the usual head and flux targets. The result is a continuously varying hydraulic conductivity field that honors existing data.

The pilot point method is attractive for the West Bend model because of the complex depositional history of the glacial deposits there. These deposits vary significantly in lithology over short vertical and horizontal distances and are unlikely to have uniform properties over large mapped zones. The West Bend model used 120 pilot points in model layers 1 and 2.

The calibration process required 58 different PEST scenerios, and each scenario exercised the flow model between 500 and 1000 times.

Results

The West Bend model is very well calibrated to steady-state conditions, and reproduces field estimates of hydraulic head and surface water discharge within reasonable limits of precision. Figure 12 shows plots of observed and simulated heads and surface water flows. Both plots fall near the 45-degree 1:1 match line, with no indication of systematic errors. The median error in head simulation is 3.8 feet, and the median error in flux simulation is 0.19 CFS. In particular it is important to note that the flux calibration is about equally good for very small streams and for the large streams such as the Milwaukee River. In addition, recall that there is significant potential error in the target estimates themselves, +/- 5 feet for head targets. Accordingly, this level of calibration is considered very good.

Calibrated parameters

The calibrated distribution of hydraulic conductivity in model layer 1 and 2 (figure 13) is well within the range of field estimates. The histograms in figure 14 compare the model-derived hydraulic conductivity distribution (bottom histogram) to field estimates based on pumping and specific capacity tests (top histogram). The ranges of the two data sets are almost identical, except that the model distribution has a lower minimum, consistent with the lack of domestic wells developed in low-permeability materials. Figure 15 represents the estimated transmissivity (hydraulic conductivity multiplied by thickness) of the unlithified materials over the model domain. Based on this figure, the calibrated transmissivity in the vicinity of the city of West Bend is between 100 and 20,000 ft^2/day, consistent with pumping tests reported by Layne Northwest (6,000 - 19,000 ft^2/day).

Analysis of the groundwater flow system

Overall groundwater flow paths

The groundwater model simulates hydraulic head in three dimensions, and allows analysis of groundwater flow direction or groundwater budgets anywhere in the model area. Groundwater in the West Bend area flows generally from west to east, following the regional slope of the landscape, but local topography, surface water features, and wells alter these flow paths. Figure 16 shows simulated water-table contours across the city, along with selected simulated flow paths west of the Milwaukee River. Most groundwater flow paths from the west terminate at the Milwaukee River; some terminate at municipal wells. The model shows that Silver Lake and Lucas Lake are flow-through lakes, with groundwater entering the lakes along their western shores and discharging along their eastern shores. Dunning and others (2002) came to a similar conclusion in their study of Silver Lake.

Effects of high-capacity wells

Drawdown

The nine West Bend municipal wells together produce a shallow cone of depression beneath the city. The groundwater model simulates this cone of depression as the difference between hydraulic heads with all wells pumping and heads with all wells turned off. Figure 17 shows the cone of depression, which has two focal points; one centered around the three northern wells (wells 4, 11, and 12) and the other centered around the six southern wells (wells 5, 7, 8, 9, 10, and 13). Maximum simulated drawdown from these wells is about 10 feet immediately adjacent to the wells; the cone extends about one mile to the west and two miles to the east.

Effects on surface water features

Groundwater pumping in the West Bend area reduces local surface water flows. Such reductions are an inevitable result of pumping because the overall system must maintain mass balance. The simulated pumping of about 416,500 ft^3/day equates to about 4.8 cfs, and overall groundwater discharge to streams and wetlands must decrease by that amount. Table 6 shows simulated baseflow in local surface water features with and without pumping. The largest *overall* impacts occur to Silver Creek, where simulated pumping reduces baseflow by 2.8 cfs, or 33 percent. The largest *percentage* impact occurs to Silverbrook Creek, where the simulated flow reduction is nearly 41 percent, or 1.04 cfs. It is important to point out that the effects of urbanization (pavement, storm sewers, channelization, wastewater discharge, etc) undoubtedly have also historically altered these streams; the groundwater model does not simulate these other impacts. Climate change might also impact baseflow to streams.

Table 6. Pumping impacts on selected local surface water features.

Surface water feature	no pumping	pumping	difference	pct change
	cfs	cfs	cfs	percent
Lower Milwaukee River above Newburg	13.53	12.84	-0.69	-5.1%
Silverbrook Creek at Silver Creek	2.54	1.50	-1.04	-40.8%
Silver Creek at Milwaukee River	8.47	5.67	-2.80	-33.0%
Silver Creek above Hwy 45	4.12	2.77	-1.35	-32.7%
Silver Creek below Hwy 45	4.35	2.90	-1.45	-0.3%
Quaas Creek at Milwaukee River	5.38	5.06	-0.32	-6.0%
Unnamed tributary to Milwaukee River	1.48	1.43	-0.05	-3.4%

Contributing areas for municipal wells

Delineation of contributing areas

One of the most useful features of the West Bend model is its ability to delineate areas of the landscape contributing water to individual wells. The contributing area for a well, also referred to as the zone of contribution, is the land surface area over which recharge enters the groundwater system and eventually flows to a well. Figure 18 illustrates the concepts and terminology of contributing areas, and shows that the contributing area is different than the cone of depression. For unconfined aquifers such as the sand and gravel at West Bend, the contributing area, also called the zone of contribution, is generally an oval-shaped area extending hydraulically upgradient from a well (figure 18, top). This area represents the projection of three-dimensional flow lines up to the land surface. However, in three-dimensional systems, the most important area of recharge might not be immediately adjacent to or even contain the well, as shown by figure 18 (bottom).

Except for well 4, the West Bend wells capture groundwater from the west to southwest (figure 19). The influence of wells 11 and 12 causes the contributing area for well 4 to extend primarily to the south and east, with some contribution from the west. The 5-year contributing areas outline the region in which simulated groundwater reaches the wells within 5 years; groundwater in the 10-year contributing area will reach the wells in 10 years. The widths of the contributing areas are proportional to pumping rates, well construction, and transmissivity around each well. Several of the contributing areas overlap because of the three-dimensional nature of the groundwater flow system. Appendix B provides more detailed maps of the contributing areas for individual wells.

Using forward particle tracking with endpoint analysis (ESI, 2004) produces a map of the most critical areas where contaminants might enter the subsurface and eventually reach a municipal well. Figure 20 shows locations where mathematical particles added to the water table in the model reached a municipal well in 5 or 10 years, regardless of their flow path. Notice that several of these areas are not adjacent to any well. These areas of recharge are equivalent to the hypothetical upgradient contributing areas shown on figure

18 (bottom). According to the model, recharge can reach all wells except wells 5 and 11 in 10 years or less, and can reach wells 7, 8, 9, 10, 12, and 13 in 5 years or less (table 7).

Comparison of contributing areas to isotopic results

The isotopic results (tritium, oxygen-18, and deuterium) suggest that water produced by the West Bend municipal wells recharged the aquifer relatively recently and that several wells may capture a component of surface water. Table 7 summarizes the isotopic results. Tritium (^3H) can be used as a qualitative indicator of relative groundwater age, or time from recharge to production by the well. Tritium values measured at West Bend range from 4.4 to 10.2 tritium units (TU). Previous studies by the WGNHS have shown that the current tritium content of precipitation is Wisconsin varies seasonally but ranges between about 5 and 15 TU. Precipitation that fell during the 1960's, a period of atmospheric nuclear testing, would have elevated tritium values. Precipitation that fell prior to the 1960s, or about 45 years ago, would contain essentially no tritium, and would have tritium values less than 0.1 TU. The range of tritium values measured in the West Bend wells suggests that most of these wells produce water with essentially present-day tritium content; this water probably fell as precipitation less than about 10 years ago. The only exception is the value of 4.4 TU in well 5, suggesting that this well produces somewhat older water; this is consistent with particle-tracking results.

Table 7. Isotopic results and interpretation for West Bend municipal wells

well	^{18}O, del permil SMOW	^2H, del permil SMOW	^3H, tritium units	surface water component indicated from $^{18}O/^2H$ interpretation	tritium interpretation	minimum simulated travel time, years	depth of casing, ft
4	-9.7	-65.4	6.8 +/- 0.8	no	"young"	8.8	89
5	-9.3	-62.3	4.4 +/- 0.8	no	older?	>50	230
7	-9.3	-63.2	8.9 +/- 0.9	no	"young"	0.1	64
8	-9.3	-62.7	10.2 +/- 0.9	no	"young"	1.7	73
9	-9.2	-63.5	8.6 +/- 0.9	possibly	"young"	0.5	76
10	-9.3	-64.3	9.9 +/- 0.9	yes	"young"	4.2	61
11	-9.0	-62.9	9.8 +/- 0.9	yes	"young"	50	62.5
12	-9.2	-63.3	9.0 +/- 0.9	possibly	"young"	0.3	80
13	-8.7	-60.5	8.4 +/- 0.8	possibly	"young"	3.8	85.5

Hydrogeologists commonly use the relationship between deuterium (^2H) and oxygen-18 (^{18}O) to indicate whether a component of surface water is present in groundwater systems. Deuterium and oxygen-18 are both stable isotopes of, respectively, hydrogen and oxygen, and both are present in water molecules. As water molecules evaporate from a water surface, such as a lake or wetland, the lighter isotopes evaporate more easily, and the remaining water is proportionally enriched in the heavier isotopes. Consequently, surface water features have a different $^2H/^{18}O$ ratio than does local precipitation. Although both ^2H and ^{18}O in precipitation vary seasonally and with temperature and weather patterns, the ratio between the two remains constant in a given geographic area. This relationship, called the *meteoric water line* (MWL), is determined by obtaining a number of samples of local precipitation and plotting a regression line of ^{18}O versus ^{2}H. Plotting groundwater analyses on the same graph indicates whether the groundwater samples contain a component of surface water. In general, points falling on or to the left of the MWL indicate that precipitation recharge rather than surface water is the primary source of water produced by the well. Conversely, points falling significantly to the right of the MWL indicate that surface water is a primary source of water for the well.

Samples from several of the West Bend wells (wells 9, 10, 11, 12, 13) show a slight but somewhat ambiguous indication of a surface water component, while samples from the remaining wells (wells 4, 5, 7, and 8) show no surface water component. Figure 21 shows the ^{18}O versus ^{2}H plot for these data, along with a meteoric water line derived from precipitation data collected near Sturgeon Bay, Door County, Wisconsin (Rayne and others, 2001). Although wells 9, 10, 11, 12, and 13 plot to the right of the MWL they are not distant enough from the line to draw a firm conclusion about surface water content. Additional samples, and collection of precipitation data at West Bend, would be necessary to clarify this interpretation.

Based on forward particle tracking using the model, the travel times from the surface to individual West Bend wells range from over 50 years to less than 0.1 years (table 7). Results of model simulations and isotopic data are generally consistent with respect to contributing areas for the West Bend wells. Table 7 summarizes these results. The “oldest” water, with no apparent surface water component, is produced by well 5, which is a dolomite well with the deepest casing of the city’s wells. All other wells have relatively shallow casings and produce relatively young groundwater. No well contains a major component of surface water, which is consistent with contributing areas extending away from major surface-water features (figure 20).

Model limitations and uncertainty

The West Bend model is well-calibrated to available data and is a useful tool for simulating the groundwater system around West Bend. Limitations and uncertainty in the model are related to data density, grid density, and steady state assumptions. First, because of its origins in a glaciofluvial environment, the hydrogeologic properties of the sand and gravel aquifer in the West Bend area are highly variable across the model domain. Localized fractures and variable hydraulic properties likely exist in the underlying dolomite aquifer. The data assembled for the West Bend model certainly does not capture all this variability. This lack of data could result in significant model errors, particularly in small-scale problems. Second, the model grid density represents a compromise between model detail and computer processing speed. Refinement of the model grid is recommended for problems requiring high detail in small areas. Third, the model assumes steady state conditions, and cannot simulate annual, seasonal, or daily changes in hydrogeology parameters such as recharge rates or pumping rates. Although the model has the ability to carry out non-steady (transient) simulations, additional data and calibration would be necessary to develop this capability.

Suggestions for future use and maintenance of the model

The West Bend groundwater flow model is a tool that can be used for analyses of groundwater flow in the West Bend, Wisconsin area. The model is designed to be portable and flexible through use of the Groundwater Vistas (ESI, 2004) graphical user interface. Suggested uses of the model include the following:

- As an illustrative educational tool to help understand groundwater flow in the West Bend area;
- to determine potential drawdown and areas of influence for existing or proposed municipal wells;
- to delineate contributing areas for wells that can be used in local wellhead protection planning;
- to delineate potential groundwater flow paths from known contaminant sources or spills;
- to investigate local groundwater-surface water interactions, and assess the impacts of wells on local surface water features; and
- to investigate the effects of other land-use changes on the groundwater system.

Summary

The Wisconsin Geological and Natural History Survey, University of Wisconsin-Extension, has developed a numerical groundwater flow model for the City of West Bend, Wisconsin. The model simulates groundwater flow in the shallow sand and gravel aquifer and in the underlying dolomite aquifer. The base of the model is the Maquoketa shale, and the model does not simulate the deeper sandstone aquifer below the shale. The model is designed to be flexible and portable, and uses the widely available MODFLOW code (McDonald and Harbaugh, 1988) developed by the US Geological Survey.

Groundwater in the West Bend area is well connected to local surface water features. The model is calibrated to numerous local water-level and streamflow data, and model calibration is considered to be very good. Groundwater flow in the area is predominately from the west, and local streams and the Milwaukee River form major groundwater discharge points. The model simulates the nine existing high capacity municipal wells operated by the City. These wells create a shallow cone of depression covering much of the city. Although the municipal wells reduce the amount of groundwater discharged to local surface water features they do not cause water to flow away from surface water features.

Both groundwater modeling and isotopic analyses of water samples obtained from the municipal wells suggest that groundwater produced by the wells is relatively young - less than 5 or 10 years from recharge to production by the wells, and the wells are relatively vulnerable to contamination from shallow surface sources.

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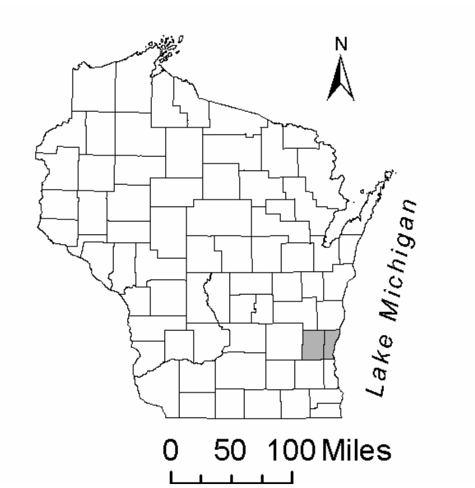
Figures

A.



B.

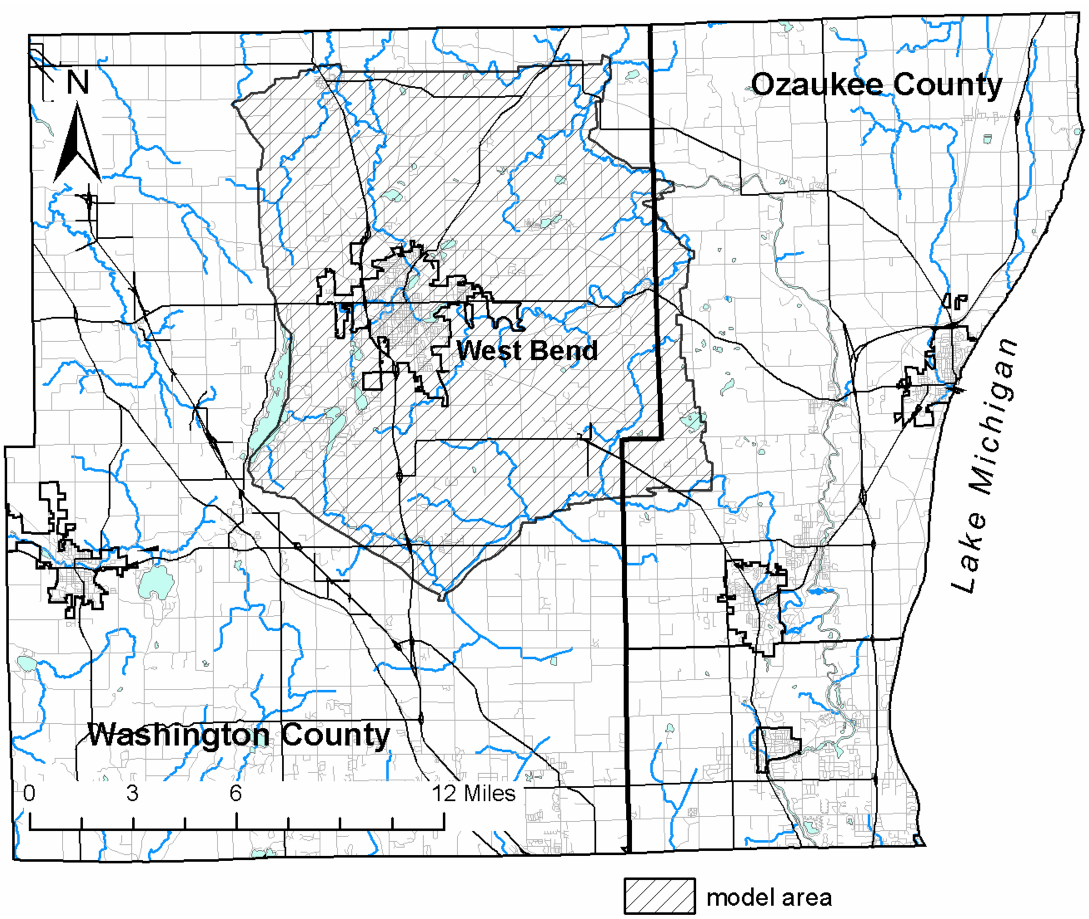


Figure 1. Location map. A. Map of Wisconsin, showing location of Washington and Ozaukee Counties. B. Map of Washington and Ozaukee Counties, showing model area.

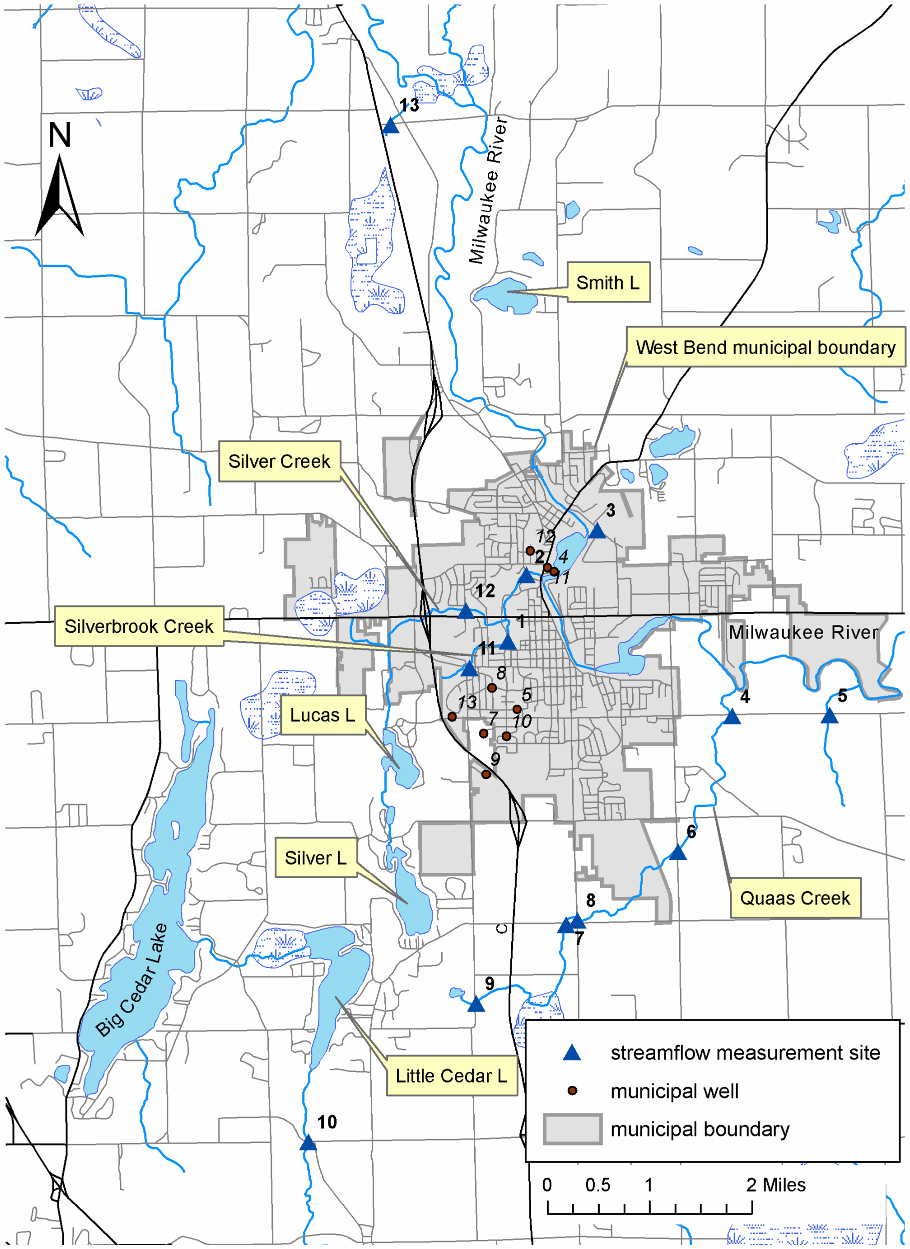


Figure 2. Important hydrologic features and streamflow measurement sites in the West Bend area. See table 2 for streamflow data.

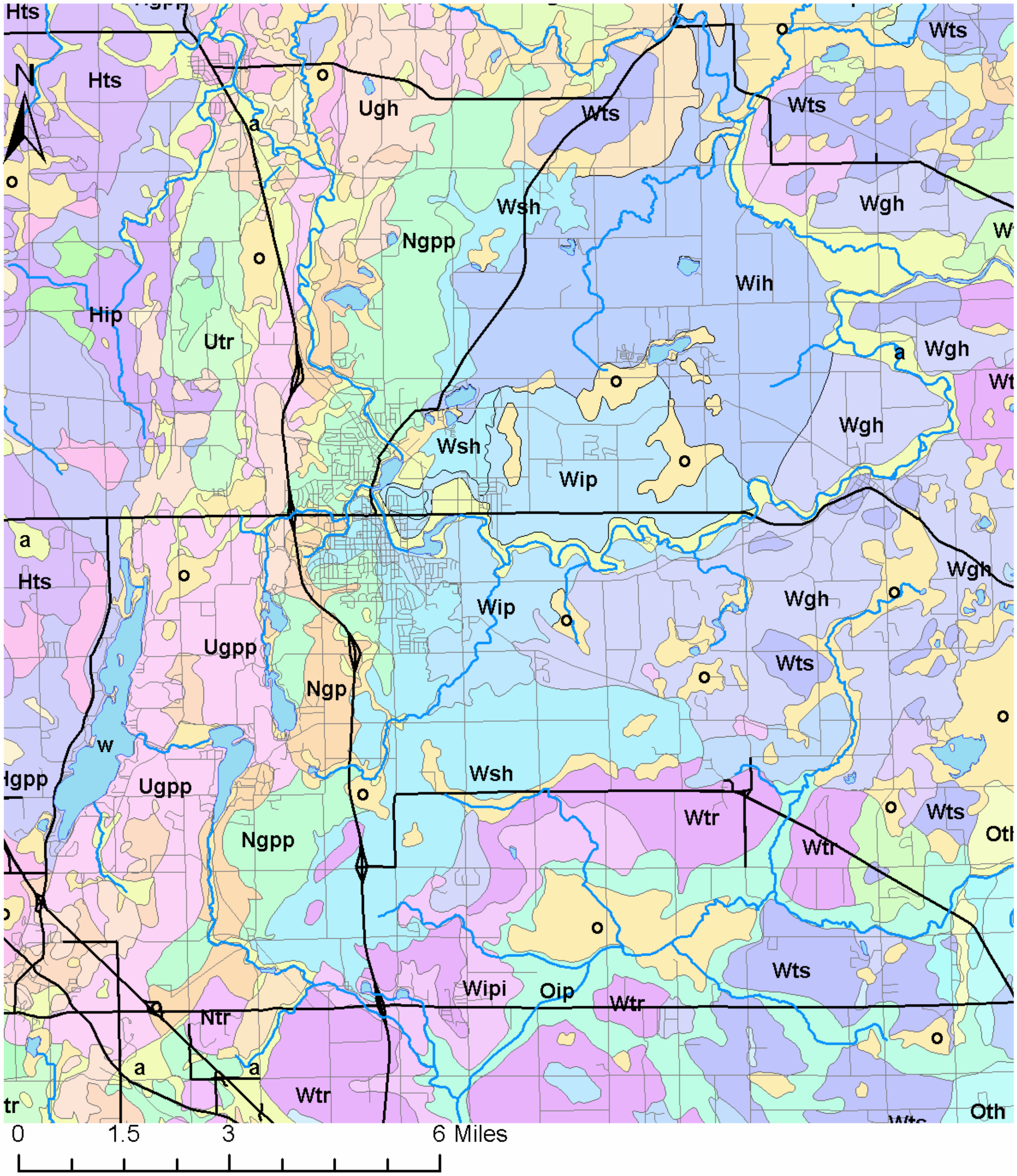


Figure 3. Surficial geology of the West Bend area. Letter codes represent geologic units. First letter denotes formation: Z- Ozaukee Member, O- Oak Creek Member, W - Waubeka Member, N- New Berlin Member, H- Horicon Member, U - undifferentiated. Second letter denotes major lithology: t - diamicton (till), g- gravel and sand, s - sand and silt, i - silt and sand, o- organic. Third letter represents topography: h- hummocky, p - flat or gently rolling, r - rolling. After Mickelson and Syverson, 1997. See Mickelson and Syverson (1997) for detailed unit descriptions.

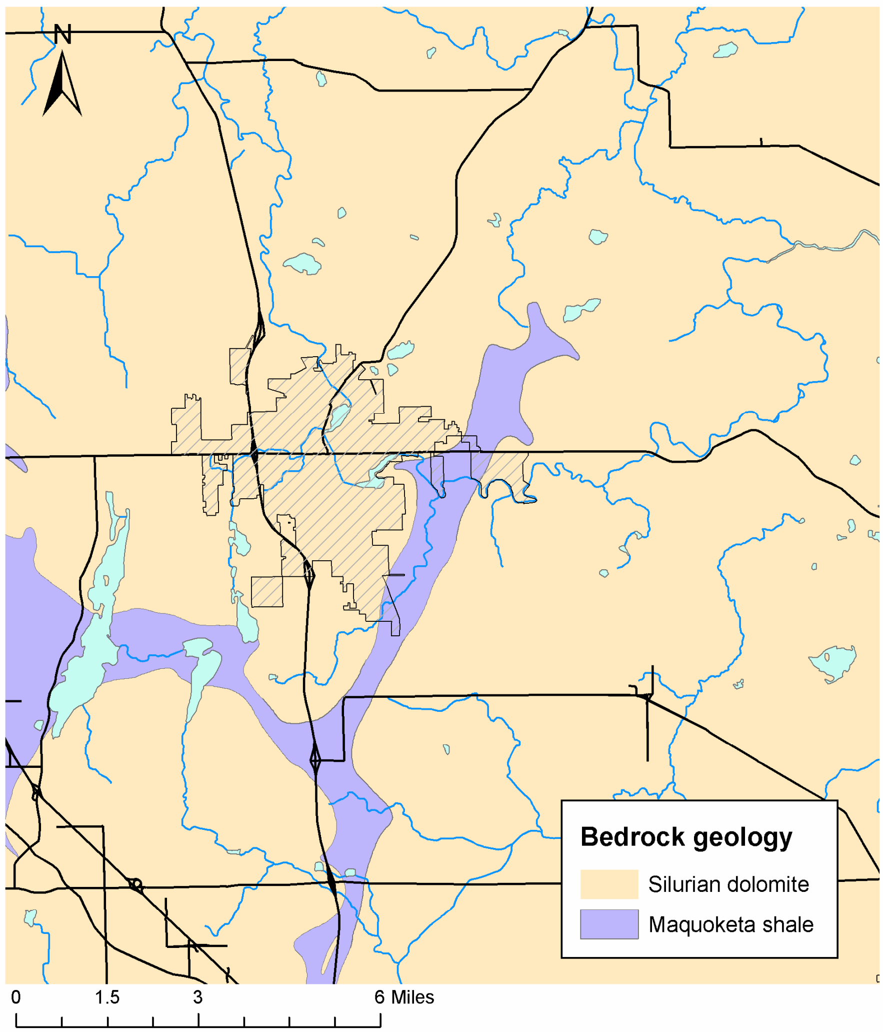


Figure 4. Bedrock geology of the West Bend area.

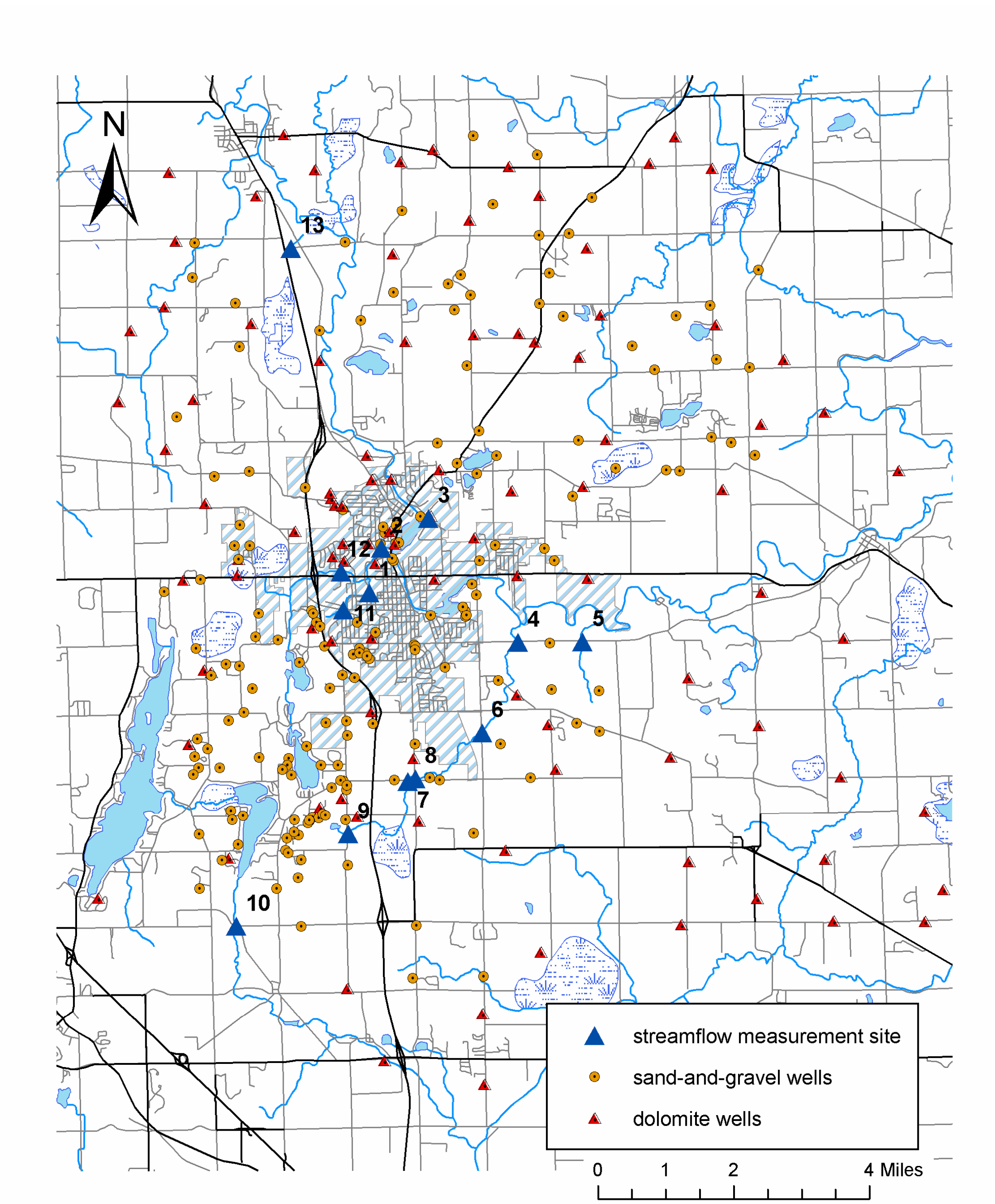


Figure 5. Model calibration targets

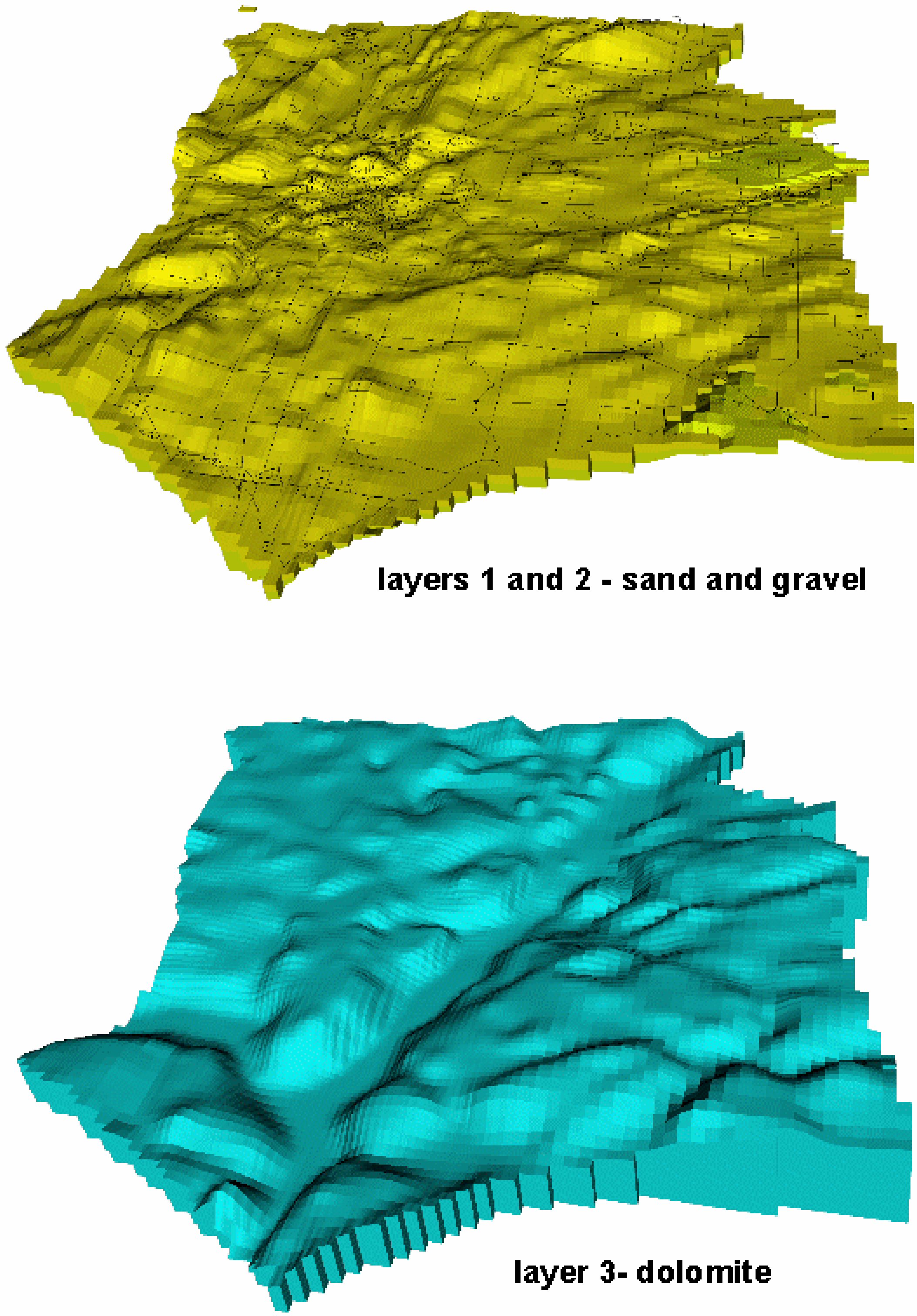


Figure 6. Three-dimensional depiction of aquifer units represented by the model (model area shown on fig 1).

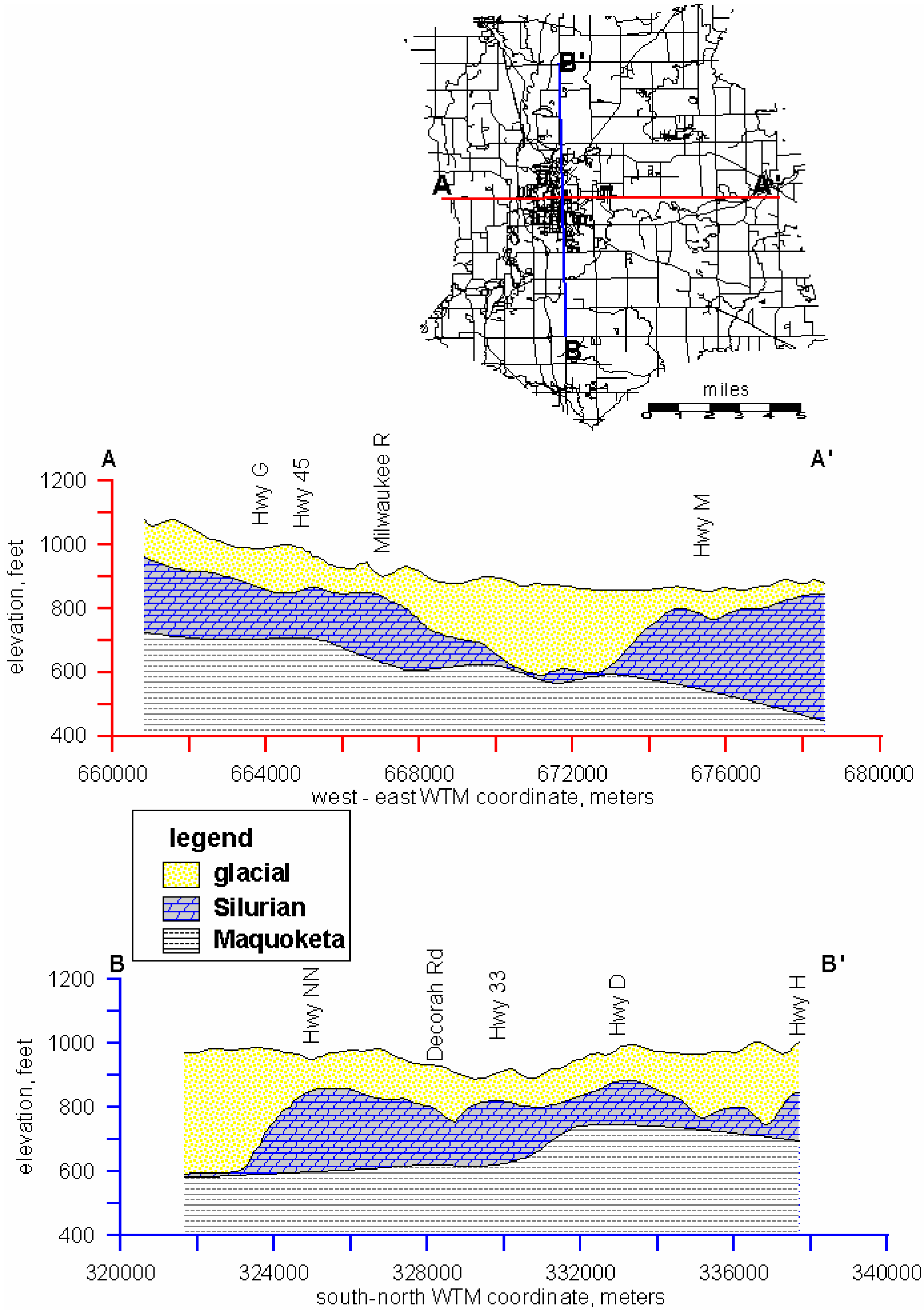


Figure 7. Cross sections through model area

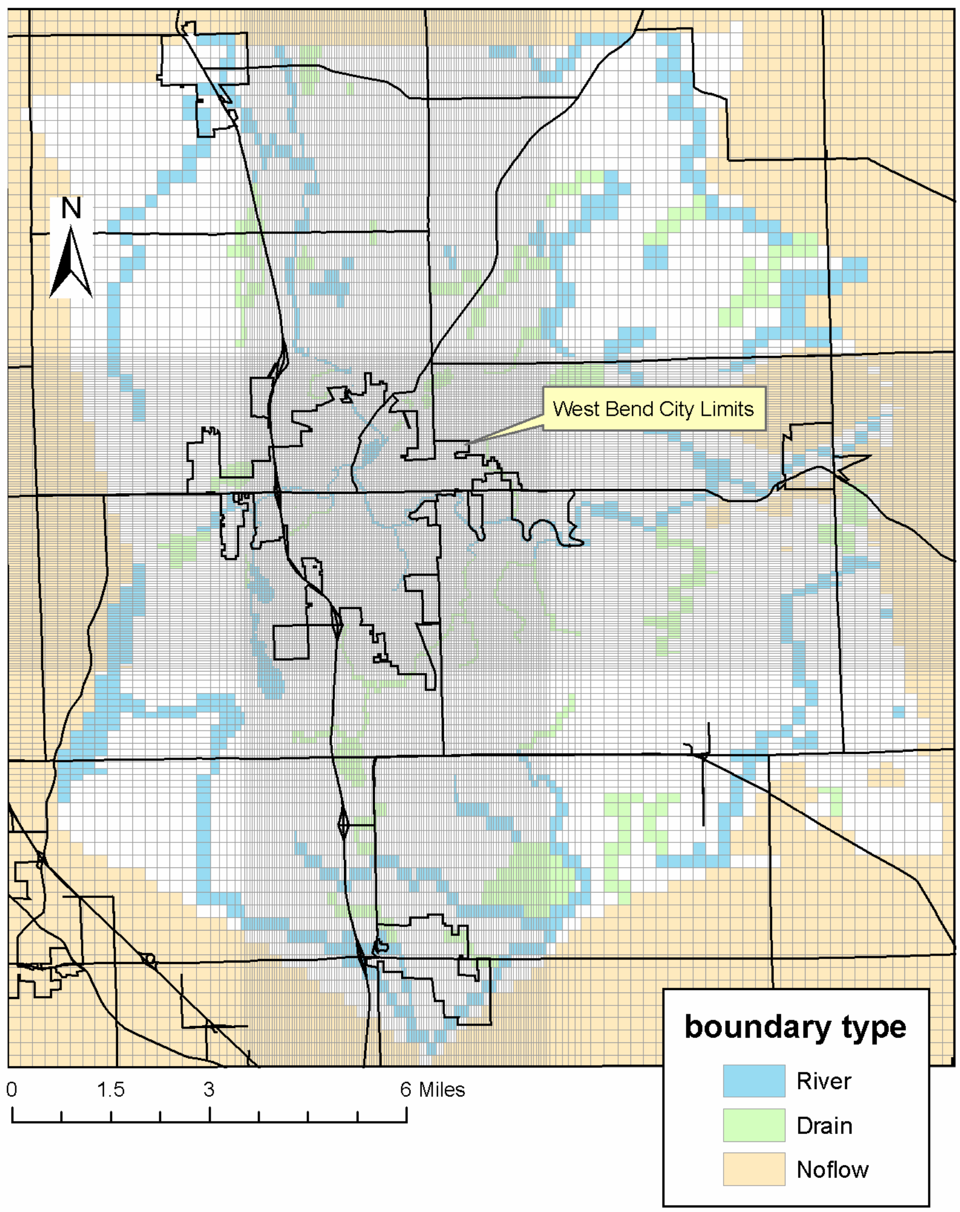


Figure 8. MODFLOW model grid and boundary conditions

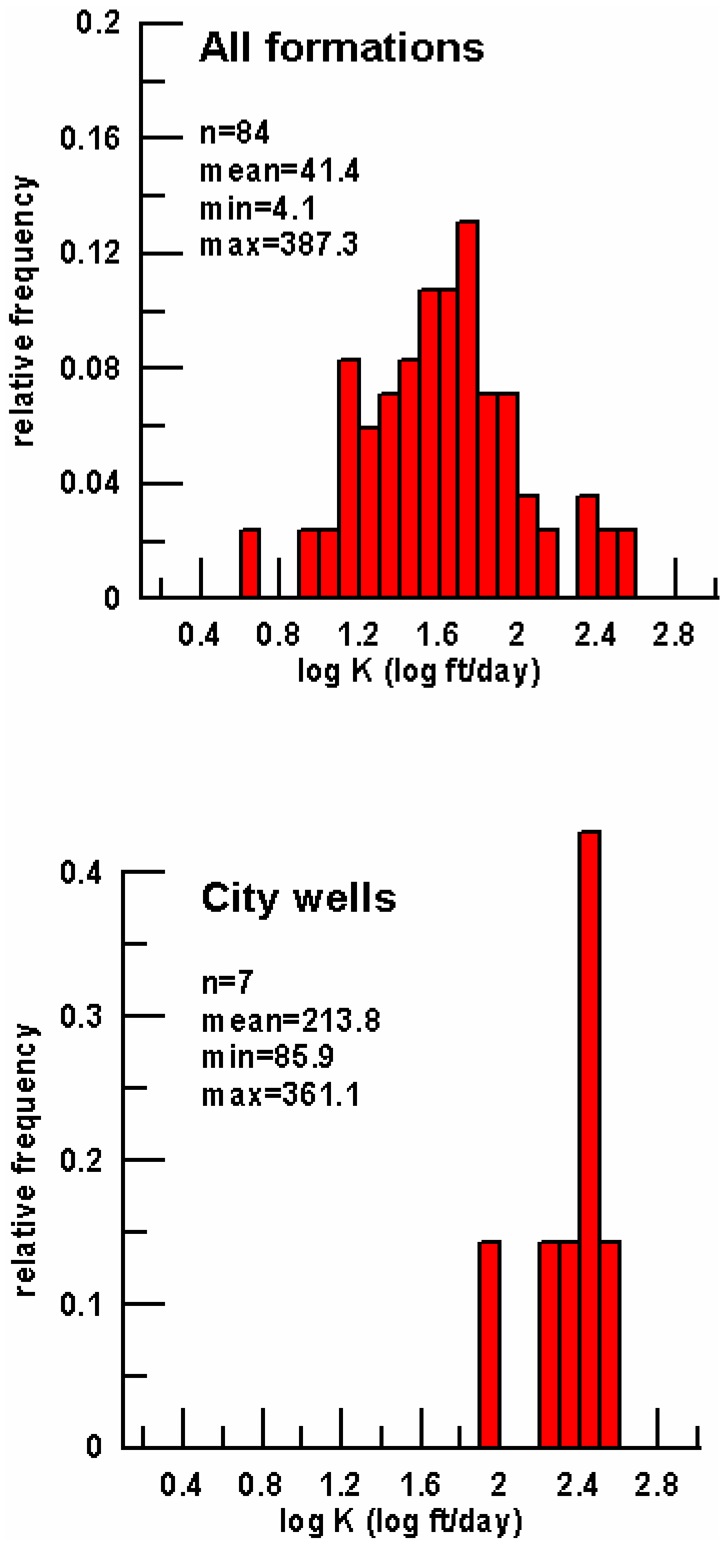
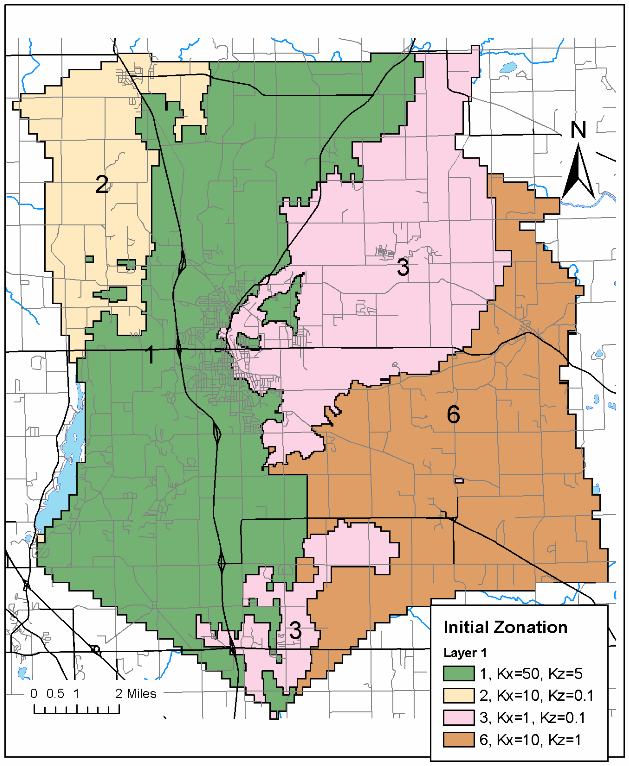


Figure 9. Histograms of results from hydraulic conductivity estimation using slug tests and pumping tests.



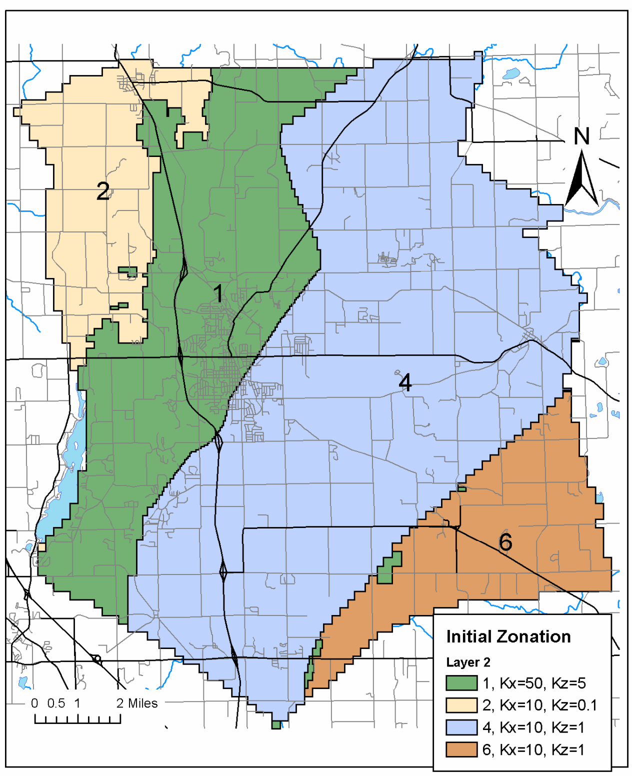


Figure 10. Initial hydraulic conductivity zonation for model layers 1 (top) and 2 (bottom).

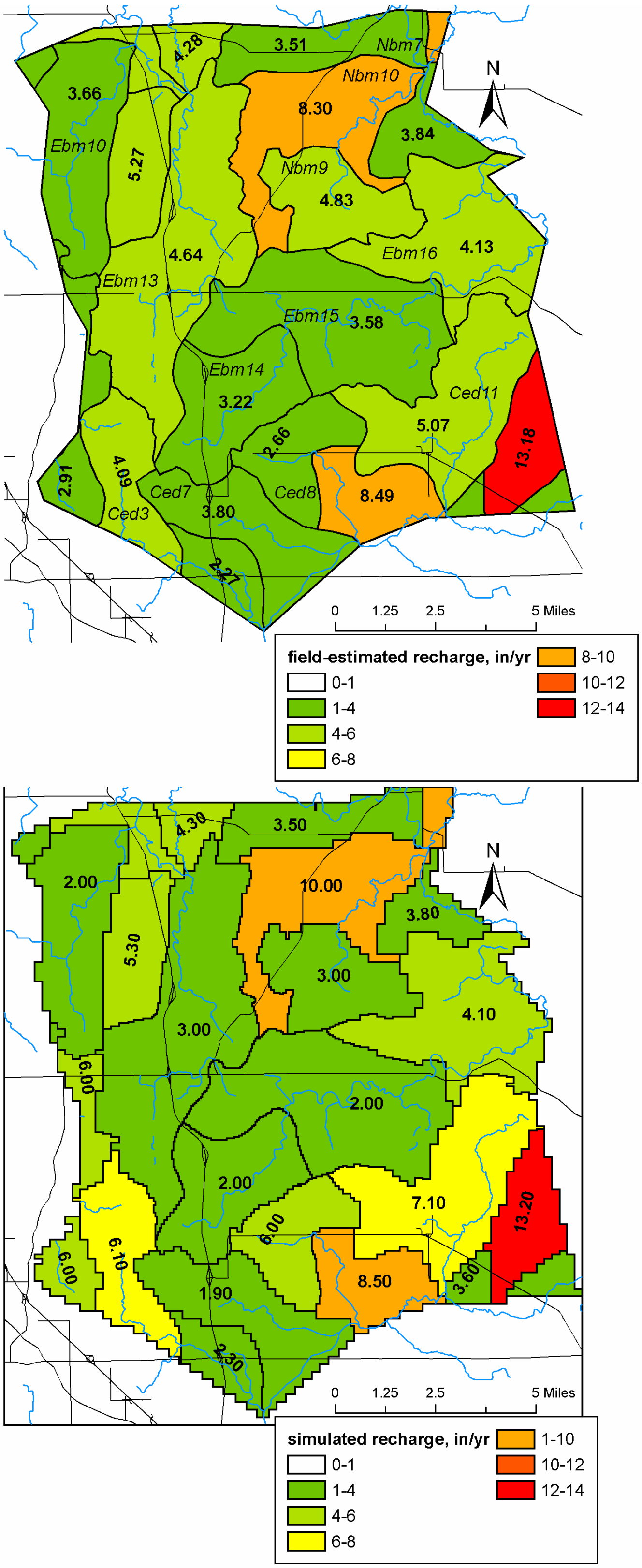
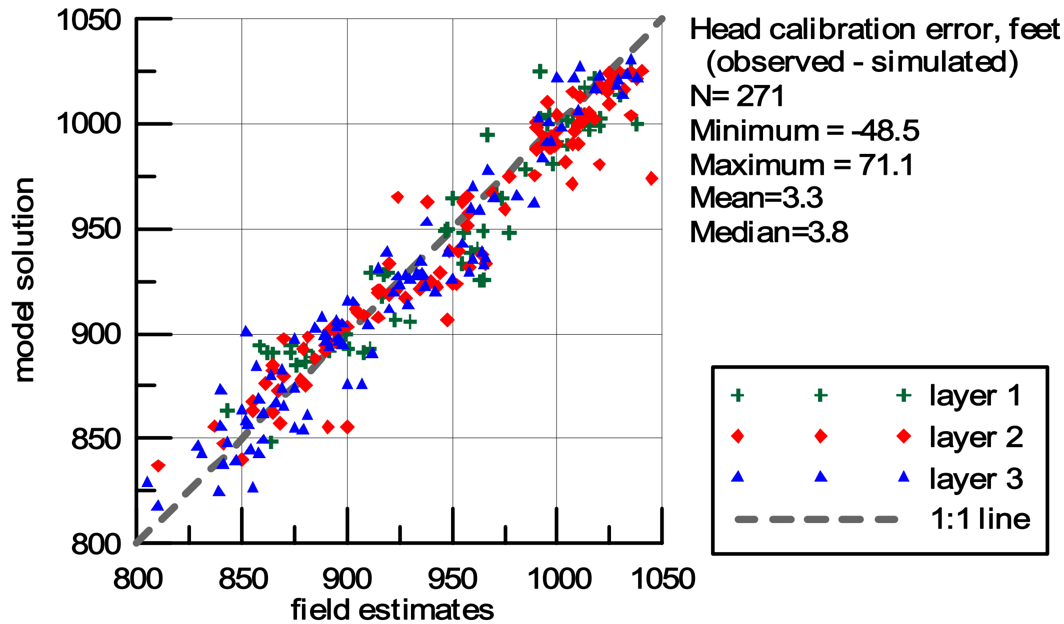


Figure 11. Estimated recharge rates. Top: rates estimated by Cherkauer (2004). Bottom: rates determined through model calibration. Italicized abbreviations refer to surface-water basins.



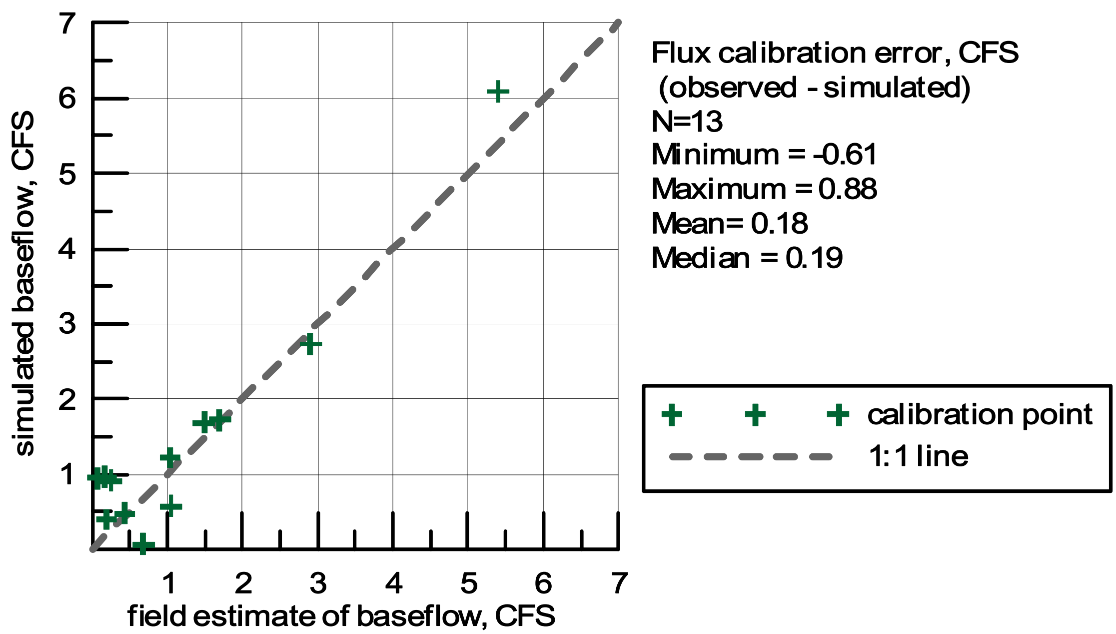


Figure 12. Model calibration results. Top: head calibration. Bottom: flux calibration.

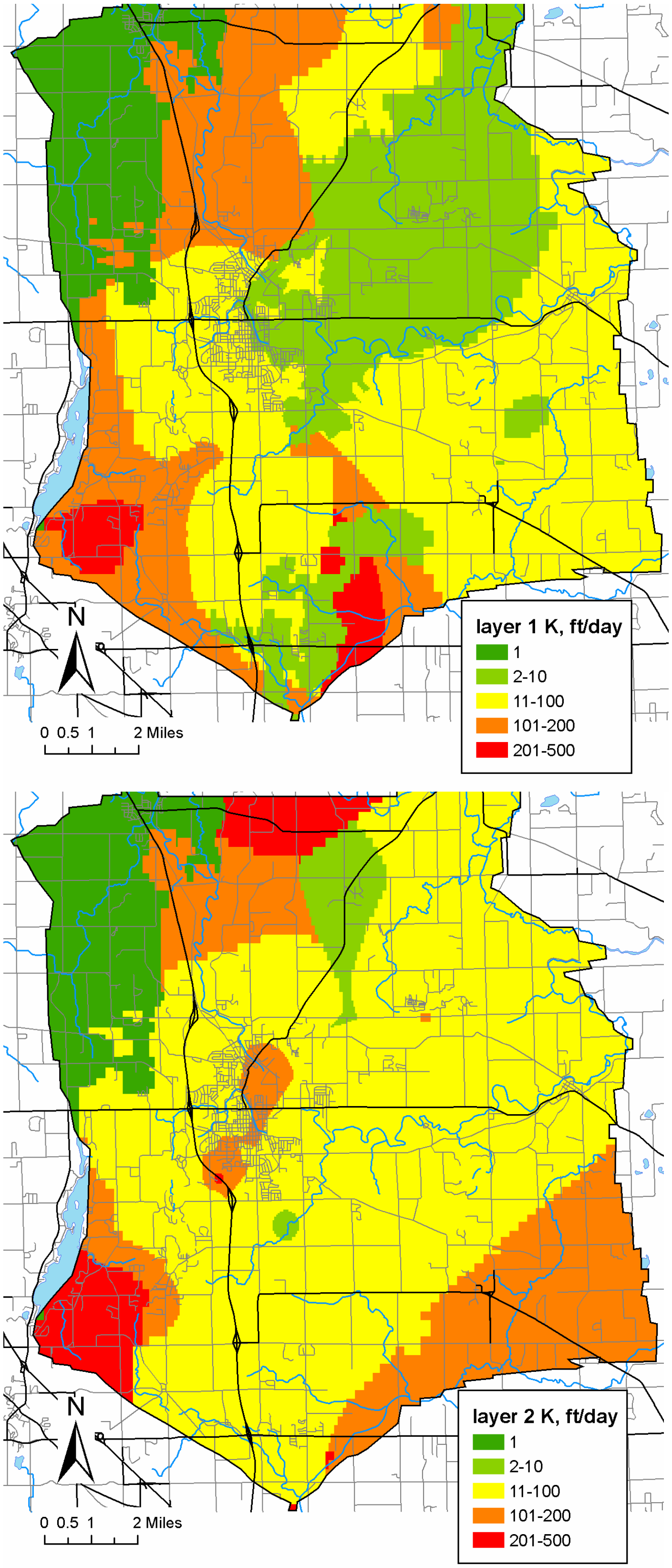


Figure 13. Calibrated hydraulic conductivity distribution for model layers 1 (top) and 2 (bottom).

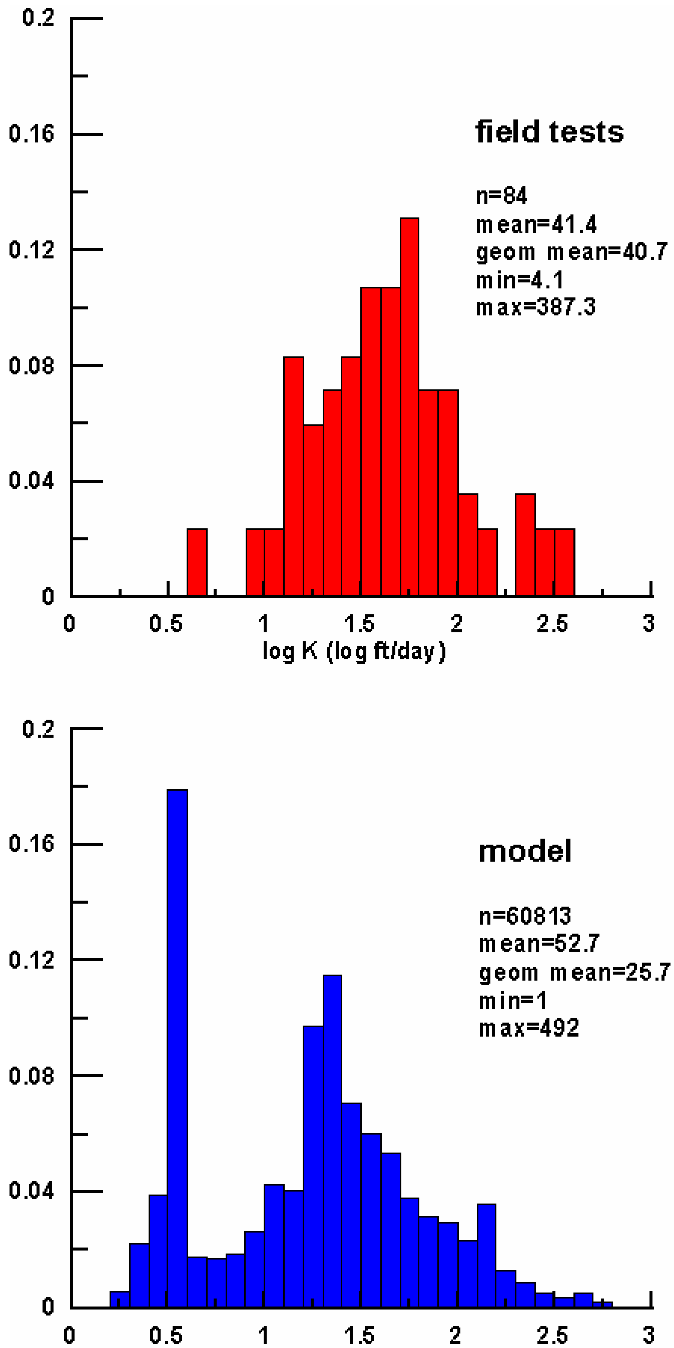


Figure 14. Comparison of field- and model-derived hydraulic conductivities for unlithified materials.

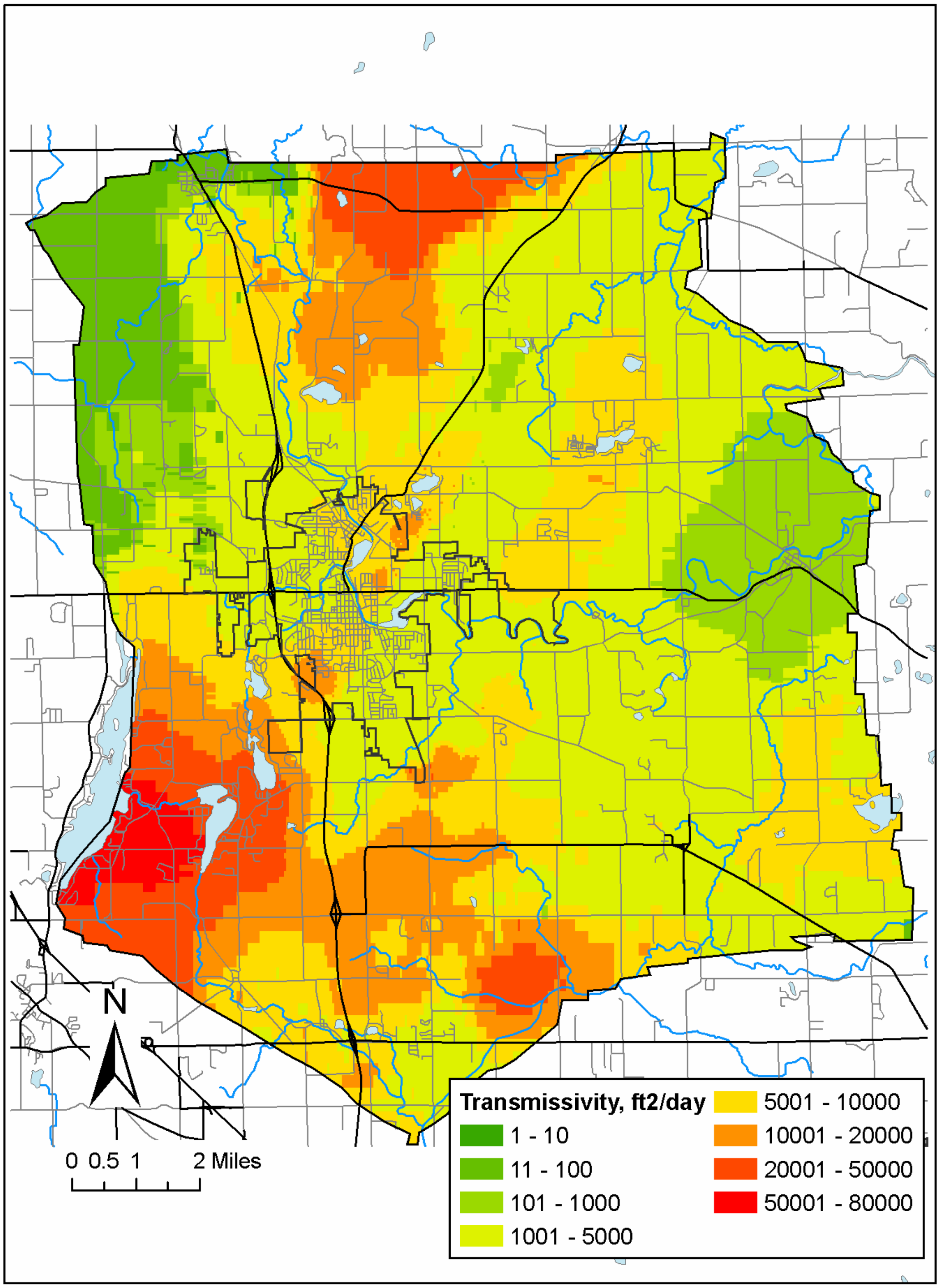


Figure 15. Transmissivity of the sand-and-gravel aquifer, based on model calibration.

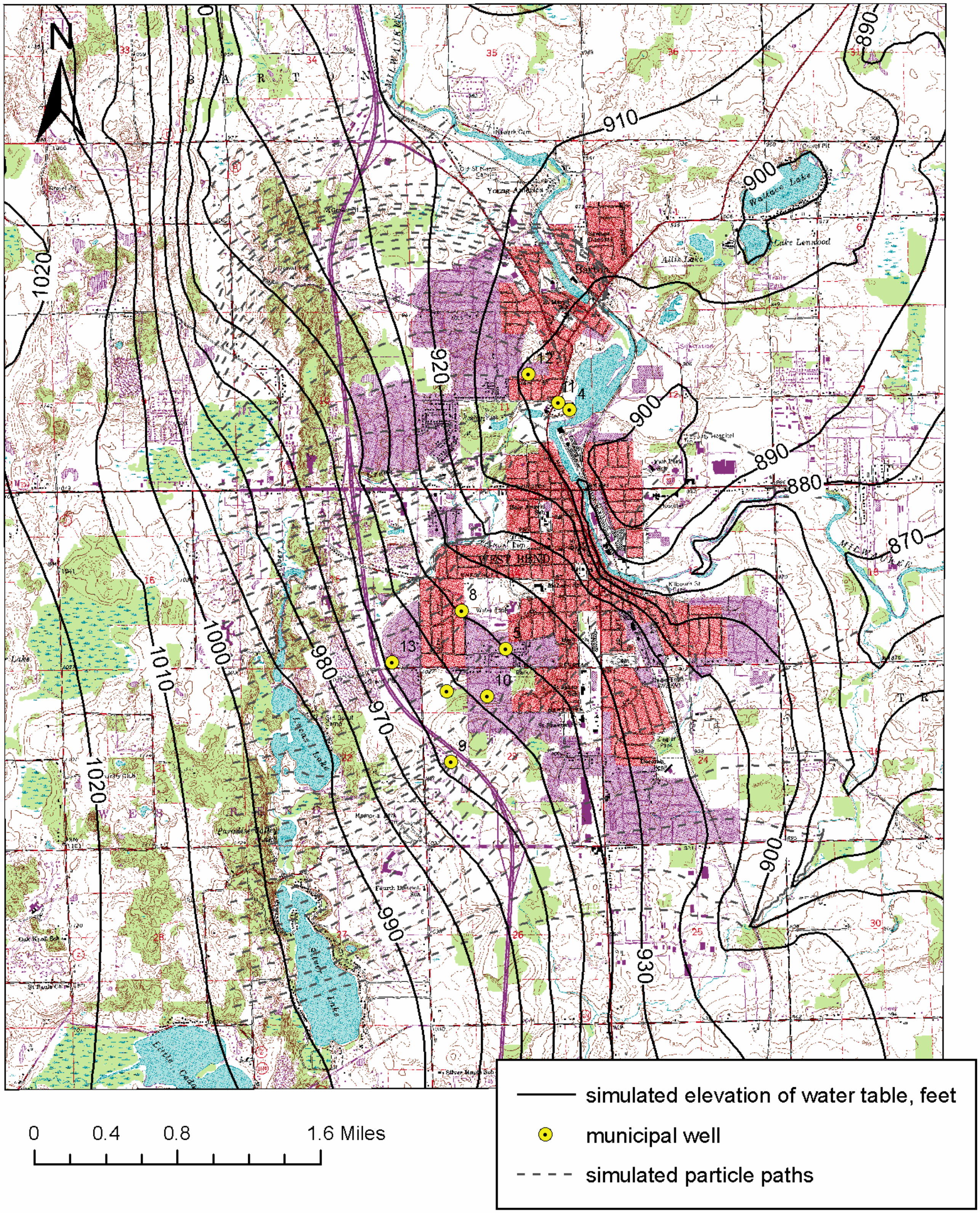


Figure 16. Simulated water table elevations and particle paths in the West Bend area.

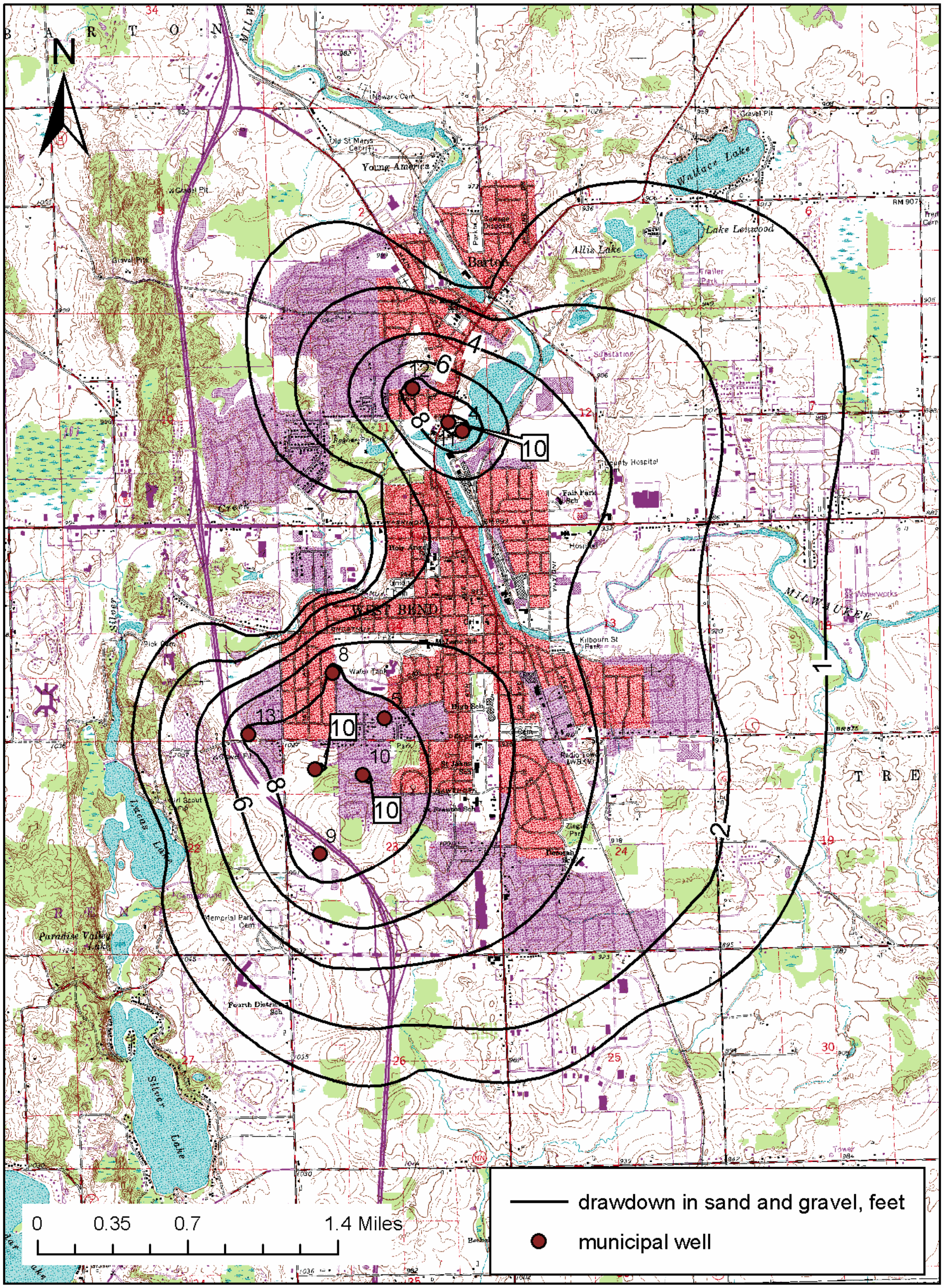


Figure 17. Simulated drawdown from municipal wells.

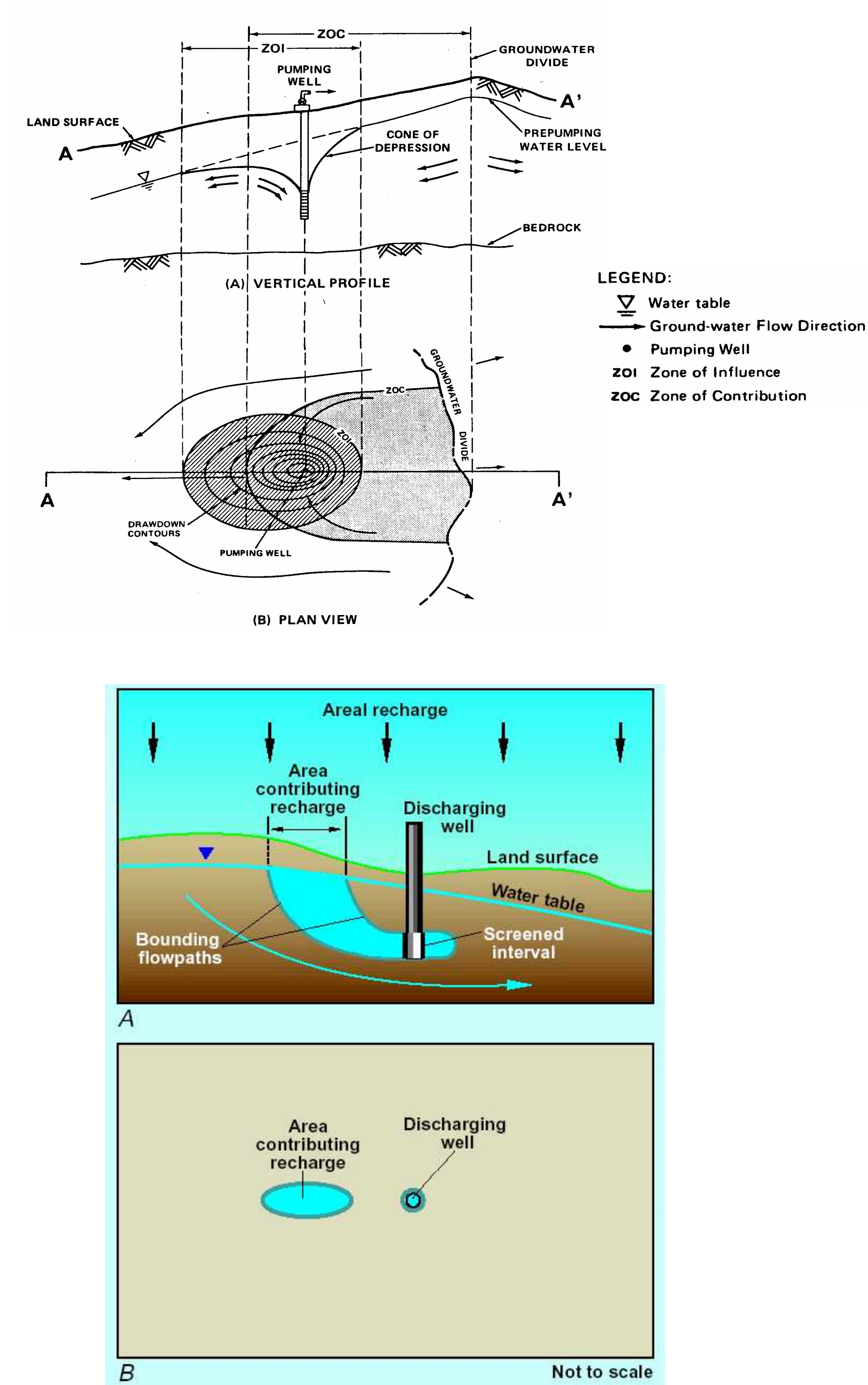


Figure 18. Concepts of contributing area for a discharging well. Top: zone of contribution terminology from USEPA (1987). Bottom, illustration of three-dimensional effects of a contributing area for a well (Focazio and others, 2002).

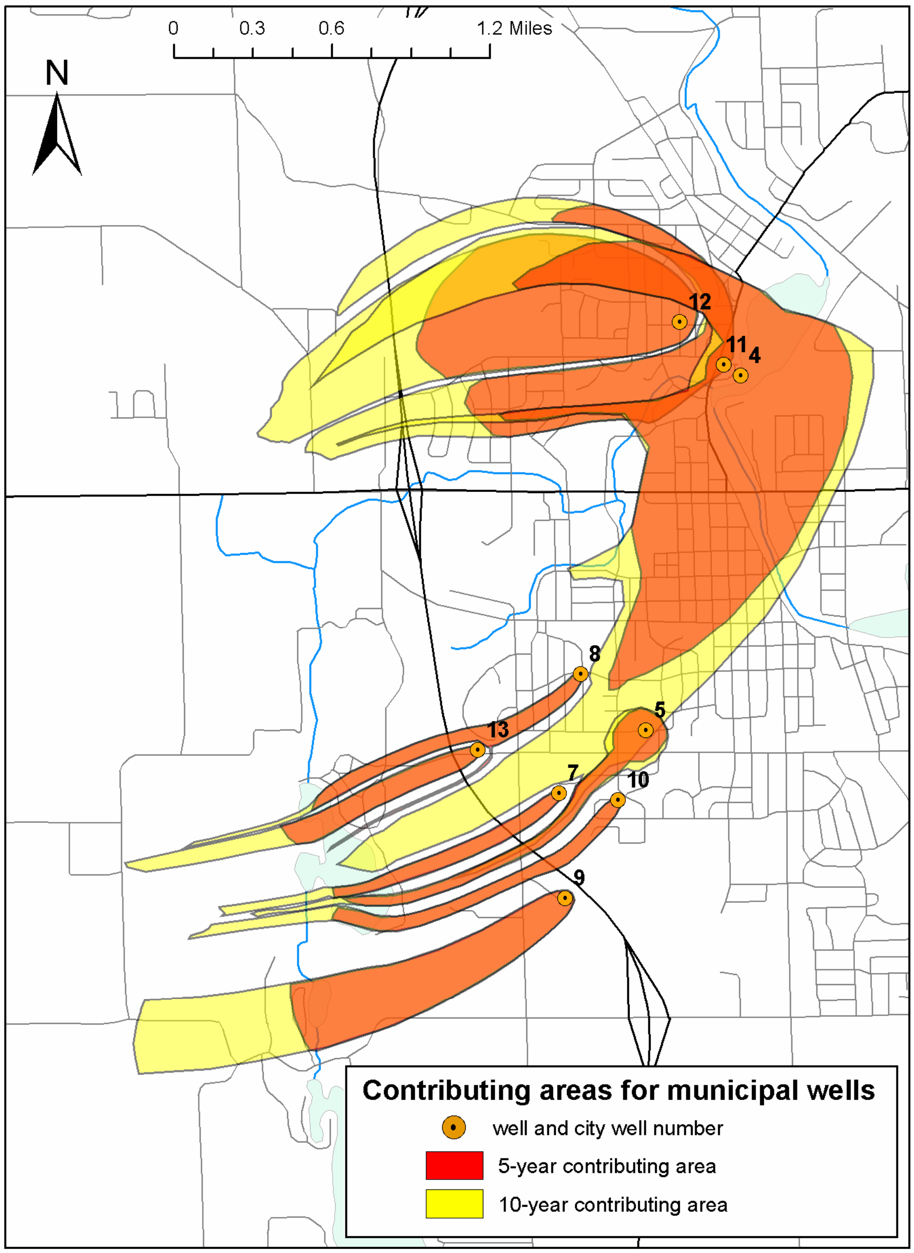


Figure 19. Surface projection of areas contributing water to West Bend municipal wells for 5- and 10-year travel times.

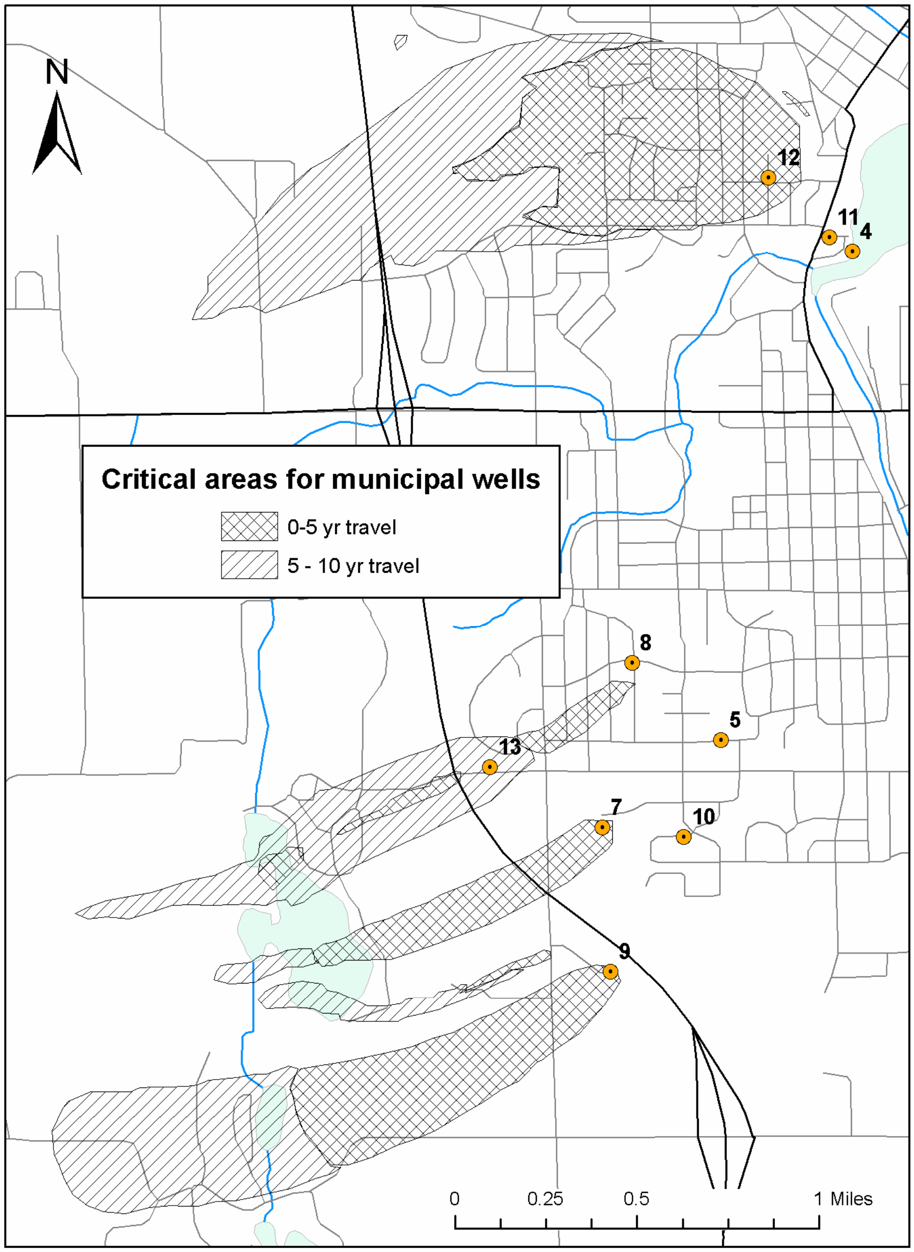


Figure 20. Areas contributing surface water and/or infiltrating precipitation to West Bend municipal wells for 5- and 10-year times of travel.

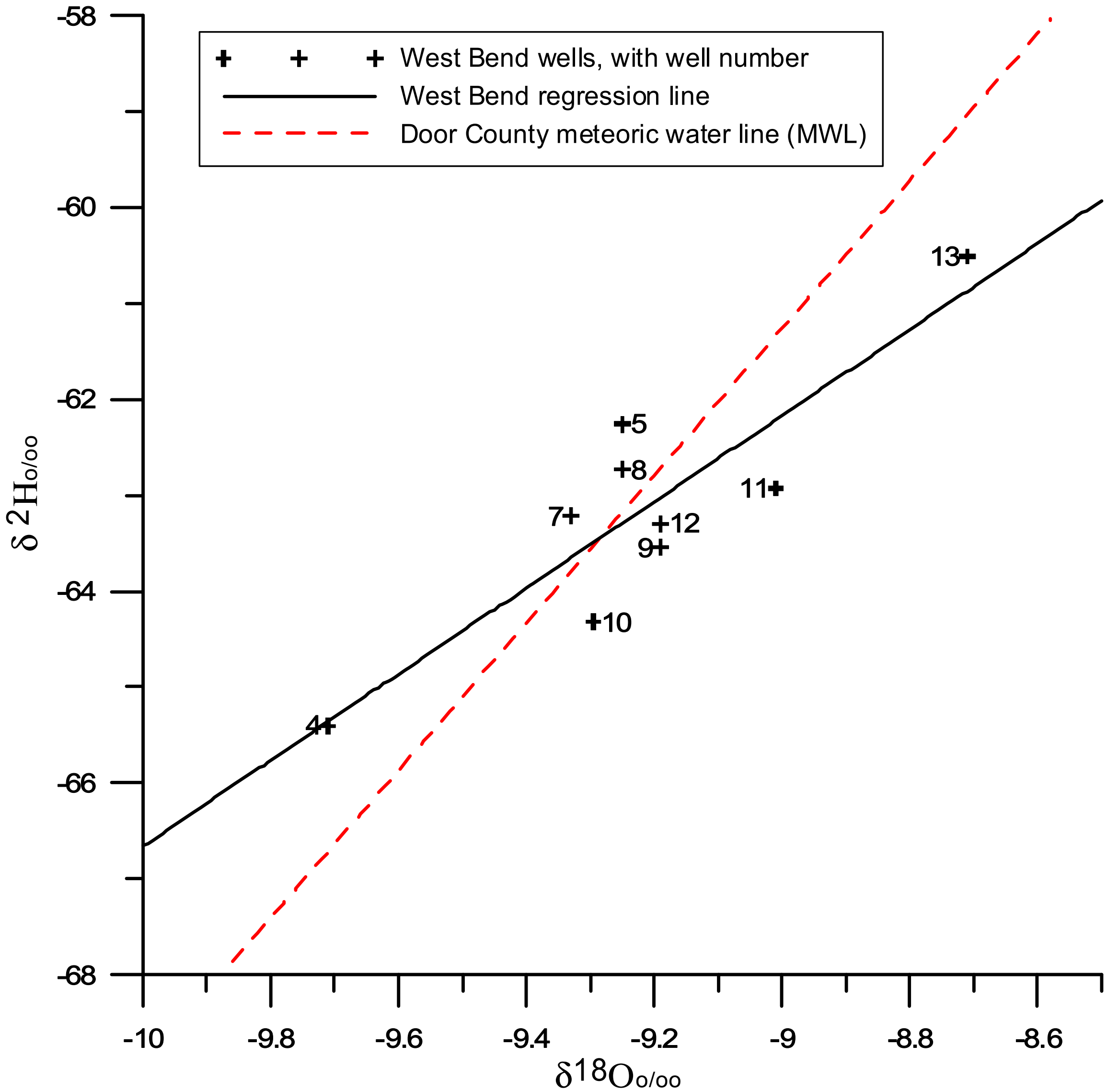


Figure 21. Oxygen-18 and deuterium results from West Bend municipal wells

Appendix A. GFLOW screening model

In order to develop boundary conditions for the MODFLOW groundwater flow model described in this report we first constructed a simple 2-dimensional analytic element screening model using the GFLOW analytic element code (Haitjema, 1995). Such screening techniques are useful in enhancing the development of numerical models because they do not require fixed boundary conditions or numerical gridding (Hunt and others, 1988). The GFLOW model covered a large area, shown in figure A1. The model used 647 linesinks, in 62 strings, to represent major surface-water features in the West Bend and Washington County region. The model used the following areally-lumped parameters to represent the combined sand and gravel and dolomite aquifers as a single layer: hydraulic conductivity 5 ft/day, bottom elevation 600 ft, recharge 1.4×10^{-3} ft/day (6.1 in/yr). Figure A1 shows hydraulic heads produced by this model. These heads, along with particle tracking available in GFLOW were used to select model boundaries for the final MODFLOW model (figure A1).

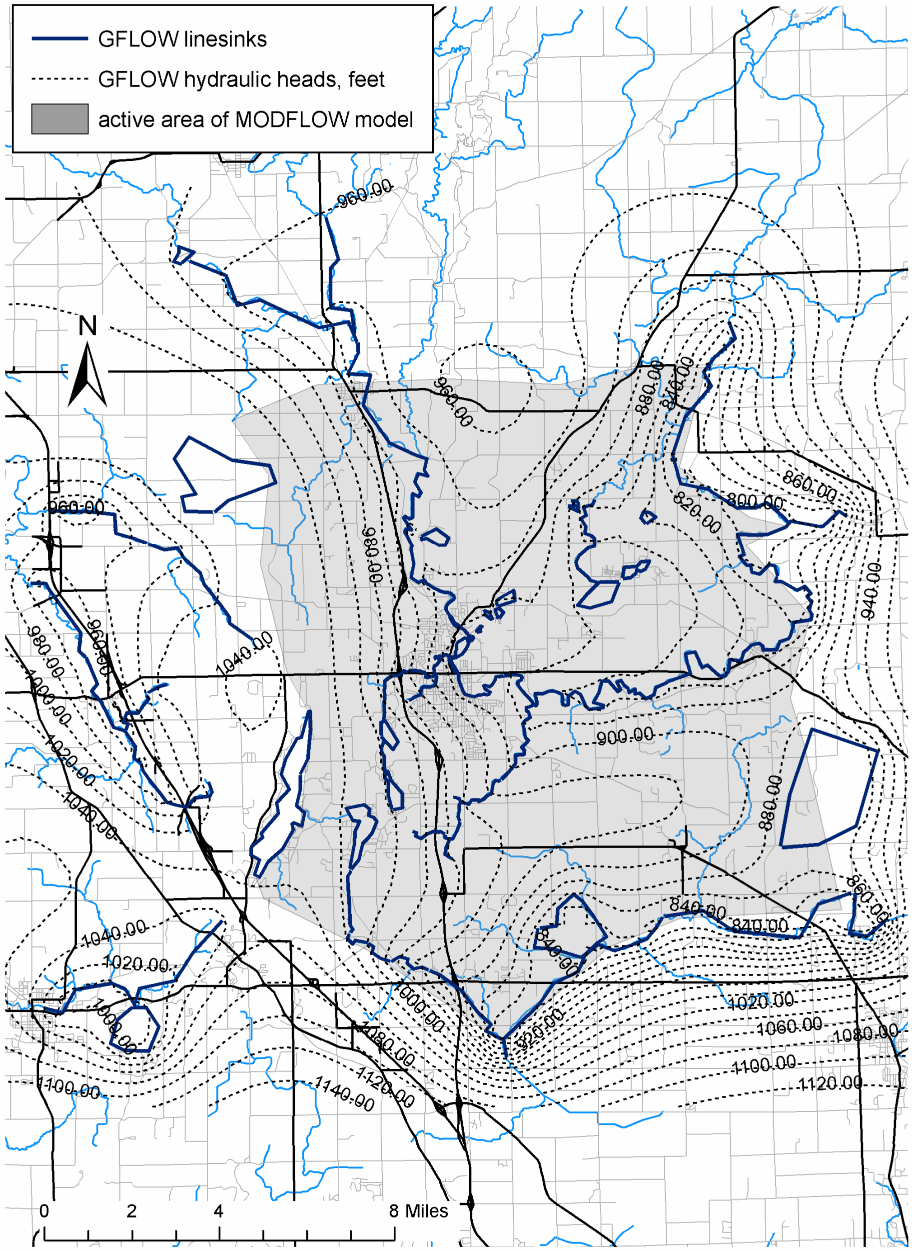


Figure A1. Extent of the GFLOW screening model developed for West Bend.

Appendix B. Detailed maps of contributing areas for municipal wells

Figures B1, B2, and B3 show the 5- and 10-year contributing areas for the West Bend municipal wells with more detail than the overview given in the main text.

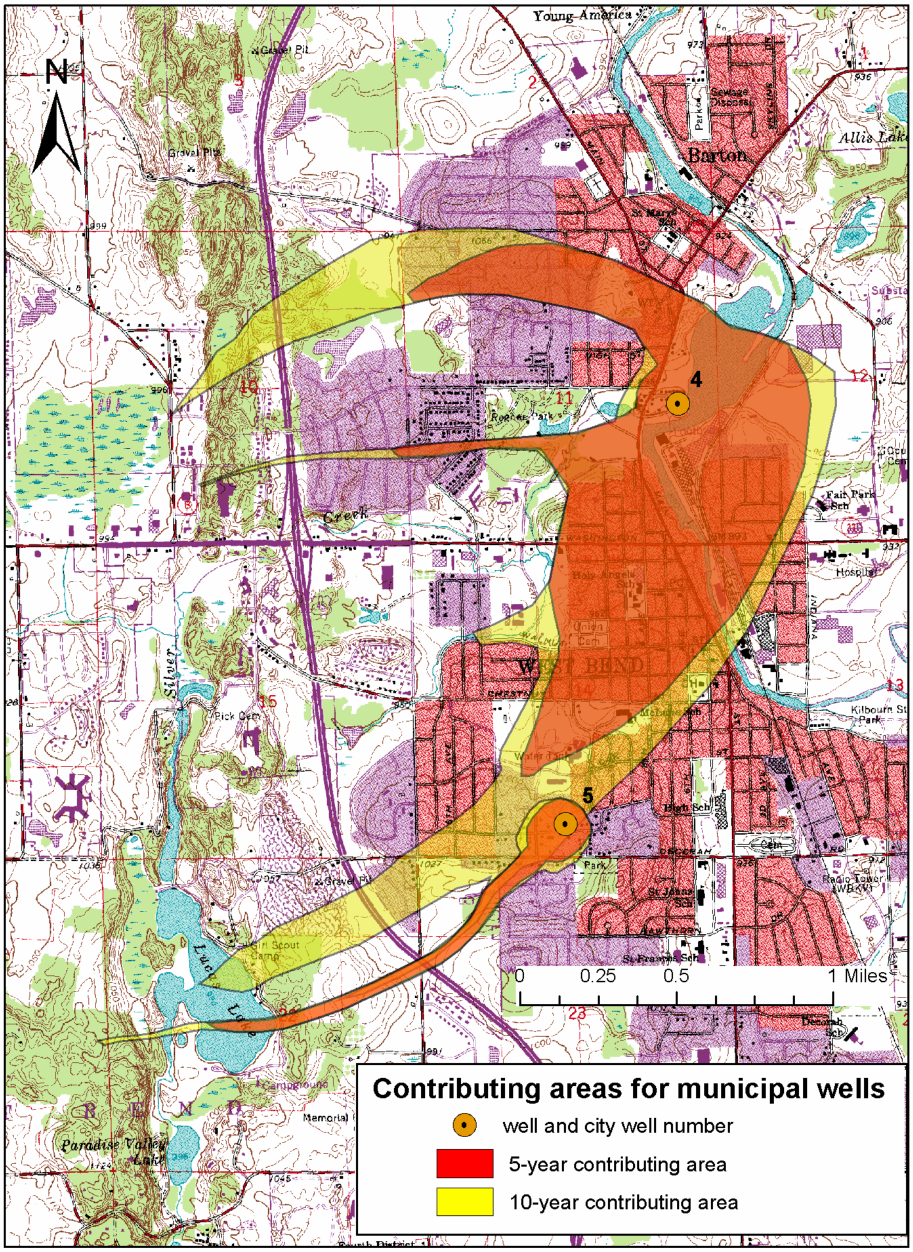


Figure B1. Detailed contributing areas for wells 4 and 5.

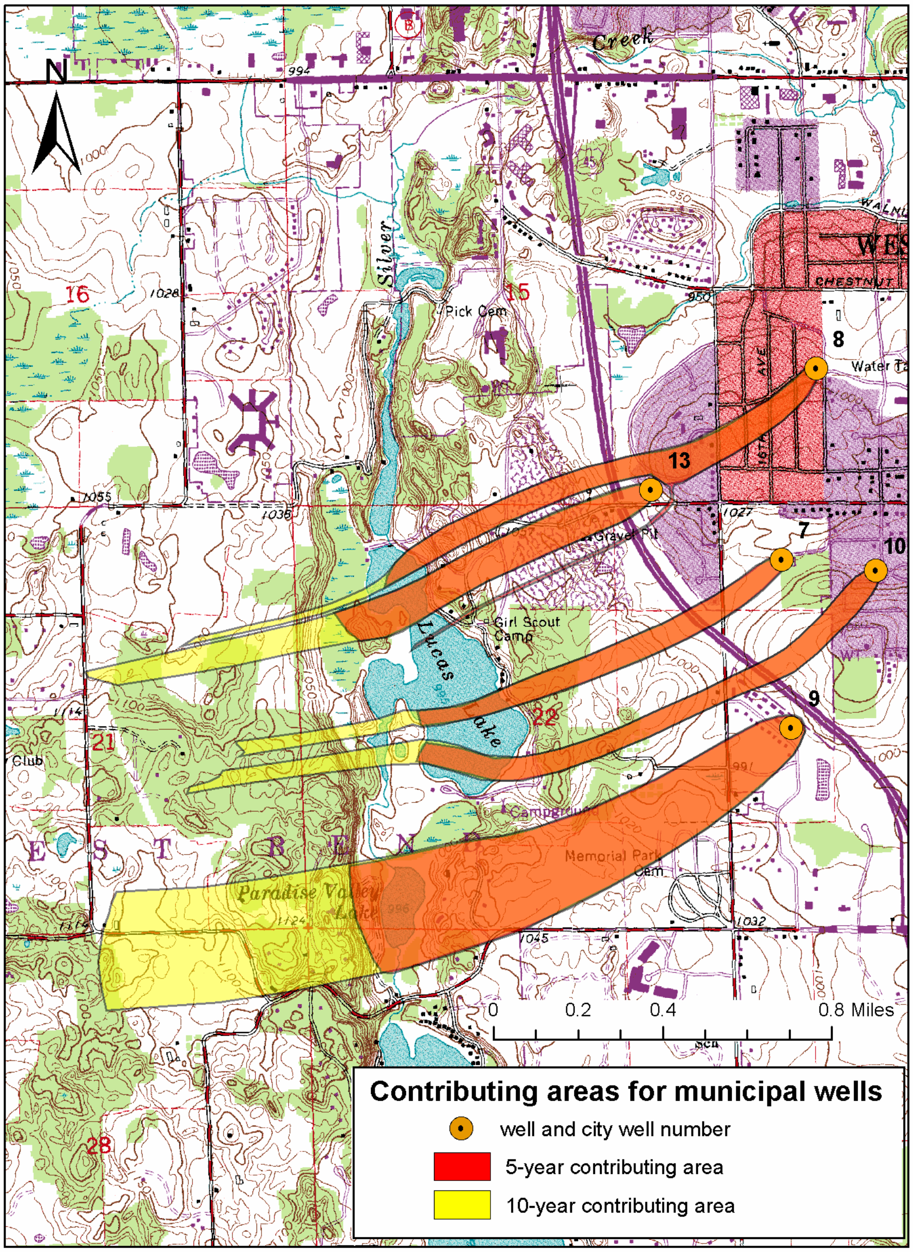


Figure B2. Detailed contributing areas for wells 7, 8, 9, 10, and 13.

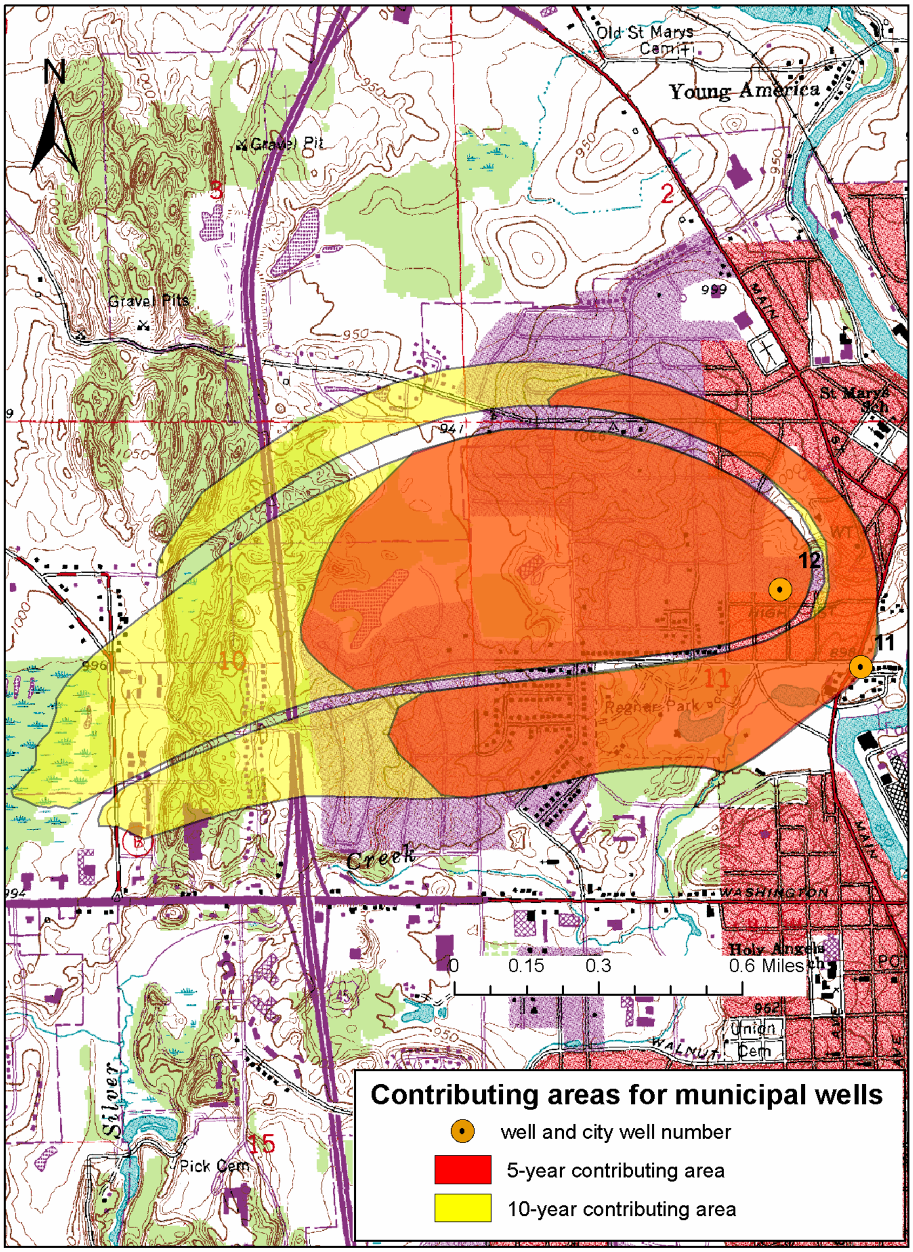


Figure B3. Detailed contributing areas for wells 11 and 12.