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Delineation of Five-Year Zones of Contribution for Municipal Wells in La Crosse County, Wisconsin

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ABSTRACT

A recently developed three-dimensional computer model of regional groundwater flow was used to determine the five-year areal zones of contribution for 36 municipal wells in La Crosse County, Wisconsin. The modeling effort and the investigations presented in this report are part of a three-year study conducted between 2000 and 2003 characterizing and simulating groundwater flow in La Crosse County. The delineations are intended for use by the Wisconsin Department of Natural Resources (WDNR) for determining the susceptibility of municipal water supply wells to potential contamination sources as part of the state's Source Water Assessment Program (SWAP). The delineations are also intended for use in wellhead protection plans to help safeguard the public health and economic development of La Crosse County.

The largest municipal groundwater withdrawals occur along the Mississippi River valley from wells finished in sand and gravel deposits. Communities using the sand and gravel aquifer include the Cities of La Crosse and Onalaska, and the Village of Holmen. The total average withdrawal rate from these wells (22 total) is about 15 million gallons per day (mgd). The City of La Crosse, with 13 currently operating sand and gravel wells, is the largest single municipal consumer, with an estimated total average withdrawal rate of 12.2 mgd. Fourteen additional municipal wells provide water for smaller communities east of the Mississippi River valley in La Crosse County. These wells draw groundwater from sandstone aquifers, and withdrawal an average of 0.8 mgd total. Communities using the sandstone aquifer include the Villages of West Salem, Bangor, and Rockland, and the Towns of Farmington, St. Joseph, and Shelby.

The delineation of areal zones of contribution for municipal wells in La Crosse County is derived from groundwater flow models and numerical particle tracking. Submodels, based on the regional flow model, provided greater grid resolution and associated numerical accuracy near specific municipal wells. The particle tracking simulations indicate that groundwater produced by municipal wells in La Crosse County originates near the wells, and that for every well the steady-state five-year zone of contribution lies entirely within the county.

The five-year contributing areas for wells in the sand and gravel aquifer are fairly large, extending up to 1.5 miles in length and 1 mile in width. In comparison, the contributing areas for wells in the sandstone aquifer are significantly smaller, extending no more than 0.30 miles in length and 0.25 miles in width, due to the lower hydraulic conductivity associated with the sandstone aquifer and to the lower pumping rates associated with wells withdrawing groundwater from sandstone aquifers. Many of the sand and gravel wells are located in discrete clusters and exhibit complex well interference patterns with adjoining delineations covering large areas. Particle tracking and water isotope analyses also indicate that in at least seven of the thirteen City of La Crosse sand and gravel wells groundwater originates at least partially as induced infiltration of river water into the groundwater system. Estimates of travel time from surface water to pumping well vary from less than a year for sand and gravel wells located near a surface water feature to over 12 years for sand and gravel wells located further inland.

Stochastic analyses of selected model parameters help quantify some of the uncertainty in the contributing area delineations. The stochastic analysis generates multiple solutions using the groundwater flow model and an estimated statistical distribution of model inputs. The results of the model runs are then used to generate a contoured probability map of the zone of contribution for each well. For this work the change in model input was limited to horizontal hydraulic conductivity. Measurements for the horizontal hydraulic conductivity of the sand and gravel deposits in the Mississippi River valley vary widely, from 3 to 1500 ft/day, and the simulated areal extent of a well's contributing area varied according to the value used in the model. We found that using an average value of 420 ft/day for the sand and gravel deposits in the Mississippi River valley encompasses the 80% and higher probabilities when a triangular distribution for horizontal hydraulic conductivity was used, meaning there is an 80% chance that the capture zone is not larger than shown in the delineation.

INTRODUCTION

This report summarizes the delineation of five-year zones of contribution (ZOCs) for municipal wells in La Crosse County, Wisconsin (fig.1). The zone of contribution for a well represents the surface area where recharging precipitation enters the groundwater system and supplies water to the well (fig.2). For shallow wells located near surface water bodies, the contributing areas may intercept groundwater that would naturally discharge to the water body, or the contributing areas may extend to the surface water body and induce infiltration into the groundwater system (fig. 2). A five-year ZOC outlines areas within which recharging precipitation takes five years or less to reach the well. Determining the five-year ZOC is a critical step in establishing wellhead protection areas for municipal wells in La Crosse County. It is also a requirement of Wisconsin's Source Water Assessment Program (SWAP), a program administered by the Wisconsin Department of Natural Resources (WDNR).

This work is part of a three-year study characterizing and simulating groundwater flow in La Crosse County (Chapel and others, in review, and Hunt and others, 2003). The study was conducted between 2000 and 2003 as a joint project of the Wisconsin Geological and Natural History Survey (WGNHS) and the United States Geological Survey (USGS) and was funded by La Crosse County and the WDNR SWAP. The main objective of a SWAP is to identify areas that contribute water to public water supply systems in order to determine the susceptibility of these systems to potential contamination sources. The delineations presented here will help protect the public health and economic development of La Crosse County in the future. The delineations are also available for La Crosse County municipalities for use in developing their own wellhead protection plans.

A glossary is provided at the end of this report to help the reader understand the more technical terminology used in the following sections.

HYDROGEOLOGIC SETTING AND MODEL PARAMETERS

La Crosse County (approx. 470 square miles in area) is located in west-central Wisconsin along the eastern side of the Mississippi River valley (fig.1). The county is located in the Driftless Area, a region in southwestern Wisconsin not covered by continental glaciers (Mickelson and others, 1982). The topography of the county consists of steep ridges rising as much as 700 ft above the river valleys (fig 1).

The bedrock of La Crosse County consists of layers of relatively flat-lying Cambrian and Ordovician age sandstones and dolomites with some shale and siltstone overlying Precambrian crystalline rocks (fig.3). These Paleozoic bedrock units are up to 1300 ft thick beneath the ridges. Within the major river valleys, the upper bedrock units have been eroded away (fig.4) and the valleys contain thick deposits (up to 200 ft) of unlithified sand and gravel, with some silt and clay. Evans (2003) describes the geology of La Crosse County in more detail.

There are four separate aquifers in La Crosse County, characterized by Chapel and others (in review); a lower bedrock aquifer consisting of the Mount Simon Formation and the sandy facies of the Eau Claire Formation, the Wonewoc aquifer consisting of the Wonewoc Formation, the ridge-top aquifer system consisting of all saturated bedrock units above the Wonewoc Formation, and the sand and gravel aquifer consisting of unlithified valley fill deposits (fig.3). The Eau Claire aquitard consists of the shaly facies of the Eau Claire Formation, and separates the Wonewoc aquifer from the lower bedrock aquifer. Chapel and others (in review) describe the hydrogeology of La Crosse County in more detail.

The USGS has developed a three-dimensional groundwater flow model for the La Crosse County area (Hunt and others, 2003). The model domain covers the entire county and portions of Trempealeau, Jackson, Monroe and Vernon counties in Wisconsin and a portion of Minnesota on the west side of the Mississippi River (fig.5). The model uses the USGS MODFLOW code (McDonald and Harbaugh, 1988) with a uniform grid spacing of 500 ft. It includes layers simulating the lower bedrock aquifer, the Eau Claire aquitard, an upper bedrock aquifer consisting of all bedrock units above the Eau Claire aquitard, and the unlithified sand and gravel aquifer (fig.3). Although separate aquifers are present in the ridge-top aquifer system above the Wonewoc aquifer, these units were not differentiated in the La Crosse County model because they are not extensively used by municipalities for drinking water (Chapel and others, in review and Hunt and others, 2003).

The flow model uses hydraulic parameters appropriate for each hydrogeologic unit simulated (table 1). Horizontal hydraulic conductivity (Kh) values were modified from estimates derived from specific capacity data (Chapel and others, in review) and values reported in previous studies (Davy Engineering, 1998 and 2001; Earth Tech, 1999; and Young, 1992) during the model calibration process (Hunt and others, 2003). Vertical hydraulic conductivity (Kv) values were also derived during the model calibration process (Hunt and others, 2003).

The effective porosity is a measure of the interconnected pore spaces in a rock or sediment that are available for fluid flow. Values of effective porosity are generally less than total porosity, which is a measure of the total pore space in a rock or sediment. Effective porosity values are needed to calculate groundwater velocities and are necessary in determining the five-year ZOCs. Unfortunately, no direct measurements are available for the effective porosities of the geologic units in La Crosse County. Reported total porosity values vary from 25-50% for unlithified sand and gravel (Fetter, 1994) and 5-30% for sandstone (Domenico and Schwartz, 1998). We assigned an effective porosity value of 25% for the sand and gravel aquifer as a more conservative estimate (produces more rapid estimates of groundwater flow and hence larger ZOCs). For the sandstone aquifers, we assigned an effective porosity value of 20%, which is similar to values used in groundwater flow models developed for other parts of Wisconsin (e.g. Dane County groundwater flow model, K. Bradbury personal communication, 2003; Feinstein and others, 2003; and Gotkowitz and others, 2002). For the Eau Claire aquitard we assigned an effective porosity value ranging from 5 to 10% to reflect the variability in shale content discussed by Chapel and others (in review). For the ridge-top aquifer system in the St. Joseph TMR model we assigned an effective porosity of 5% to reflect the finer grained rock units and potential fracturing found in the Lone Rock and St. Lawrence Formations discussed by Chapel and others (in review).

LA CROSSE COUNTY MUNICIPAL AND HIGH CAPACITY WELLS

There are currently 36 municipal water supply wells in La Crosse County (fig.5). Pumping rates assigned to municipal wells in the model are based on measured annual averages or estimates provided by well operators (table 2). All municipal wells located within the Mississippi River valley (22 total) draw water from the sand and gravel aquifer and are some of the most productive wells in the county. Total groundwater withdrawals from sand and gravel municipal wells in La Crosse County average about 20 million gallons per day. Communities drawing groundwater from the sand and gravel aquifer include the Cities of La Crosse and Onalaska, and the Village of Holmen. The City of La Crosse currently operates 13 of the city's 15 municipal wells, and is the largest single municipal consumer with a total average withdrawal rate of 12.2 million gallons per day. Because capture zone delineations are required for all potentially active municipal wells by the WDNR all 15 City of La Crosse wells were included in the model with an assigned total groundwater withdrawal rate of 16.6 million gallons per day (table 2).

Communities located east of the Mississippi River valley draw water mainly from the lower bedrock aquifer. These communities include the Villages of West Salem, Bangor and Rockland; and the Towns of Shelby, and Farmington. The Town of St. Joseph is the only community to draw water from the upper bedrock aquifer. Total groundwater withdraws from the bedrock municipal wells averages about 0.80 million gallons per day.

The groundwater model simulates all municipal wells in La Crosse County. In addition to the 36 municipal wells, 147 private high-capacity wells (authorized pumping rates greater than 70 gallons per minute) were included in the model (fig.5). It is important to include private high-capacity wells in the groundwater flow model because pumping from these wells affects local groundwater flow paths and alters the contributing areas for nearby municipal wells. Unless yearly averages were available, simulated private high-capacity wells were assigned "normal pumpage" rates, which are calculated by the WDNR as the design capacity of the well multiplied by 12 hours (i.e. rate when well is pumped 50% of the time and pumping at design capacity) (table 3).

METHODOLOGY

Model Refinement and Particle Tracking

Particle tracking is a common modeling procedure used for delineating the contributing areas for pumping wells. The method involves tracing mathematical particles in the groundwater flow model backwards to areas up gradient from the pumping well. The areas traced out by the particles delineate the contributing areas to the well.

The 500-ft model grid spacing used in the La Crosse County groundwater flow model was too coarse for accurate delineation of ZOCs for most county wells (see model sensitivity section below). For many municipal wells the drawdown in heads, which are averaged over the entire grid cell containing a well, were too small to resolve enough detail of the groundwater velocity field required for the particle tracking method (see the weak sink problem in Zheng and Bennett, 1995). To improve model precision near the wells of interest we used a series of telescopic mesh-refined (TMR) groundwater flow models extracted from the regional model (fig.6). The mesh refinement procedures were carried out using Groundwater Vistas version 3.38 (Environmental Simulations, Inc., 1996-2002), a graphical interface and pre- and post-processor for MODFLOW. The TMR models were extracted around specific municipal wells with results from the regional model used as boundary conditions at the edges of the TMR models. Care was taken to make the TMR model extractions large enough so that the boundary conditions did not unrealistically influence groundwater flow near municipal wells of interest. A uniform grid spacing of 50 ft in the TMR models provided improved resolution of the head distribution near municipal wells and greater detail of the velocity field required for the particle tracking method. The refinement to a 50 ft grid spacing constitutes a 90% reduction from the original grid spacing and based on our professional experience was judged to be more than adequate to provide the required resolution.

For most municipal wells (see additional refinements made for selected wells below) the refinement from the regional model to the TMR model involved only reducing the grid size with no modifications of internal boundary conditions, such as river nodes. For justification, we performed one TMR model simulation for a sand and gravel municipal well located near the Mississippi River with the river node locations refined using 7.5 minute topographic maps and found very little difference in the 5-year ZOC delineation compared with no refinement of river node locations. As a result, ZOC delineations were assumed to be relatively insensitive to the refinement of these model inputs/boundaries and therefore the changing of internal boundary conditions and model recalibration was not performed during this study.

Additional refinements were performed for the Town of St. Joseph TMR model. The Town of St. Joseph operates the only municipal wells in La Crosse County not drawing groundwater from the lower bedrock or sand and gravel aquifers. The town has one primary well that was originally pumping from the lower bedrock aquifer, but this well was recently reconstructed due to elevated iron concentrations and now draws groundwater from the upper bedrock aquifer (mainly from the Wonewoc Formation). The town also operates a small backup well that draws water from the Lone Rock Formation (the bedrock unit above the Wonewoc and part of the ridge-top aquifer system).

The USGS model lumps the Wonewoc Formation and all bedrock units above it into one hydrostratigraphic unit (fig.3). Instead of modeling both municipal wells in the top layer of the regional model, we added a layer to the Town of St. Joseph TMR model in order to represent the Wonewoc aquifer and the ridge-top aquifer system separately (fig. 3).

For the St. Joseph model, the hydrogeologic properties for the Wonewoc aquifer were kept at the same values used for the upper bedrock aquifer in the USGS La Crosse County model (table 1) while the values for the ridge-top aquifer system were systematically changed until the modeled groundwater head best matched that of the static water level (SWL) in the backup municipal well (table 1).

Other methodology variations included performing two different model simulations for City of La Crosse wells #12, 16, 17, and 22. These wells are located in close proximity to 3 recently installed private high-capacity remediation wells (WDNR permit #2968, 3000, 3001) whose future pumping rates are uncertain. In order to incorporate this uncertainty we ran particle-tracking simulations both with and without the remediation wells pumping and encircled the capture areas from both simulations.

Two different simulations were also performed on the City of Onalaska municipal well #9 to incorporate uncertainty. The capture area for this well extends across two hydraulic conductivity zones for the sand and gravel aquifer, one for the Mississippi River valley with a value 420 ft/day and another for the La Crosse River valley with a value of 40 ft/day. Because the location of the boundary between these two units is uncertain and because of the inherent uncertainty in the K-values, we ran two simulations, one with the K-value of the La Crosse River valley sand and gravel deposits set at 40 ft/day and another with the K value set at 420 ft/day, encircling the capture areas from both simulations.

The pumping rate assigned to all municipal wells for their five-year ZOC delineation is based on guidelines outlined by the SWAP of the WDNR (email from Jeff Helmuth, WDNR, 2001), and uses the higher of either ½ the operation capacity or 15% more than the average pumping rate (table 2). The operation capacity is the operating pumping rate of the well, as reported by municipalities to the WDNR, multiplied by 24 hours (i.e. rate when well is pumped continuously and pumping at operating capacity). The ZOC pumping rate is intended to be larger than a well's average pumping rate in order to obtain a larger, more conservative, estimate of the five-year ZOC. Average pumping rates (based on measured annual averages or estimates provided by well operators) are assigned to the surrounding municipal wells when simulating the ZOC for a particular well.

The particle tracking code MODPATH (Pollock, 1988, 1989) was used to delineate the five-year ZOC for each well by tracking mathematical particles backwards from the well's location for a travel time of five years. Rings of 50 mathematical particles were placed within the top; middle and lower portions of each model layer intersected by the well so that multiple flow paths to the well were represented. The rings were centered on the middle of the cell containing the well, which was often slightly different than the actual location of the well because MODFLOW places the well in the center of a model cell regardless of its actual location within the cell. The five-year particle traces were then exported into a geographic information system (GIS) where the surface area encompassing the particle traces was outlined and visually adjusted to the correct geographic well location.

Using Isotopes of Water to Determine Surface Water Contribution to Municipal Wells

There is concern that wells located in the sand and gravel aquifer near river shorelines might now or in the future draw in significant amounts of surface water and degrade the quality of water produced in the wells. For example, surface water can be a source of bacteria, viruses, protozoa and endocrine disrupters to drinking water.

Analyzing the ratios of naturally occurring isotopes of oxygen and hydrogen in water ($^{18}O/^{16}O$ and $^{2}H/^{1}H$) is useful for investigating hydrologic systems and determining sources of groundwater (Mazor, 1997; Clark and Fritz, 1997). Groundwater originating as recharge from precipitation on the land surface has an isotopic composition similar to the local precipitation. In comparison, evaporation from surface water bodies fractionates the water by preferentially removing the lighter isotopes (^{16}O and ^{1}H). As a result, surface water has an isotopic composition heavier (more ^{18}O and ^{2}H) than the local precipitation. Identifying heavier isotopes in municipal well water can therefore help indicate whether the well is capturing significant amounts of surface water.

The USGS collected a number of water samples for isotope analysis from 13 City of La Crosse municipal wells between 2001 and 2002. These samples were analyzed for oxygen-18 (^{18}O), oxygen-16 (^{16}O), hydrogen (^{1}H) and deuterium (^{2}H) at the USGS Stable Isotope Laboratory in Reston, Virginia. Details of the sample collection and laboratory methods can be found in Hunt and others (in review).

RESULTS

Sand and Gravel Wells

The large pumping rates associated with the sand and gravel wells and the high hydraulic conductivity of the sand and gravel aquifer cause the five-year ZOCs of these wells to be the largest in the county, extending up to 1.5 miles long and up to 1.0 mile wide (fig.7).

Many of the sand and gravel municipal wells are located in close proximity to one another leading to well interference with adjoining delineations covering large areas (fig. 7). La Crosse City wells #13, 14, 15, 20, and 21 in particular are some of the most tightly clustered municipal wells in the county and show considerable interference and complex, adjoining ZOC delineations (fig.7).

Model simulations show that pumping in several locations has lowered the water table below the level of the normal stage of the Mississippi River (Hunt and others, 2003) and many ZOC delineations for municipal wells located near the Mississippi River, Black River, La Crosse River, and Halfway Creek extend out into these waterways suggesting a surface water contribution to the well. The particle tracking simulation allows estimates of travel times from the surface water contribution area to the wells. To estimate representative travel times we used the average pumping rate instead of the higher ZOC pumping rate (table 2). The model simulations indicate that there are at least 13 and perhaps 15 municipal wells in the Mississippi River Valley likely capturing some amounts of surface water with approximate travel times varying from less than 1 year to over 12 years (table 4). It is important to note that longer travel times generally indicate longer travel paths and therefore increased potential degradation of contaminants, while those with shorter travel times have less potential for degrading contaminants. The isotopic signature of well water collected for selected municipal wells in the City of La Crosse also indicate surface water contribution for 7 of these wells (see surface water contribution, below).

Many of the five-year ZOC delineations for the sand and gravel wells also extend across major highways. Because of the relatively shallow depth to groundwater (about 30 ft) and high permeability of the sand and gravel in the Mississippi River valley, road salt may be a potential contaminant to these wells. Indeed, increasing salinity has been observed in the municipal wells over the last 17 years (Tom Berendes, City of La Crosse Water Utility, written communication, February 2003). Other potential contaminants of concern include nitrates, pesticides, and volatile organic compounds. Chapel and others (in review) discuss groundwater quality and contaminant susceptibility in La Crosse County in more detail.

Sandstone Wells

The five-year ZOC delineations for the sandstone wells are much smaller than the ZOCs for the sand and gravel wells, extending no more than 0.30 miles in length and 0.25 miles in width. The smaller five-year ZOCs are due to the much lower hydraulic conductivity associated with the sandstone aquifers and to the lower pumping rates associated with the sandstone wells. Figure 8 shows the five-year ZOC delineations for municipal wells in the Villages of West Salem; Bangor; and Rockland; and the Towns of St. Joseph and Farmington. The five-year ZOC delineations for the Town of Shelby are shown in figure 7. These communities are much smaller than the populated areas along the Mississippi River valley and therefore have much lower demands for water.

The sandstone wells are generally less vulnerable to contamination than the sand and gravel wells because of the much lower hydraulic conductivity of the sandstone aquifer, the protection of the Eau Claire aquitard, and the overall greater depth of well placement associated with these wells.

Surface Water Contributions to the City of La Crosse Municipal Wells

Over an 18-month period, the USGS collected multiple water samples from 13 City of La Crosse municipal wells for stable isotope analysis. Figure 9 is a plot of the isotopic ratios ($^{18}O/^{16}O$ and $^{2}H/^{1}H$) using standard delta notation (see glossary). The local meteoric water line (LMWL) in figure 9 represents the local isotopic composition of precipitation, which was defined from non-fractionated surface water analyses available in the USGS database (Black River at Galesville, WI; written communication from Tyler Coplen, USGS) for a site located approximately 16 miles north of La Crosse. Samples with an isotopic composition heavier than local precipitation plot to the right of the line and indicate a surface water component. In general the data form two groups: one group of 6 wells that plots tightly around the LMWL and approximates a flattened ellipse, and a second group of 7 wells that has two or more samples residing to the right of the LMWL. The first group is typical of meteoric groundwater recharge that has not been appreciably affected by evaporative fractionation. The second group shows effects of evaporative fractionation indicating the presence of surface water (city wells #10, 17, 19, 21, 23, 24, 26).

The results of the isotope data are fairly consistent with the results from the particle tracking. All wells indicating a surface water component from the isotope data also show particle paths extending into surface water bodies (table 4). However, the particle tracking simulations indicate there are additional City of La Crosse municipal wells that are likely capturing some portion surface water that are not supported by the isotope data (wells #15, 20, 22, and 25). The reason for the inconsistency may be that the samples do have a surface water component, but reflect infiltrating surface water with an isotopic signature similar to groundwater values due to the seasonal variation in the isotopic composition of precipitation. Additional sampling events might verify this hypothesis, but were beyond the scope if the present study. Alternatively, the amount of surface water in the municipal well might be sufficiently small so that the isotopic signature cannot be discerned. A third possibility is that the model incorrectly simulates flow from the river to the well, when in reality, river water does not reach the well. The model may yield incorrect results if significant heterogeneities in the sand and gravel aquifer (e.g. preferential flow paths and low conductivity barriers that limit capture from surface water) are not represented. For example, the City of La Crosse encountered a highly conductive gravel unit in the Mormon Creek valley upgradient from well #25 (Tom Berendes, personal communication, 2001); this unit was not input into the model due to uncertainties in its extent and hydraulic properties. The isotopic results and methodology are discussed further in of Chapel and others (in review) and Hunt and others (in review).

MODEL SENSITIVITY

Model sensitivity refers to the response of the model to variations in model inputs. Model inputs such as hydraulic conductivity, recharge, effective porosity, well pumping rates, model boundary conditions, aquifer thickness and extent, and model grid spacing, can all affect the shape and size of a well’s five-year ZOC. The purpose of a sensitivity analysis is to quantify the uncertainty in the model outputs due to the uncertainty in the model inputs. A rigorous sensitivity analysis of all model inputs was beyond the scope of this study. Hunt and others (2003) investigated the sensitivity of horizontal and vertical hydraulic conductivity, recharge, and streambed leakance values on the simulated hydraulic heads in the La Crosse County regional model. We considered three parameters that can affect the shape and extent of a well’s five-year ZOC: model grid spacing, effective porosity, and the horizontal hydraulic conductivity of the sand and gravel aquifer.

Grid Spacing

We found the 500-ft grid spacing in the regional La Crosse County model did not provide an adequate resolution of the head distribution to accurately delineate the five-year ZOCs for many municipal wells (fig.10). For example, with the 500-ft grid spacing, particle paths for La Crosse City well #24 tended to be confined to a narrow zone and did not show capture from the eastern river as reported by Hunt and others (in review). In addition, isotope results (fig 9) suggest that well #24 receives a component of surface water. With a 50-ft grid spacing, particle paths traced out a wider area that did show capture from the eastern river. The sensitivity in grid spacing is a result of the particle tracking method, which uses differences in groundwater head in adjacent cell nodes to calculate groundwater velocity and to interpolate the particle path direction within a cell. For many wells the drawdown, which is averaged over the entire cell containing the well, was too small to resolve the velocity field required to calculate particle capture in a cell containing a well. This is known as the weak sink problem (Zheng and Bennett, 1995). Grid refinement to a 50-ft spacing overcame this problem by providing a higher resolution of groundwater heads. As discussed in the methodology, the refinement to a 50 ft grid spacing constitutes a 90% reduction from the original grid spacing and based on our professional experience was judged to be more than adequate to provide the required resolution.

Effective Porosity

An aquifer's effective porosity controls groundwater velocities and it is a required parameter in the particle tracking simulation. The groundwater velocity is inversely proportional to the effective porosity. Faster velocities are therefore associated with smaller porosities. Five-year ZOC delineations in the sand and gravel and in the sandstone aquifers vary with different effective porosity values (fig.11). Lower porosity values result in larger five-year ZOCs because of the higher velocities. Unfortunately there are no direct measurements available for the effective porosity of the geologic materials in La Crosse County. Effective porosity values were therefore assigned (table 1) based on typical values of total porosity found in the literature for similar geologic materials and remains a source of uncertainty in the model simulations.

Horizontal Hydraulic Conductivity

Estimates of the horizontal hydraulic conductivity for the sand and gravel aquifer in the Mississippi River valley range over three orders of magnitude, from 3 to 1500 ft/day (fig.12) with an average value of 93 ft/day based on 831 estimates from specific capacity data and published aquifer pumping tests. Five-year ZOC delineations for wells in the sand and gravel aquifer vary systematically with different values of hydraulic conductivity (fig.13). For higher K values, ZOCs are long and narrow; for lower K values, ZOCs are short and wide. Determining a reasonable estimate of the K value is necessary because over half the municipal wells requiring a five-year ZOC delineation in La Crosse County are drawing water from the sand and gravel aquifer in the Mississippi River valley. Instead of using the average value of 93 ft/day based on 831 estimates, we chose a subset of the estimates that would be more representative of the aquifer material around municipal wells. Municipal and other high capacity wells are some of the largest and deepest wells in the sand and gravel aquifer and are strategically located to draw water from the highest water yielding horizons in the sediment. A single value of 420 ft/day was assigned to the sand and gravel aquifer in the Mississippi River valley based on the average of 39 estimates from specific capacity data for the municipal wells, specific capacity data for private high-capacity wells located near the municipal wells, and published pumping tests (fig.12).

Because most of the county's municipal wells are in the Mississippi sand and gravel aquifer it was important for us to quantify the uncertainty in the simulated ZOCs due to uncertainty in horizontal hydraulic conductivity of this aquifer. A stochastic analysis helps quantify the degree of the uncertainty of physical parameters included in the analysis. The procedure allows a model input parameter, such as recharge, hydraulic conductivity, or effective porosity, to vary according to a statistical distribution specified by the user. The model is run numerous times, each time with a different value of the input parameter randomly sampled from the specified distribution. Each model run provides a slightly different solution and is called one *realization* of the stochastic solution. By condensing many realizations into a probability distribution the model results can be presented in statistical terms. The probability distribution represents the probability that a particle placed in a particular cell will be captured by a municipal well given the uncertainty in model parameters included in the analysis.

For La Crosse County, we performed a stochastic analysis for all municipal wells in the sand and gravel aquifer by varying the horizontal hydraulic conductivity from 100 to 700 ft/day and specified a triangular distribution with the most probable value being 400 ft/day (fig.14). To perform the analysis we used the software package *Stochastic Modflow* (Environmental Simulations, Inc., 1998), which interfaces with Groundwater Vistas. Because the stochastic method involves extremely intensive computations we did not use the 50-ft gridded TMR models constructed for the ZOC delineations, instead we extracted three additional TMR models with 150-ft grid spacing encompassing all sand and gravel municipal wells for the City of La Crosse; the French Island area and City of Onalaska; and the Village of Holmen (fig.15).

For each TMR model we performed 100 realizations (we found 100 realizations was enough to capture the range of potential stochastic solutions) and removed those realizations where the head distribution did not fall into reasonable calibration with the head targets. This process is called *conditioning* and strives to preserve reasonable solutions while eliminating solutions that are obviously unacceptable (Ruskauff, 1998).

The Monte Carlo runs and conditioned probability results were obtained using *Stochastic Modpath* (Environmental Simulations, Inc., 1998). Stochastic Modpath is a particle-tracking code that performs forward tracking for each realization of the Stochastic Modflow run. This analysis tracks particles over a large area surrounding the pumping well and calculates the probability that each particle will reach the well. The result is a contoured map of the capture probability zone (0-1 or 0-100% probability of capture, where 0% indicates a particle is not captured in any realizations and 100% means that a particle is captured in every realization).

The results of the capture probability analysis indicate that in most instances the 5-year ZOC delineations simulated using a single average horizontal hydraulic conductivity of 420 ft/day encompasses the 80% and higher probability areas (figs.16-18), meaning there is an 80% chance that the capture zone is not larger than shown in the delineation. This is not surprising given the highest probability in the statistical distribution for the K-value was 400 ft/day (fig.14). It is however important to note in figures16-18 that the probabilities are fairly "tight", meaning lower probabilities do not extend out much further than the higher probabilities and that the capture zones are not very sensitive to K values significantly less than or more than 400 ft/day, given the probability distribution. The stochastic results therefore increased our confidence in using a single average value of 420 ft/day as an acceptable estimate for the horizontal hydraulic conductivity of the sand and gravel aquifer in the Mississippi River valley.

Some noticeably disparities between some of the ZOC delineations using a single K-value of 420 ft/day and the probability capture areas may be related to differences in grid size. The stochastic simulations use a grid spacing of 150-ft to save on computational time and the simulations that use a single K-value of 420 ft/day use a grid spacing of 50-ft for a better head resolution. Grid spacing can affect the shape and extent of a ZOC delineation using the particle tracking method (see sensitivity in grid spacing section above). The probability of capture areas for City of La Cross well #23 and Village of Holmen wells #4 and #5 in figures 17 and 18 are distinctly more narrow than the ZOC delineations and are likely due to the coarser grid size used in the stochastic simulations. Additional 5-year ZOC simulations using a single K-value of 420 ft/day could be performed with the 150-ft grid spacing for a better comparison between the two simulations.

Ideally probability capture zones could be simulated for the other areas of La Crosse County (areas not encompassed by boxes in figure 15) and integrated into a wellhead protection plan, but this was beyond the scope of the project. The simulations were performed for the sand and gravel wells in La Crosse County to illustrate the uncertainty in the horizontal hydraulic conductivity value associated with these deposits. It is also important to keep in mind that the probability capture zones in figures 16-18 reflect the uncertainty in just one parameter. Other physical parameters such as effective porosity, recharge, and pumping rates are also inherently uncertainty and have an effect on the size and shape of the ZOC delineations to varying degrees. Additional stochastic analyses could quantify the uncertainty associated with these parameters.

SUMMARY

This report documents our work in delineating the five-year zones of contribution for 36 municipal wells in La Crosse County. The three major findings are as follows:

1) Twenty-two of the municipal wells are located in the sand and gravel aquifer along the Mississippi River Valley and have large 5-year ZOCs (up to 1.5 miles long and 1 mile wide). The remaining 14 municipal wells are located in sandstone aquifers east of the Mississippi River and have much smaller 5-year ZOCs (up to 0.30 mile long and 0.25 ft mile).

2) Many of the municipal wells along the Mississippi River valley are located in discrete clusters and have adjoining delineations, and some extend to surface water bodies indicating surface water contribution to well water. The presence of surface water was found in 7 of 13 City of La Crosse municipal wells as evidenced by an isotopically enriched signature in the well water. The particle tracking simulations also showed these 7 wells capturing surface water along with four additional City of La Crosse wells that did not have isotopically enriched signatures. Model simulations indicate travel times between surface water and pumping wells range from less than a year to over 12 years.

3) A stochastic analysis of the uncertainty associated with the horizontal hydraulic conductivity of the sand and gravel aquifer in the Mississippi River valley demonstrated that a single value of 420 ft/day encompasses the 80% probability in most cases, meaning there is an 80% chance that the capture zone is not larger than shown in the delineation. This result therefore increased our confidence in the use of a single value for this parameter.

The delineations are intended for use in the state's Source Water Assessment Program administered by the WDNR for determining the susceptibility of municipal water supply wells to potential contamination sources. The delineations are also intended for use in wellhead protection plans to help safeguard the public health and economic development of La Crosse County in the future.

GLOSSARY

Aquifer: A rock unit that is sufficiently permeable so as to supply economically useful amounts of water to wells.

Aquitard: A rock layer of lower permeability that contains water but does not yield economically useful amounts of water to wells.

Boundary Condition: Mathematical statements specifying how much flow or the groundwater elevation at the boundaries of a groundwater flow model. A constant head boundary condition sets the head in the boundary node at a constant value and does not change during the simulation process.

Cone of Depression: A depression in the water table that forms around a pumping well. Unless the water table is completely flat the cone of depression is not the same as the zone of contribution (ZOC) to a pumping well (figure 2). With a head gradient, the ZOC can extend further up gradient, past the cone of depression, to capture groundwater.

Delta (δ) Notation: A standard comparison of the isotopic ratio, $^{18}O/^{16}O$ and $^{2}H/^{1}H$, of a sample to the standard mean ocean water (SMOW) expressed as per mille (parts per thousand):

$$\delta^{18}O = \{(^{18}O/^{16}O)sample \div {}^{18}O/^{16}O)SMOW) - 1\} \times 1000$$
$$\delta^{2}H = \{(^{2}H/^{1}H)sample \div (^{2}H/^{1}H)SMOW) - 1\} \times 1000$$

Head: The total pressure at a point within the groundwater system. In general head is the same as the elevation of the water level in a piezometer (a nonpumping well, generally of small diameter, that is used to measure the elevation of the water table).

Groundwater flow: The movement of water through pores in sediment and rock; is governed by Darcy's Law: Q=KIA, where Q is the volumetric discharge, K is the hydraulic conductivity, I is the hydraulic gradient, and A is the cross sectional area perpendicular to flow.

Head target: A field-measured value of head used as a calibration target in the modeling procedure. Independent variables, such as the hydraulic conductivity (K), are systematically changed until the dependent variable (head) most closely matches the target.

Hydraulic Conductivity (K): A measure of how easily water moves through a permeable medium. The horizontal hydraulic conductivity is a measure of how easily water can move in the horizontal direction and the vertical hydraulic conductivity is a measure of how easily water can move in the vertical direction. Due to the stratified nature of geologic materials, the horizontal hydraulic conductivity is typically higher than the vertical hydraulic conductivity by one or more orders of magnitude.

Isotope: Isotopes of a particular element have the same atomic number but different atomic weights due to a different number of neutrons in the nucleus.

Particle Tracking: A modeling procedure that traces out flow paths, or pathlines, by tracking the movement of mathematical particles placed in the modeled groundwater flow field.

Porosity (Total): The ratio of the volume of void spaces in a rock or sediment to the total volume of the rock or sediment.

Porosity (Effective): The ratio of the volume of void spaces through which water or other fluids can travel in a rock or sediment to the total volume of the rock or sediment. The effective porosity is typically less than the total porosity because many void spaces in a rock or sediment are either not interconnected or are too small to allow fluids to pass through.

Specific Capacity: A measure of a wells productivity, obtained by dividing the rate of discharge of water from the well by the drawdown of the water level in the well. Methods exist for estimating the transmissivity (hydraulic conductivity multiplied by the saturated thickness of the aquifer) of an aquifer from specific capacity values.

Telescopic Mesh-Refined (TMR) method: A method where a model with a smaller domain and finer grid spacing is extracted from a larger (regional) model and which uses the solution of the larger model to define the boundary conditions of the small model.

Travel Time: The time is takes a molecule of groundwater to move from one point to another.

Realizations: One model solution from a single sampling of the random variable (i.e. K-value) from a specified probability distribution. Many realizations provide a range of solutions and can be used to assess the likelihood of an event occurring (i.e. particle capture by well)

Stochastic Analysis: A procedure to address the uncertainty in a model solution by assuming that the input parameters are random variables with a specified probability distribution.

Well Interference: A phenomena that occurs when the cones of depressions of nearby wells intersect with one another. Well interference can affect the shape and extent of a well's ZOC.

Zone of Contribution (ZOC): The land surface area where recharging precipitation enters a groundwater system and eventually flows to a well.

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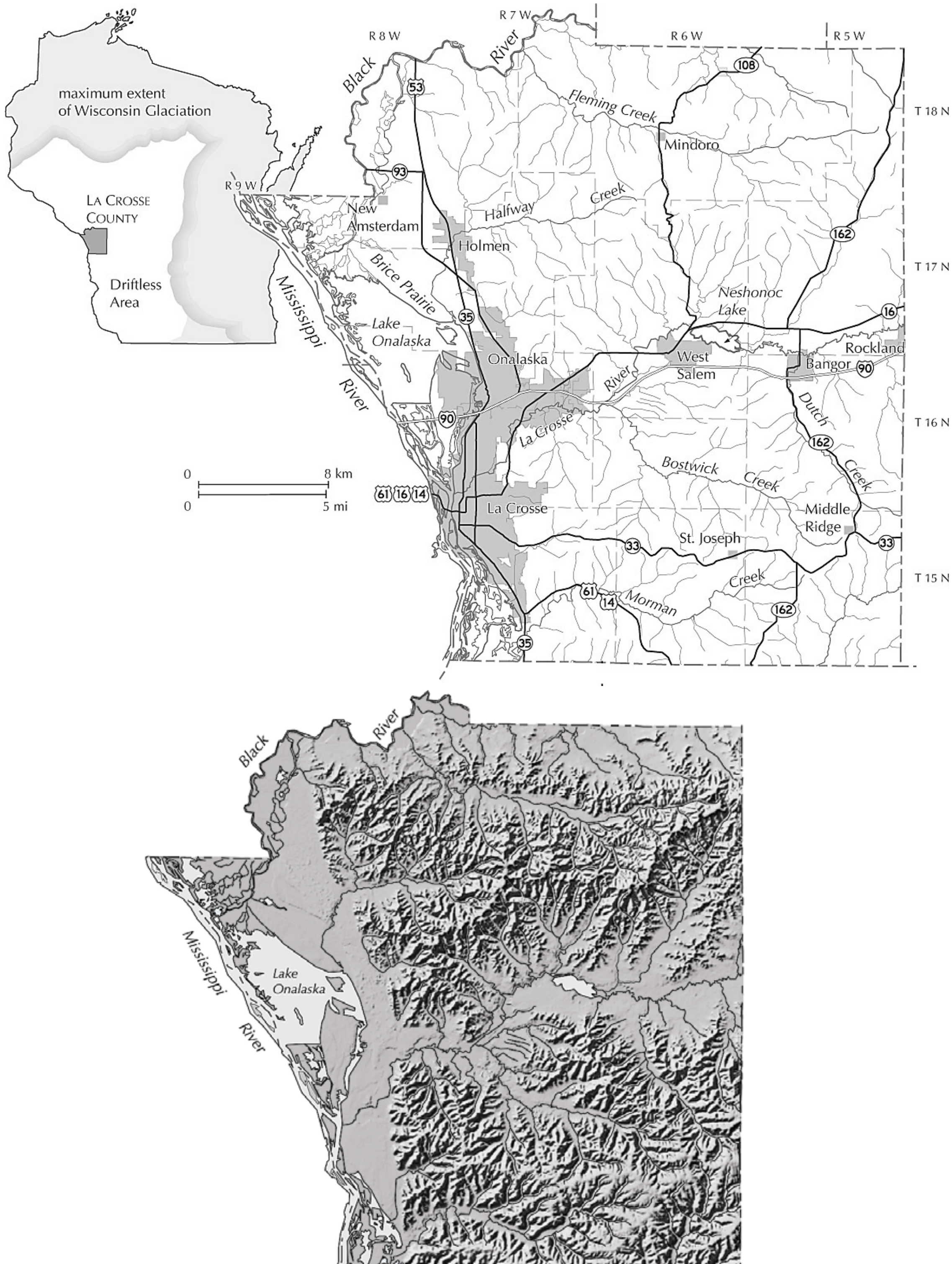
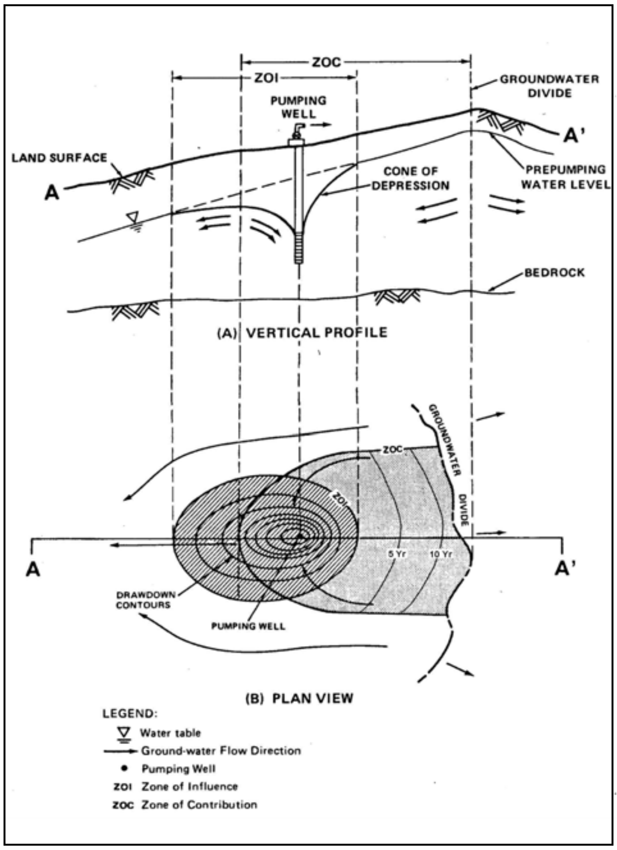
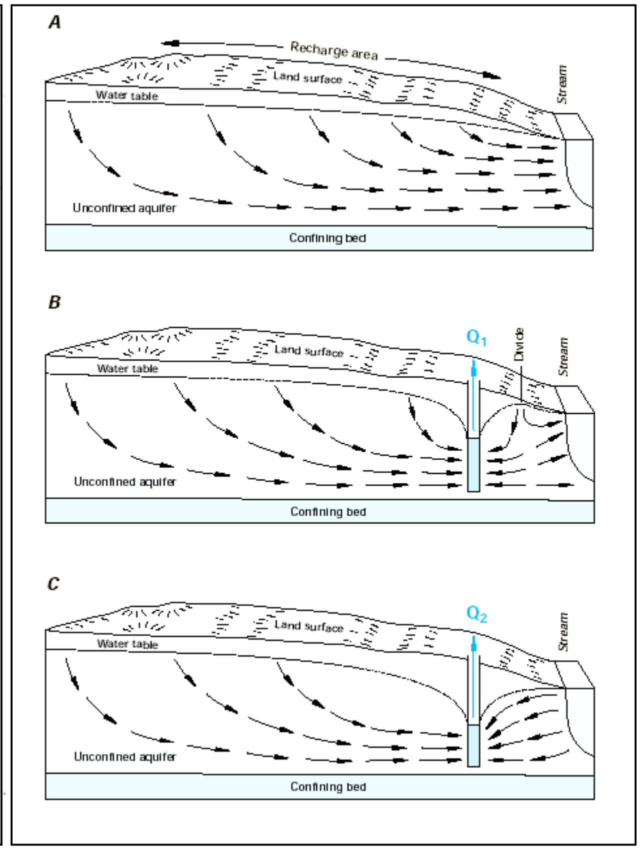


Figure 1: Location and shaded relief map of La Crosse County, Wisconsin (from Evans, 2003)



A. Conceptualization of a ZOC



B. Effect of pumping near surface water body

Figure 2:

A. Conceptualization of a zone of contribution (ZOC) in a uniform flow field. The zone of influence (ZOI) outlines the cone of depression in the water table caused by the pumping well, while the ZOC outlines areas contribution groundwater to the pumping well (from USEPA, 1987).

B. For shallow wells located near surface water bodies, the contributing areas of a well pumping at a rate of Q_1 may intercept groundwater that would naturally discharge to the water body, or with higher pumping rates (Q_2) the contributing areas may extend to the surface water body and induce infiltration into the groundwater system (from Winters and others, 1998)

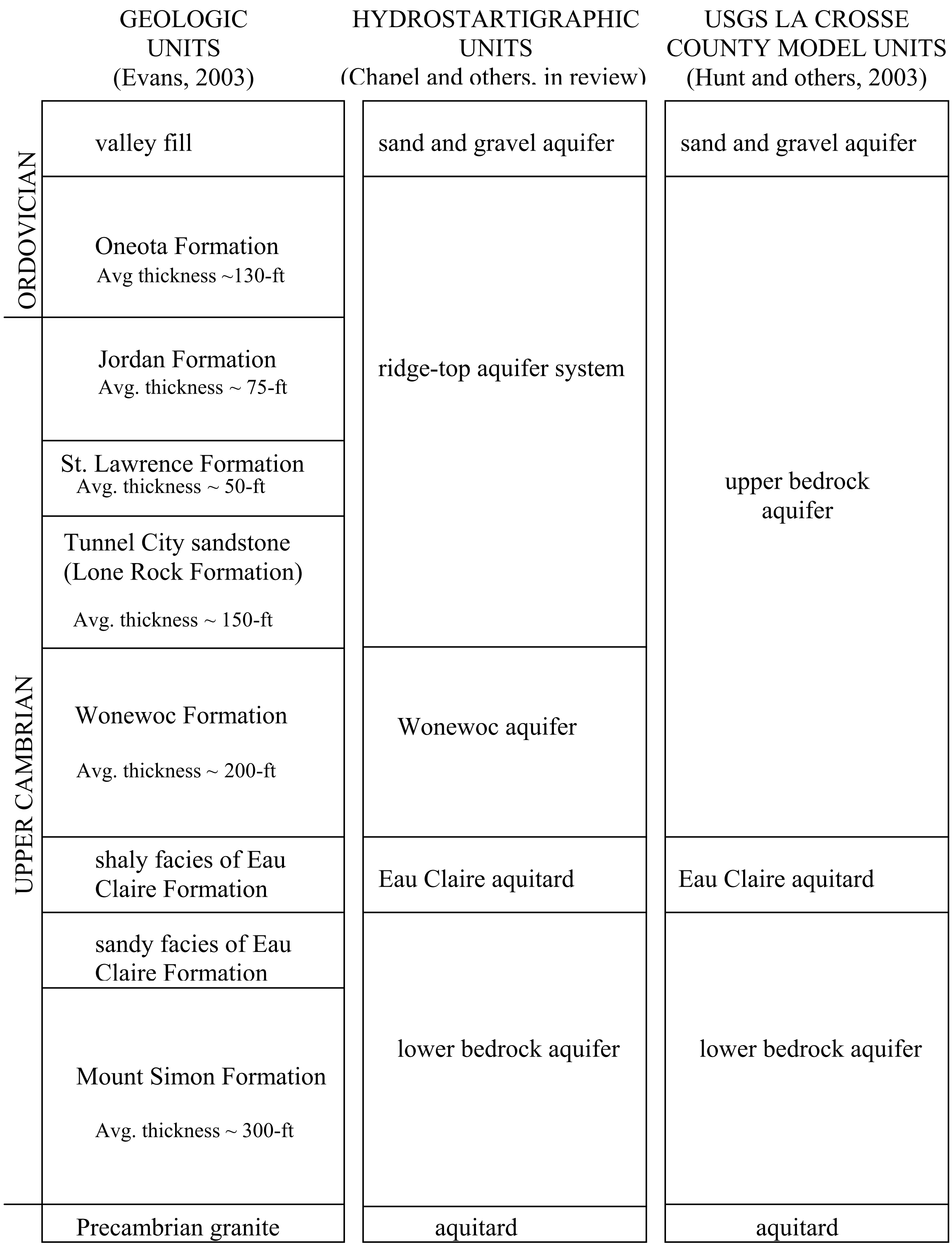


Figure 3: Geologic and hydrostratigraphic units of La Crosse County. The La Crosse County regional model lumps all bedrock aquifers above the Eau Claire aquitard into one hydrostratigraphic unit (upper bedrock aquifer). The Precambrian aquitard forms a lower no flow boundary in the model.

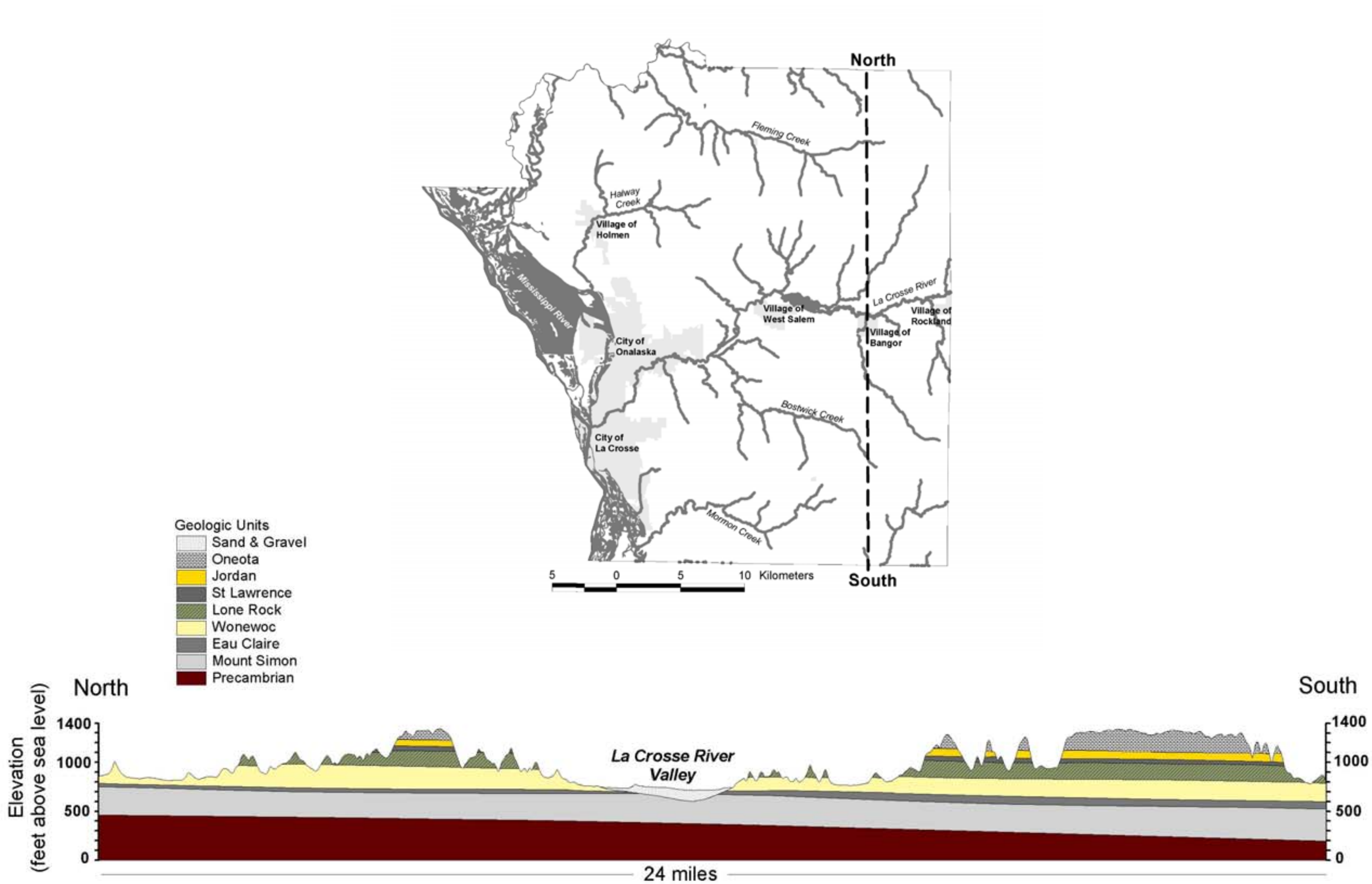


Figure 4: Geologic cross-section across county showing subsurface stratigraphy and extent of valley erosion. Cross section location shown in top figure.

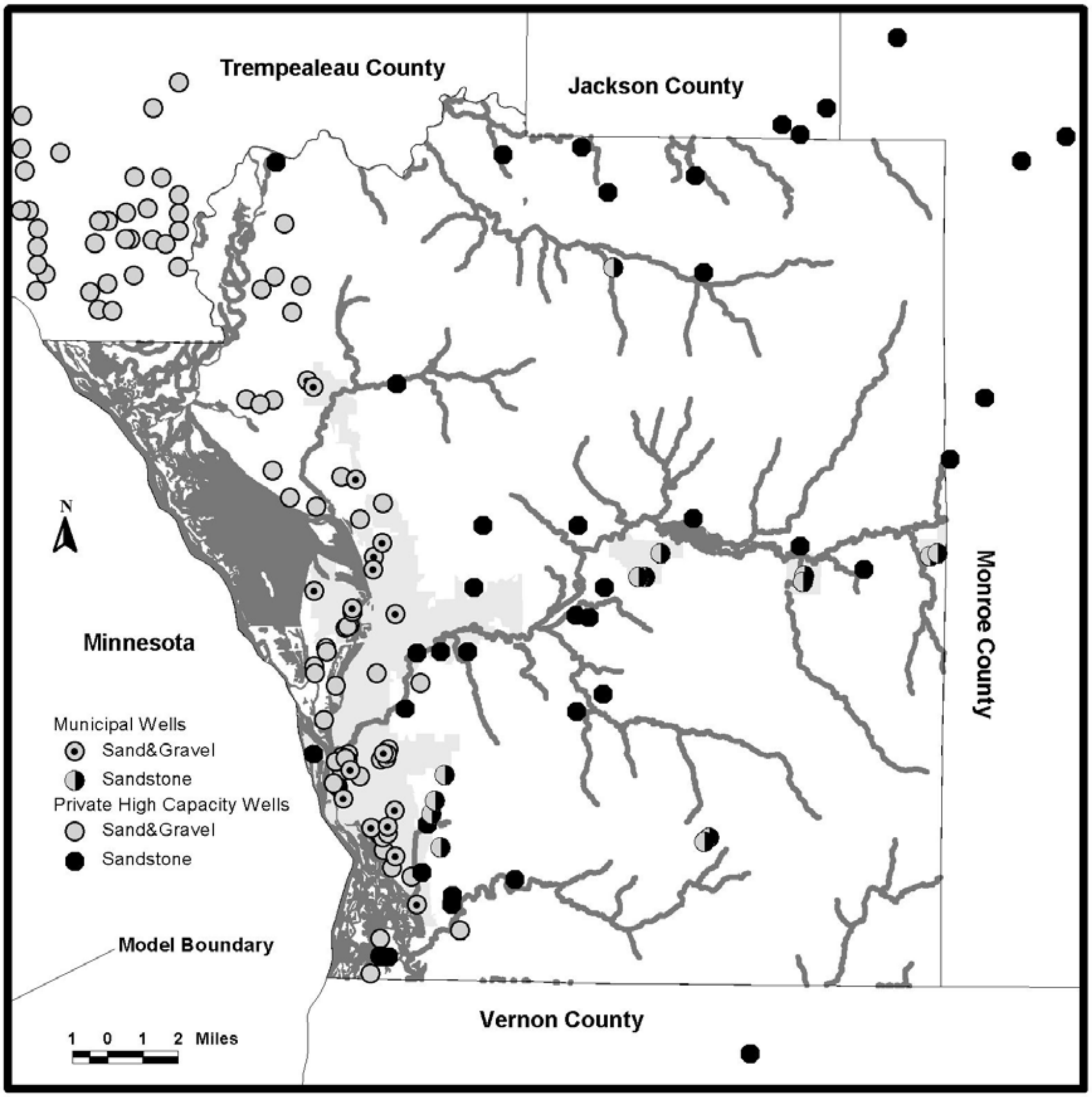


Figure 5: Area modeled in regional groundwater flow model with locations of all municipal and private high-capacity wells used in the model.

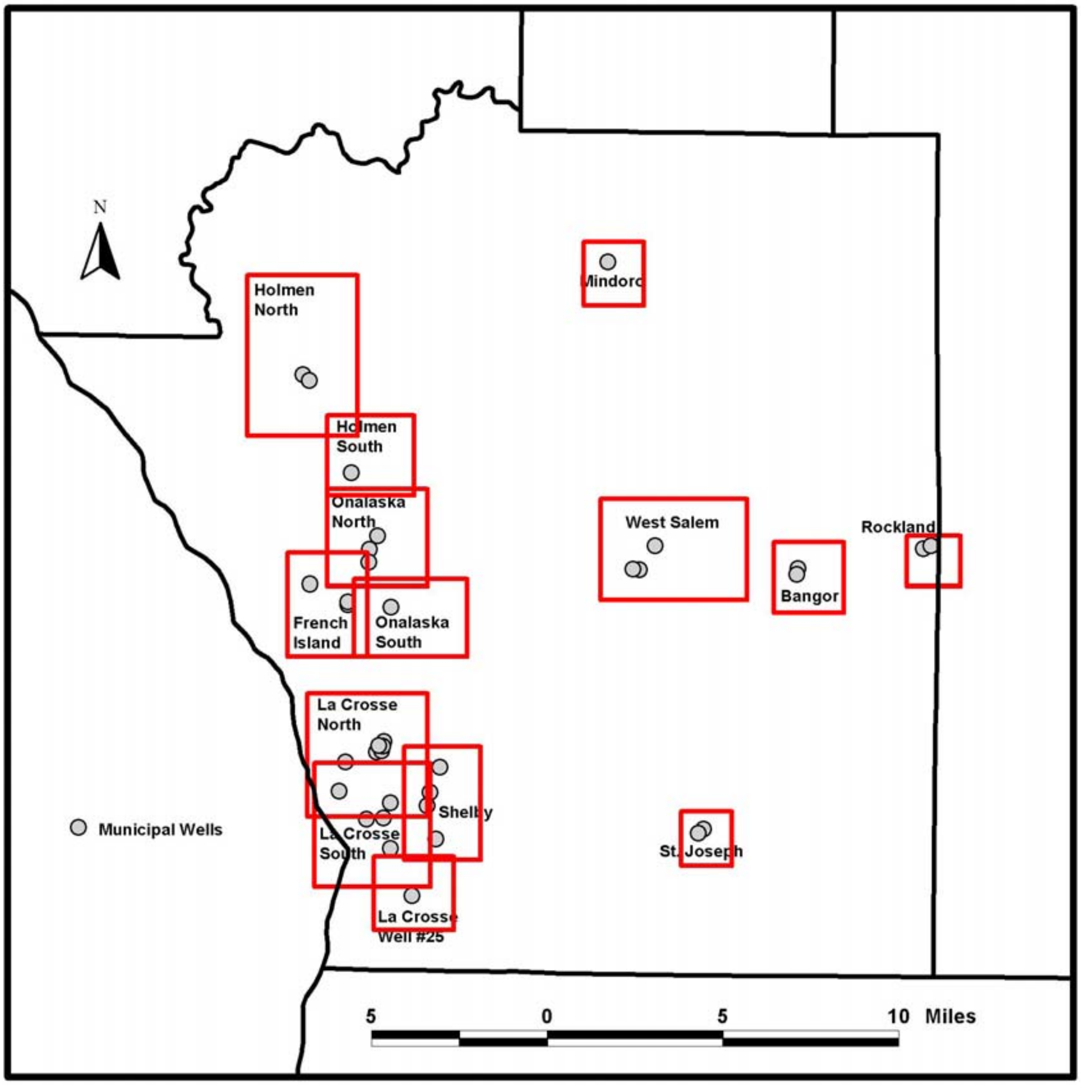


Figure 6: To improve the resolution of the head distribution around municipal wells fourteen telescopic mesh-refined (TMR) models with a refined grid spacing of 50 ft were extracted from the solution to the La Crosse County groundwater flow model. The boundaries of the TMR models are shown as rectangles in this figure.

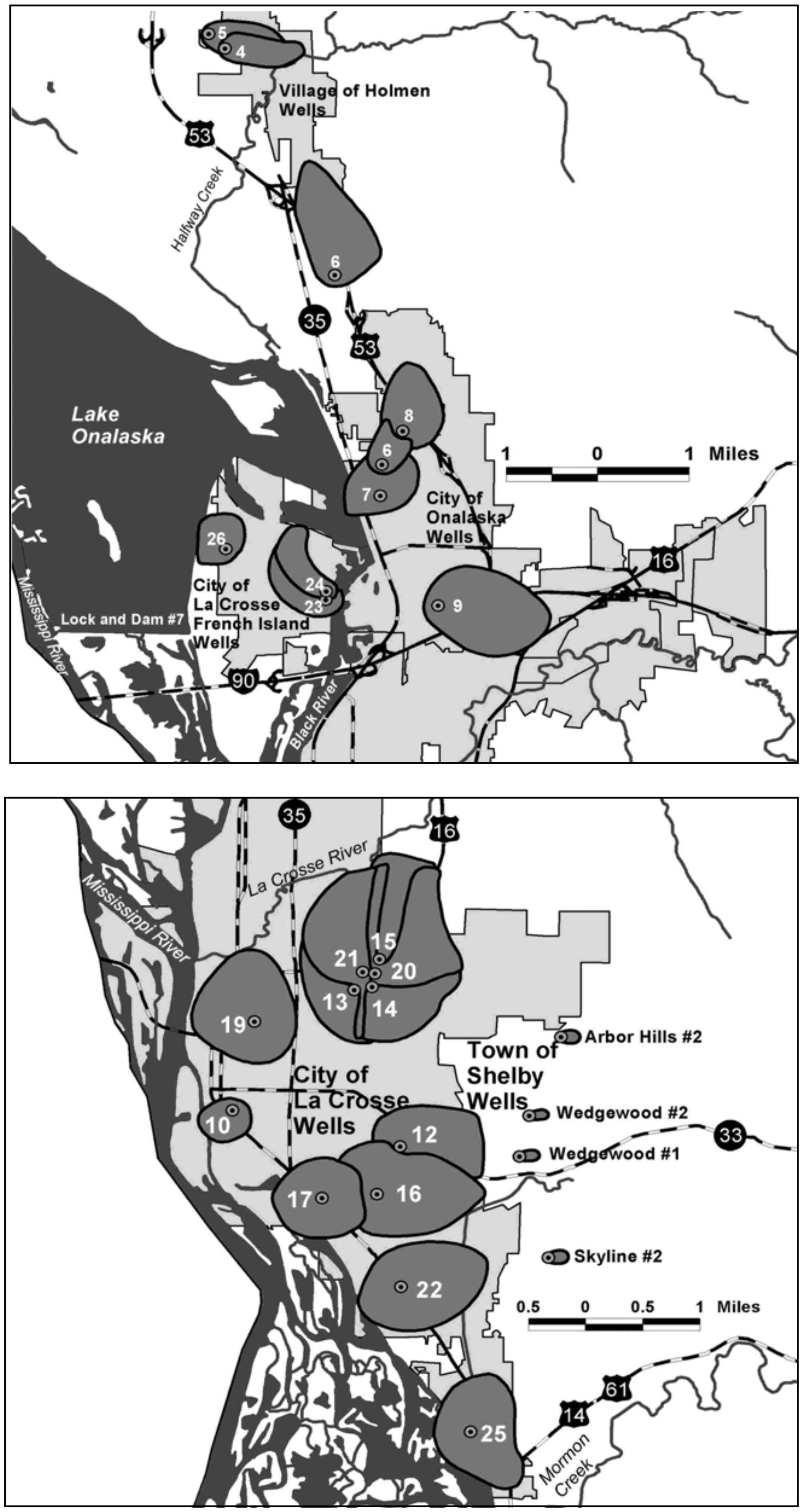


Figure 7: Five-year ZOC polygons for municipal wells (municipal well# shown) in the City of La Crosse, City of Onalaska, Village of Holmen and the Town of Shelby.

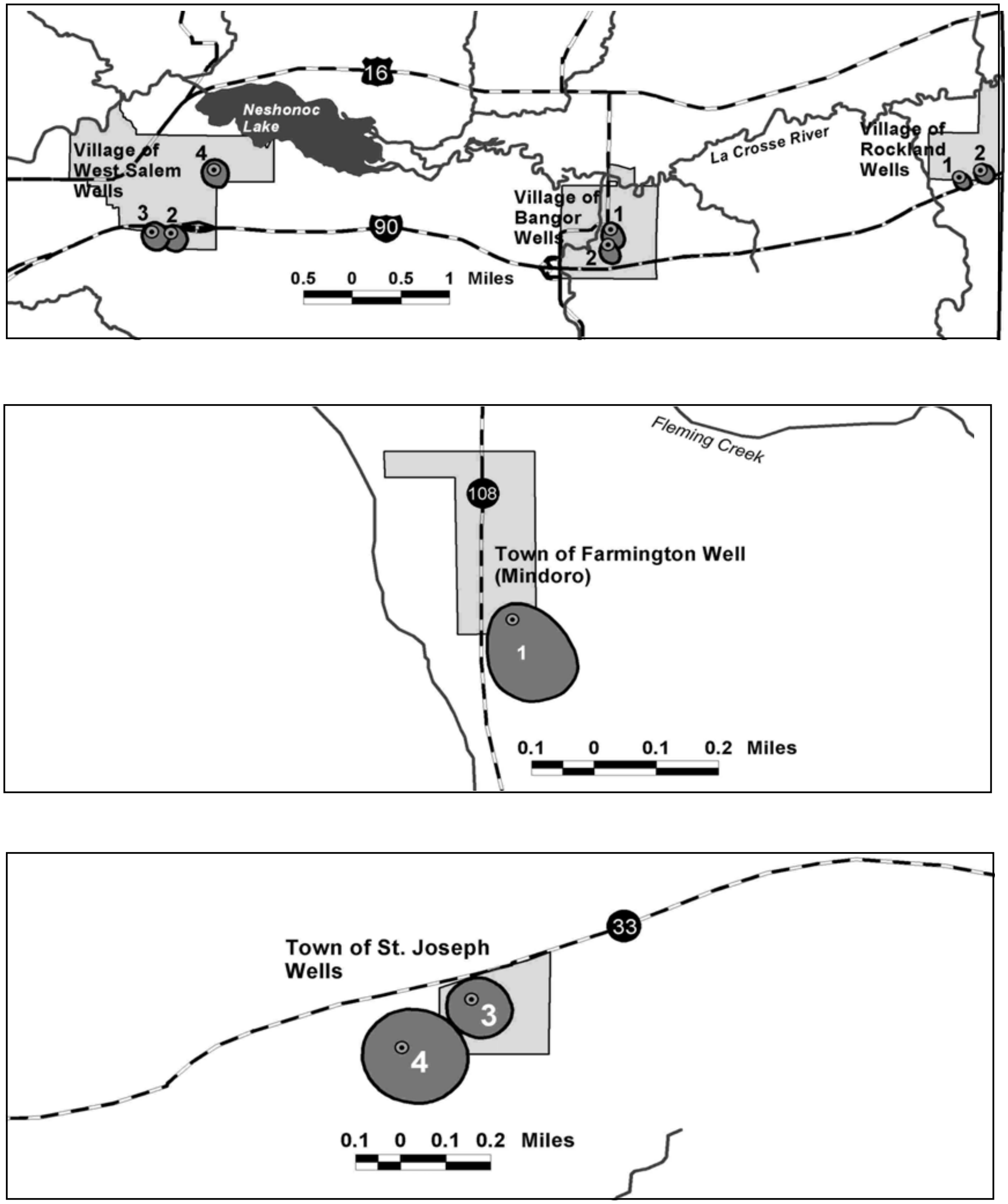


Figure 8: Five-year ZOC polygons for municipal wells in the Village or West Salem, Village of Bangor, Village of Rockland, Town of Farmington, and Town of St. Joseph.

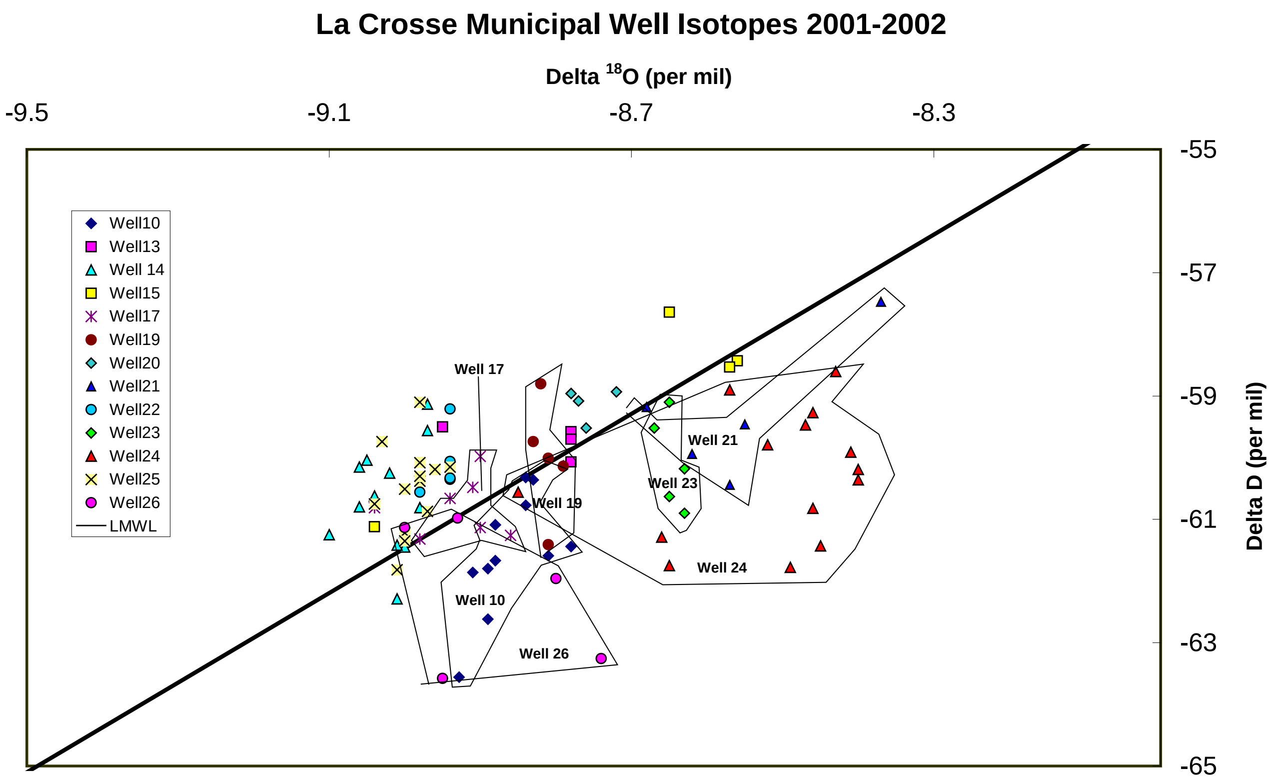


Figure 9: Results of oxygen-18/deturium sampling of La Crosse city wells. Isotopic signature of wells #10, 17, 19, 21, 23, 24, 26 indicate surface water contribution to well water. See text for further discussion.

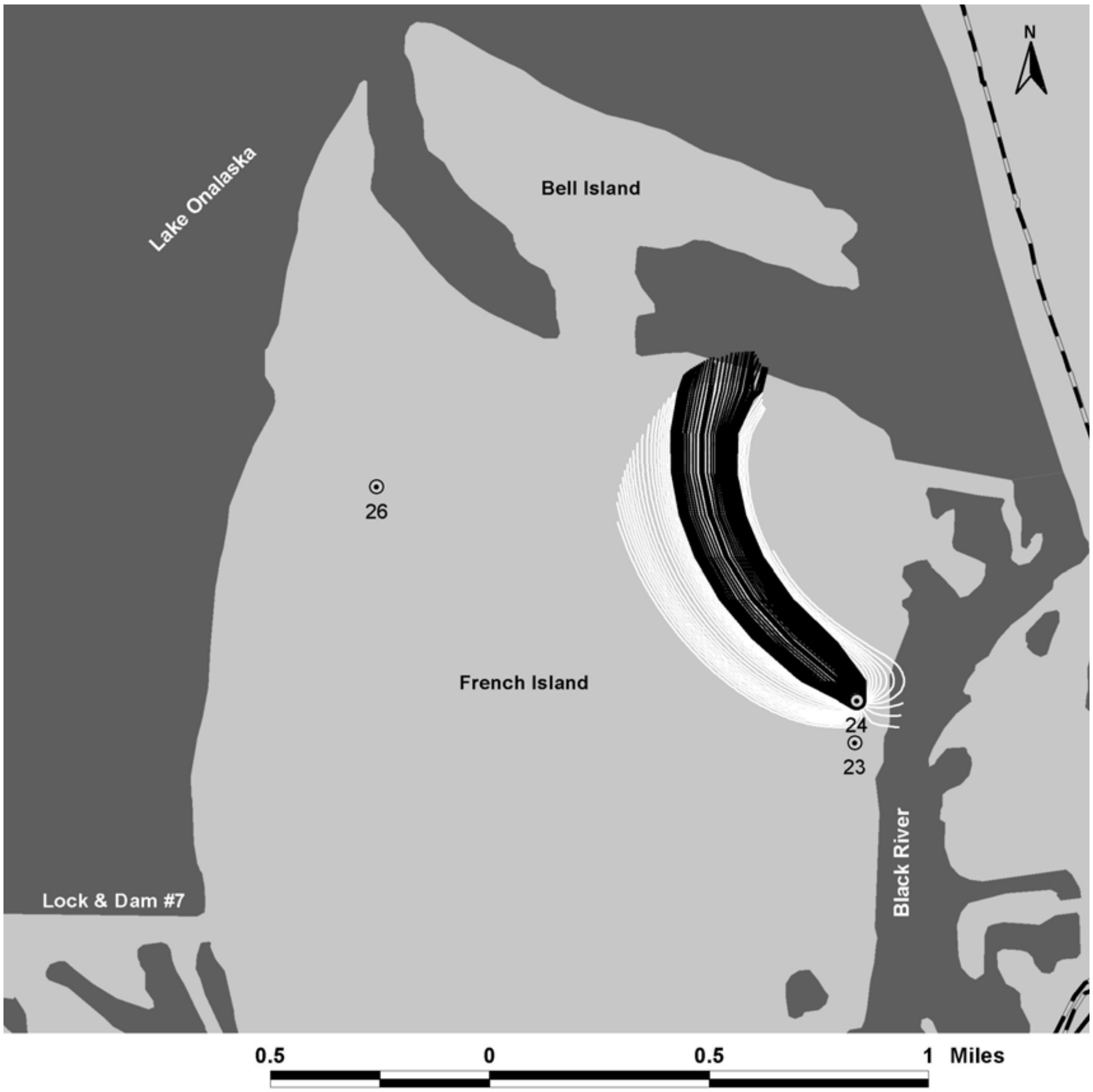


Figure 10: Five-year particle paths are sensitive to model grid size. The 500-ft grid spacing used in the regional La Crosse County model (black particle paths) provided less resolution of the head distribution than the 50-ft grid spacing used in the TMR models (white particle paths).

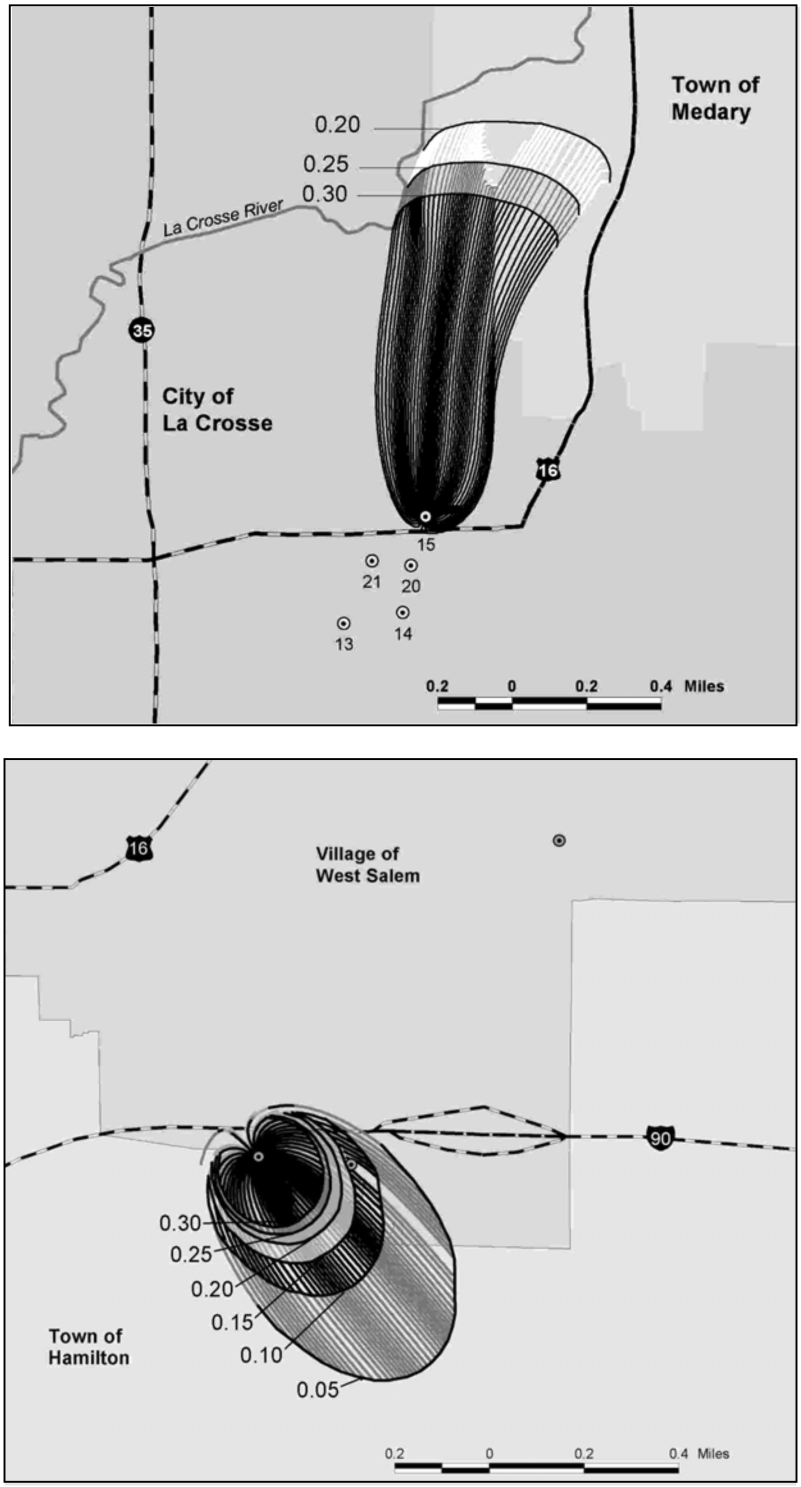


Figure 11: Five-year particle paths are sensitive to aquifer effective porosity values (sand & gravel top figure, sandstone bottom figure). Lower values result in longer paths.

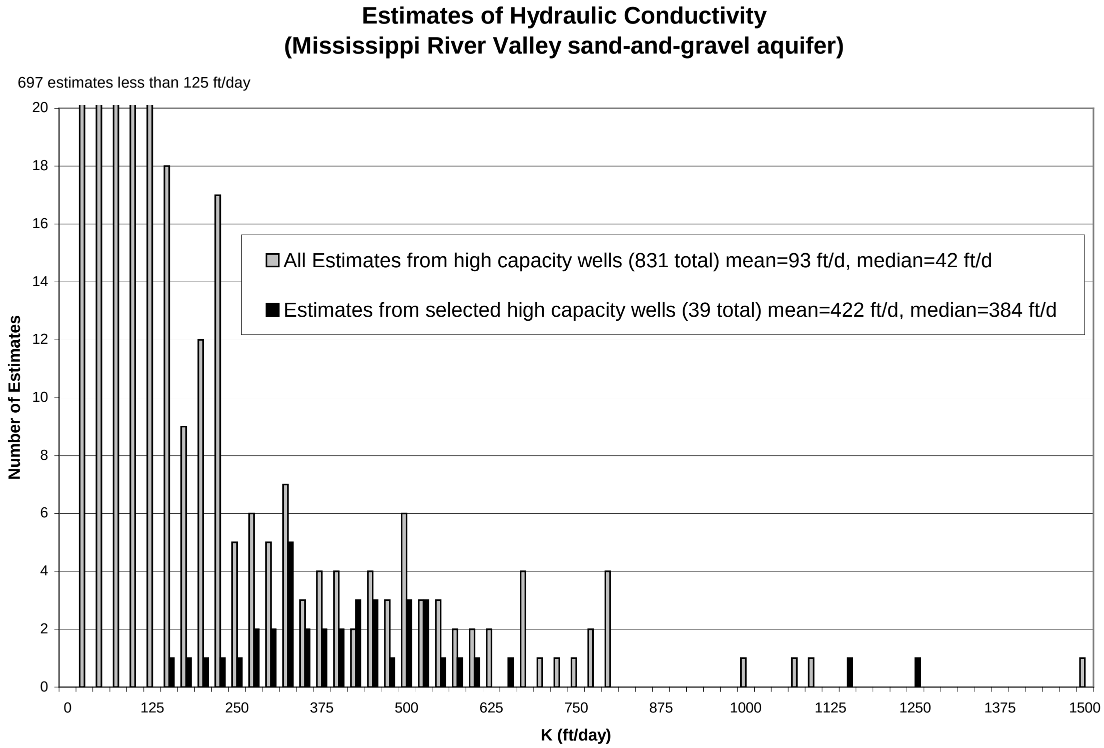


Figure 12: Estimates of horizontal hydraulic conductivity (K) from sand and gravel wells in the Mississippi River valley, La Crosse County, based on specific capacity data and published pumping tests. Selected estimates are limited to specific capacity data for municipal and other nearby high-capacity wells.

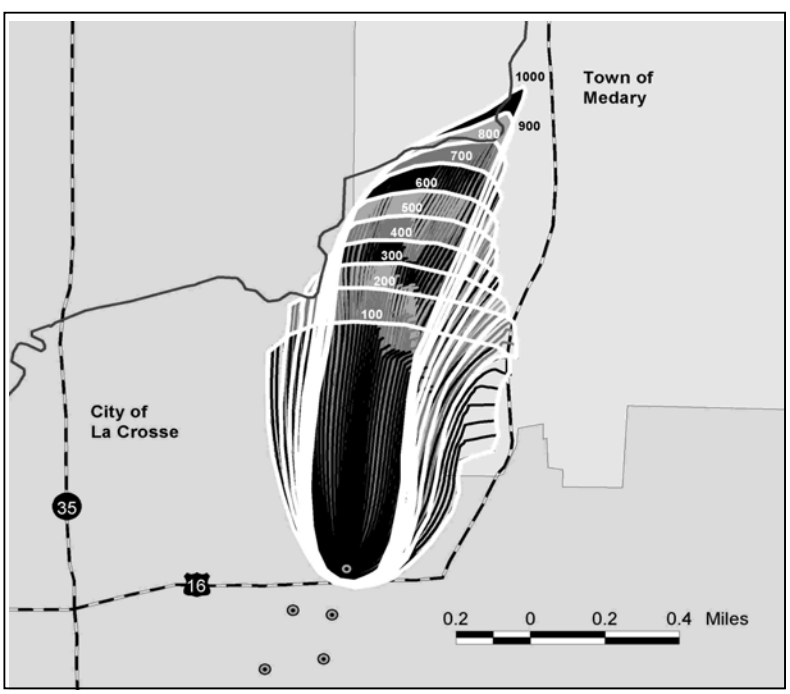


Figure 13: Five-year particle paths in the sand and gravel aquifer are sensitive to K values (100-1000 ft/day). Higher values result in longer and narrower path lines.

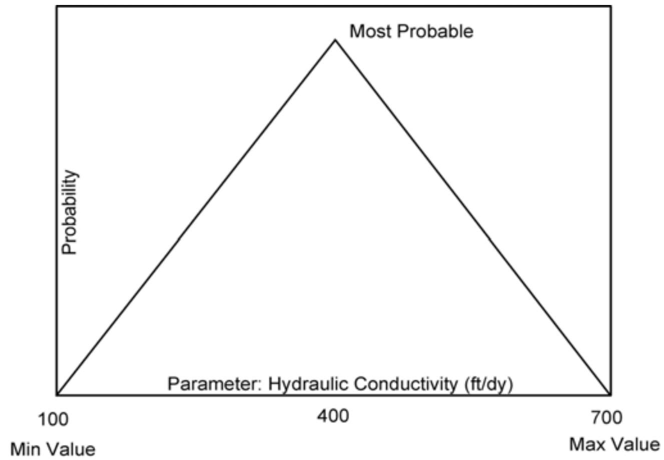


Figure 14: A triangular distribution is characterized by a most probable value, minimum and maximum values, with a linear decrease in probability from the most probable (middle value) to the minimum and maximum values.

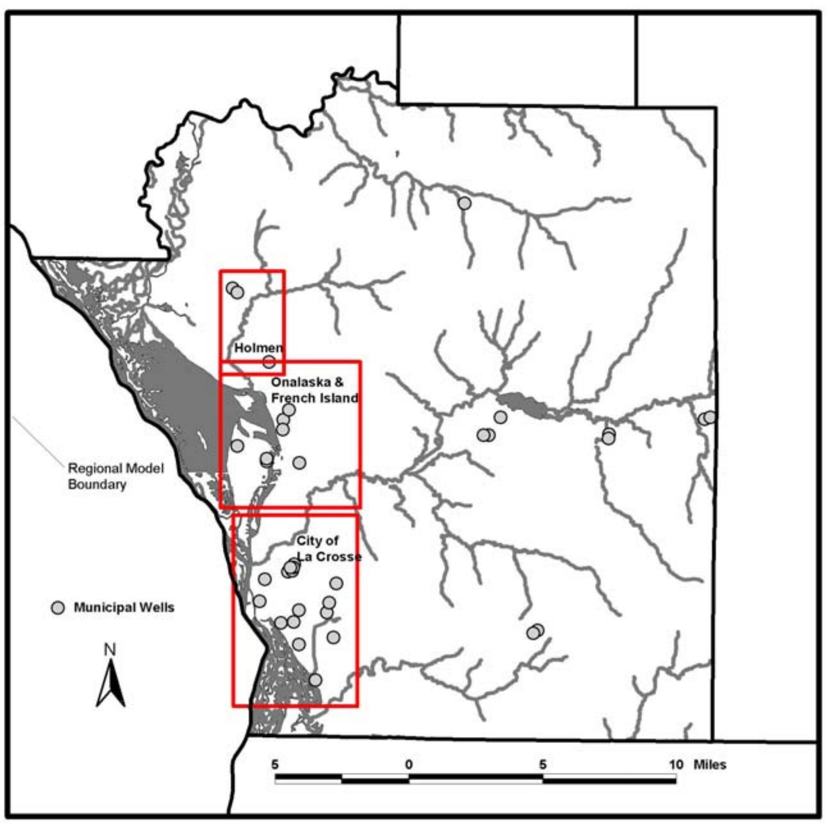


Figure 15: Three TMR models with a refined grid spacing of 150-ft were extracted from the solution to the regional La Crosse County groundwater flow model for stochastic model runs.

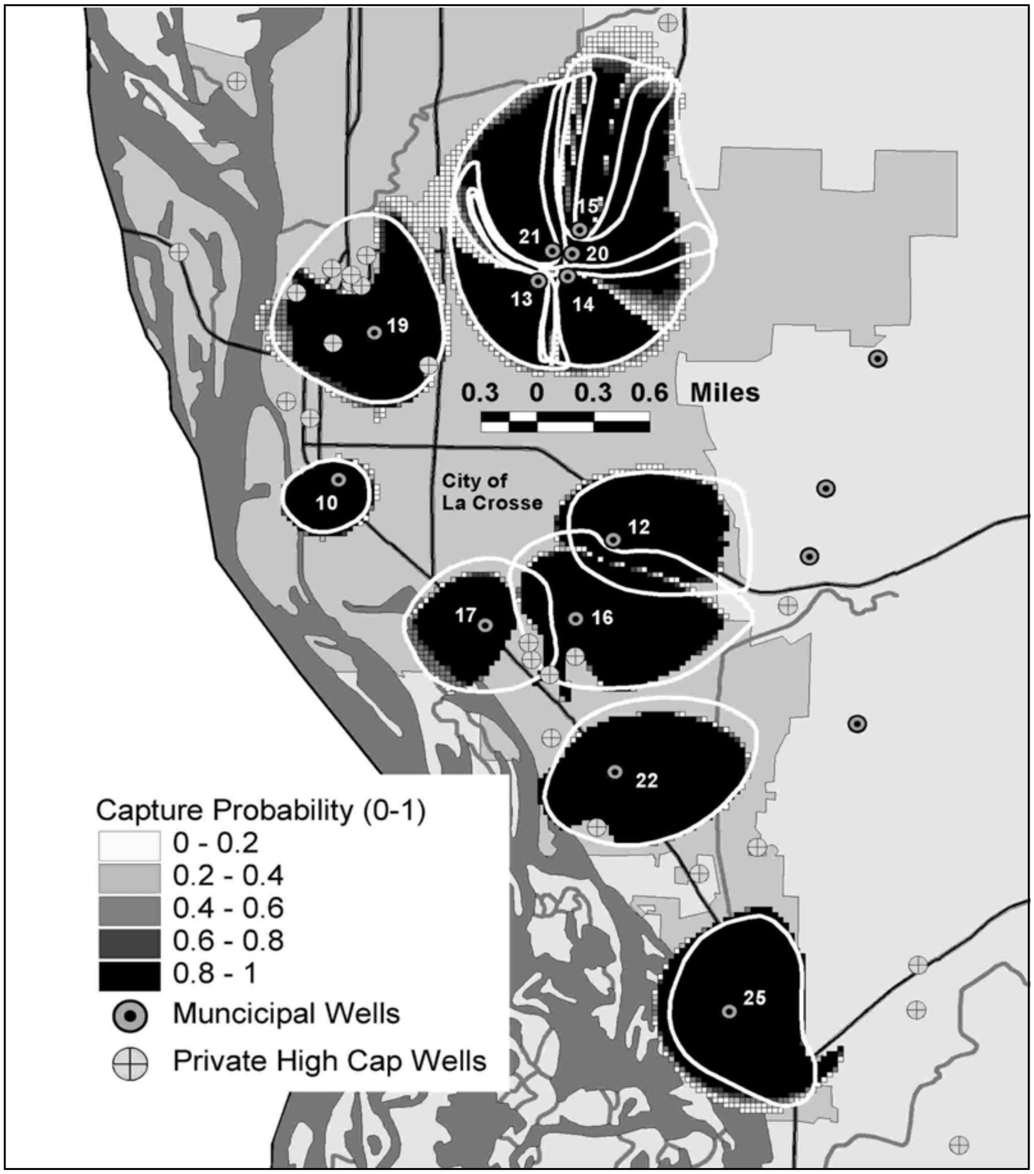


Figure 16: Five-year capture probabilities for City of La Crosse municipal wells using the statistical distribution in figure 14. Five-year ZOC delineations using 420 ft/day are outlined in white and enclose either all or most of the 80% and higher probabilities. Note that ZOC delineations using a single K of 420 ft/day for wells #12, 16, 17, and 22 extend further than the lowest probabilities. This is because the uncertainty associated with nearby private high-capacity wells at these locations is included (there are 3 private remediation wells nearby whose current pumpage influence the shape of the ZOC, but whose future pumpage is uncertain). The ZOC delineations for these wells encircle two simulations: one with the private high capacity wells included in the simulation and one without.

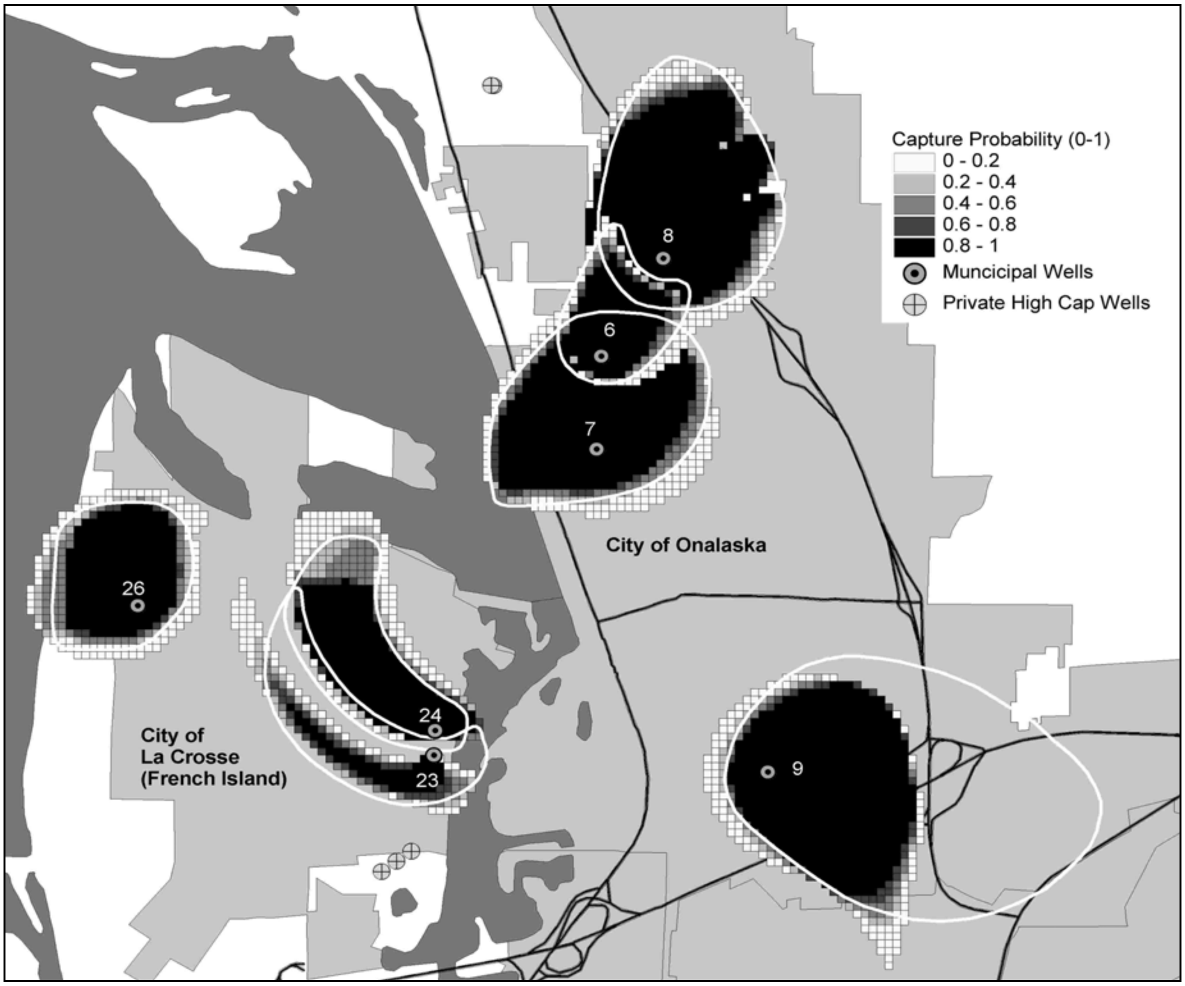


Figure 17: Five-year capture probabilities for City of La Crosse (French Island area) and City of Onalaska municipal wells. Five-year ZOC delineations using 420-ft/dy are also shown as white outlines. Note that the ZOC delineation for Onalaska city well #9 extends past the probability capture area. The boundary between the sand and gravel deposits of the Mississippi River valley (K = 420 ft/day) and the La Crosse River valley (K = 40 ft/day) is located within this well's capture path. Because of the uncertainty in the location of this boundary and the K value of the sand and gravel in the La Crosse River valley, the ZOC delineation encompasses two simulations: one with the K value of the La Crosse River valley sand and gravel deposits set at 40 ft/day and another with it set at 420 ft/day. The probability capture area was simulated with the K value of the La Crosse River valley sand and gravel deposits set at 40 ft/day and is therefore diverted from this relatively low-K area into the higher K of the Mississippi River valley deposits. Also note that the probability capture area for the City of La Crosse well #23 is narrow. This is likely a result of the coarser grid size (150-ft) used in the stochastic simulations.

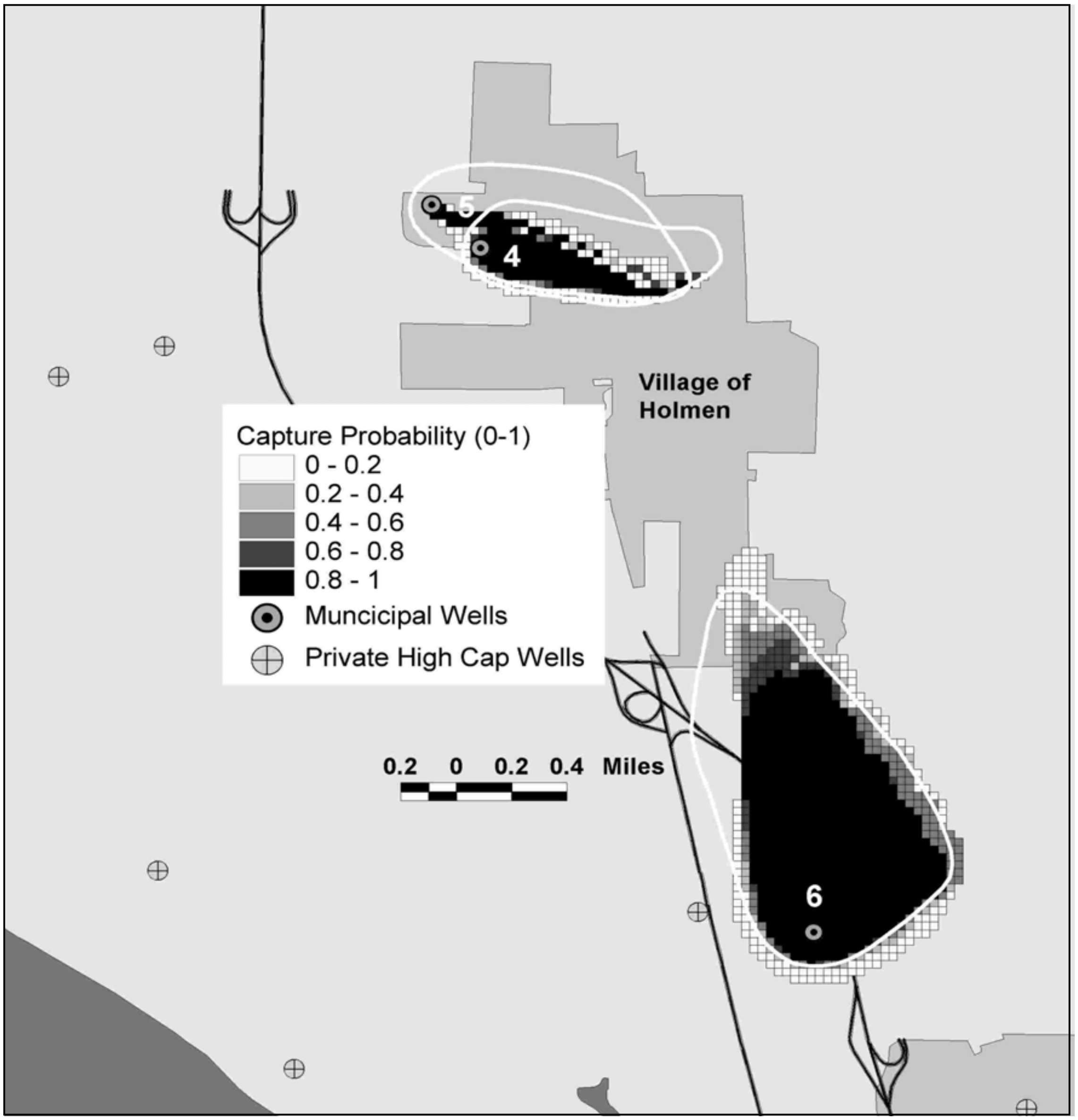


Figure 18: Five-year capture probabilities for Village of Holmen municipal wells. Five-year ZOC delineations using 420-ft/day are also shown outlined in white. Note that the probability capture area for wells #4 and #5 are relative narrow, a result most likely due to the coarser grid size (150-ft) used in the stochastic simulations.

Table 1: Horizontal and vertical hydraulic conductivity and effective porosity values used in the regional La Crosse County groundwater flow and TMR model simulations.

Aquifer/Aquitard	***Kh (ft/dy)***	***Kv (ft/dy)***	***n (porosity)***
lower bedrock aquifer	12	1.2	0.2
Eau Claire aquitard	2	0.006-0.6	0.05-0.1
upper bedrock aquifer	7.94	0.0265	0.2
ridge-top aquifer system (St. Joseph TMR model)	1	0.0005	0.05
sand & gravel aquifer (Mississippi River valley)	420	4.2	0.25
sand & gravel aquifer (Black River valley)	200	2	0.25
sand & gravel aquifer (other tributary valleys)	40	0.4	0.25

Table 2: Municipal water supply wells in La Crosse County used in the groundwater model simulations. Actual pumping rates are based on annual averages or estimates provided by well operators. ZOC pumping rates are based on guidelines outlined by the WDNR SWAP (see text). Rates are reported in gallons per minute (gpm).

Wisconsin Unique No	***Aquifer***	***Average rates based on yearly averages or estimates***	***Average Rate (gpm)***	***ZOC Rate (gpm)***	***Municipality Name***	***Well No***
BG140	Mount Simon	average for 2000	90	190	Bangor	1
BG141	Mount Simon	Bangor utilities estimate	4	150	Bangor	2
BG144	Sand & Gravel	average for 2001	176	550	Holmen	4
AY364	Sand & Gravel	average for 2001	233	550	Holmen	5
NO815	Sand & Gravel	average for 2001	247	550	Holmen	6
BG146	Sand & Gravel	average for 1989-1998	278	468	La Crosse	10
BG147	Sand & Gravel	future estimate provided by utilities	304	600	La Crosse	12
BG148	Sand & Gravel	average for 1989-1998	694	1050	La Crosse	13
BG149	Sand & Gravel	average for 1989-1998	759	1000	La Crosse	14
AX019	Sand & Gravel	average for 1989-1998	683	1250	La Crosse	15
BG151	Sand & Gravel	future estimate provided by utilities	951	1250	La Crosse	16
BG152	Sand & Gravel	average for 1989-1998	759	1035	La Crosse	17
BG154	Sand & Gravel	average for 1989-1998	873	1650	La Crosse	19
BG155	Sand & Gravel	average for 1989-1998	1137	1500	La Crosse	20
BG156	Sand & Gravel	average for 1989-1998	960	1500	La Crosse	21
BG157	Sand & Gravel	average for 1989-1998	1116	1284	La Crosse	22
BG158	Sand & Gravel	future estimate provided by utilities	761	1000	La Crosse	23
BG159	Sand & Gravel	future estimate provided by utilities	761	925	La Crosse	24
BG178	Sand & Gravel	average for 1989-1998	715	1000	La Crosse	25
AC716	Sand & Gravel	average for 1989-1998	761	925	La Crosse	26
BG168	Mount Simon	Mindoro utilities estimate	24	95	Mindoro	1
BG171	Sand & Gravel	average for 1999-2001	162	300	Onalaska	6
BG172	Sand & Gravel	average for 1999-2001	362	1000	Onalaska	7
BG173	Sand & Gravel	average for 1999-2001	410	925	Onalaska	8
BG179	Sand & Gravel	average for 1999-2001	413	1300	Onalaska	9
BG175	Mount Simon	average 2001	30	90	Rockland	1
QO656	Mount Simon	future estimate based on well #1	30	125	Rockland	2
BG164	Mount Simon	average for 2001	19	100	Shelby	Arbor Hills #1
BG165	Mount Simon	average for 2001	12	133	Shelby	Skyline #1
BG166	Mount Simon	average for 2001	29	88	Shelby	Wedgewood #1
BG167	Mount Simon	average for 2001	23	75	Shelby	Wedgewood #2
BG162	Tunnel City	St. Joseph utilities estimate	0.1	12.5	St. Joseph	3
BG163	Wonewoc	St. Joseph utilities estimate	29	125	St. Joseph	4
BG176	Mount Simon	West Salem utilities estimate	11	260	West Salem	2
BG177	Mount Simon	West Salem utilities estimate	11	300	West Salem	3
KW459	Mount Simon	West Salem utilities estimate	278	319	West Salem	4

Table 3: Private high-capacity wells used in the La Crosse County groundwater model. Unless annual average rates were available, pumping rates were assigned "normal" pumping rates, which are estimated rates reported by the well owner to the WDNR when the well if first constructed. Rates are reported in gallons per minute (gpm).

Wisconsin Unique No	DNR High-Cap Permit No	Pumping Rate (gpm) Used In Model	Pumping rate based on "normal" rates reported to WDNR or yearly averages	County Location
DN422	386	35	Normal rates reported to WDNR	La Crosse
	454	583	Normal rates reported to WDNR	Trempealeau
FX401	535	25	Normal rates reported to WDNR	La Crosse
AR244	536	26	Normal rates reported to WDNR	La Crosse
	560	3	Normal rates reported to WDNR	La Crosse
	561	20	Normal rates reported to WDNR	La Crosse
ER489	819	75	Normal rates reported to WDNR	La Crosse
	828	3	Normal rates reported to WDNR	La Crosse
CC826	929	88	Normal rates reported to WDNR	La Crosse
	930	88	Normal rates reported to WDNR	La Crosse
	931	50	Normal rates reported to WDNR	La Crosse
	932	50	Normal rates reported to WDNR	La Crosse
	1041	100	Normal rates reported to WDNR	Monroe
EP382	1110	400	Normal rates reported to WDNR	La Crosse
GK750	1186	139	Normal rates reported to WDNR	La Crosse
HS234	1189	66	Normal rates reported to WDNR	La Crosse
IA199	1246	118	Normal rates reported to WDNR	La Crosse
GJ900	1255	52	Normal rates reported to WDNR	La Crosse
	1345	87	Normal rates reported to WDNR	La Crosse
	1430	19	Normal rates reported to WDNR	La Crosse
	1431	10	Normal rates reported to WDNR	La Crosse
	1432	45	Normal rates reported to WDNR	La Crosse
	1433	10	Normal rates reported to WDNR	La Crosse
	1434	9	Normal rates reported to WDNR	La Crosse
	1435	5	Normal rates reported to WDNR	La Crosse
	1437	10	Normal rates reported to WDNR	La Crosse
	1476	167	Normal rates reported to WDNR	La Crosse
	1900	83	Normal rates reported to WDNR	La Crosse
CR133	1926	500	Normal rates reported to WDNR	La Crosse
FP273	2042	225	Normal rates reported to WDNR	Trempealeau
NX499	2076	238	Normal rates reported to WDNR	La Crosse
ML802	2135	56	Normal rates reported to WDNR	La Crosse
MF556	2203	63	Normal rates reported to WDNR	La Crosse
MD549	2250	500	Normal rates reported to WDNR	Trempealeau
MD548	2274	50	Normal rates reported to WDNR	Monroe
FP245	2558	4	Normal rates reported to WDNR	Trempealeau
ML951	2559	4	Normal rates reported to WDNR	Trempealeau
ML934	2562	3	Normal rates reported to WDNR	Trempealeau
	2725	500	Normal rates reported to WDNR	La Crosse
NB889	2733	174	Normal rates reported to WDNR	La Crosse
OT100	2774	139	Normal rates reported to WDNR	La Crosse
	2968	170	2001 reported average	La Crosse
	3000	400	2001 reported average	La Crosse
	3001	150	2002 reported average	La Crosse
NO856	3003	600	Normal rates reported to WDNR	Trempealeau
	3118	13	Normal rates reported to WDNR	La Crosse

Table 3: Continued

Wisconsin Unique No	DNR High-Cap Permit No	Pumping Rate (gpm) Used In Model	Pumping rate based on "normal" rates reported to WDNR or yearly averages	County Location
QT225	3427	50	Normal rates reported to WDNR	La Crosse
OT028	3496	139	Normal rates reported to WDNR	La Crosse
BC168	12101	500	Normal rates reported to WDNR	Jackson
	12102	500	Normal rates reported to WDNR	Jackson
BC170	12103	417	Normal rates reported to WDNR	Jackson
BC302	14201	250	Normal rates reported to WDNR	La Crosse
BC304	14203	19	Normal rates reported to WDNR	La Crosse
BC305	14204	250	Normal rates reported to WDNR	La Crosse
BC306	14205	33	Normal rates reported to WDNR	La Crosse
BC308	14208	600	Normal rates reported to WDNR	La Crosse
BC309	14209	500	Normal rates reported to WDNR	La Crosse
BC310	14210	600	Normal rates reported to WDNR	La Crosse
BC311	14211	233	Normal rates reported to WDNR	La Crosse
BC312	14212	267	Normal rates reported to WDNR	La Crosse
BC313	14213	167	Normal rates reported to WDNR	La Crosse
BC314	14214	22	Normal rates reported to WDNR	La Crosse
BC315	14215	250	Normal rates reported to WDNR	La Crosse
BC316	14216	250	Normal rates reported to WDNR	La Crosse
	14217	200	Normal rates reported to WDNR	La Crosse
BC557	20212	667	Normal rates reported to WDNR	Monroe
BC560	20216	300	Normal rates reported to WDNR	Monroe
BC564	20221	250	Normal rates reported to WDNR	Monroe
BD617	31903	500	Normal rates reported to WDNR	Trempealeau
BD619	31905	500	Normal rates reported to WDNR	Trempealeau
BD620	31906	500	Normal rates reported to WDNR	Trempealeau
BD622	31908	500	Normal rates reported to WDNR	Trempealeau
BD624	31910	600	Normal rates reported to WDNR	Trempealeau
BD625	31911	500	Normal rates reported to WDNR	Trempealeau
BD627	31913	900	Normal rates reported to WDNR	Trempealeau
BD629	31917	400	Normal rates reported to WDNR	Trempealeau
BD630	31918	600	Normal rates reported to WDNR	Trempealeau
BD631	31919	525	Normal rates reported to WDNR	Trempealeau
BD632	31920	500	Normal rates reported to WDNR	Trempealeau
BD634	31922	833	Normal rates reported to WDNR	Trempealeau
BD635	31925	500	Normal rates reported to WDNR	Trempealeau
BD636	31926	500	Normal rates reported to WDNR	Trempealeau
BD639	31929	500	Normal rates reported to WDNR	Trempealeau
BD640	31930	600	Normal rates reported to WDNR	Trempealeau
BD641	31931	500	Normal rates reported to WDNR	Trempealeau
BD642	31932	500	Normal rates reported to WDNR	Trempealeau
BD643	31933	500	Normal rates reported to WDNR	Trempealeau
BD644	31934	500	Normal rates reported to WDNR	Trempealeau
BD645	31935	500	Normal rates reported to WDNR	Trempealeau
BD647	31937	500	Normal rates reported to WDNR	Trempealeau
BD648	31938	500	Normal rates reported to WDNR	Trempealeau
BD649	31939	500	Normal rates reported to WDNR	Trempealeau
BE605	51202	89	Normal rates reported to WDNR	La Crosse
BE608	51206	210	2000 reported average	La Crosse
BE616	51215	46	Normal rates reported to WDNR	La Crosse
BE617	51216	46	Normal rates reported to WDNR	La Crosse

Table 3: Continued

Wisconsin Unique No	DNR High-Cap Permit No	Pumping Rate (gpm) Used In Model	Pumping rate based on "normal" rates reported to WDNR or yearly averages	County Location
BE618	51217	111	Normal rates reported to WDNR	La Crosse
BE619	51219	17	Normal rates reported to WDNR	La Crosse
BE620	51220	104	Normal rates reported to WDNR	La Crosse
BE621	51221	250	Normal rates reported to WDNR	La Crosse
BE623	51223	90	Normal rates reported to WDNR	La Crosse
BE624	51224	139	2000 reported average	La Crosse
BE625	51225	800	2000 reported average	La Crosse
BE626	51226	21	Normal rates reported to WDNR	La Crosse
	51227	139	Normal rates reported to WDNR	La Crosse
	51228	139	Normal rates reported to WDNR	La Crosse
	71861	34	1979-1989 reported average	La Crosse
	71862	3	1988 reported average	La Crosse
AX677	71863	92	1/2 Normal Rate "Fire Protection"	La Crosse
	71864	92	1/2 Normal Rate "Fire Protection"	La Crosse
	80802	19	Normal rates reported to WDNR	La Crosse
	80803	19	Normal rates reported to WDNR	La Crosse
BG111	80810	4	Normal rates reported to WDNR	La Crosse
BG112	80811	17	Normal rates reported to WDNR	La Crosse
BG113	80812	43	Normal rates reported to WDNR	La Crosse
	80813	21	Normal rates reported to WDNR	La Crosse
BG115	80814	1	Normal rates reported to WDNR	La Crosse
BG117	80816	26	Normal rates reported to WDNR	La Crosse
BG119	80818	56	Normal rates reported to WDNR	La Crosse
JB057	80819	6	Normal rates reported to WDNR	La Crosse
FX399	80820	4	Normal rates reported to WDNR	La Crosse
BG122	80821	261	1978-1990 reported average	La Crosse
BG123	80822	327	1978-1990 reported average	La Crosse
BG124	80823	557	1978-1990 reported average	La Crosse
BG125	80824	117	Normal rates reported to WDNR	La Crosse
BG126	80825	50	Normal rates reported to WDNR	La Crosse
BG127	80826	117	Normal rates reported to WDNR	La Crosse
	80827	8	Normal rates reported to WDNR	La Crosse
	80828	10	Normal rates reported to WDNR	La Crosse
BG130	80829	103	Normal rates reported to WDNR	La Crosse
	80832	35	Normal rates reported to WDNR	La Crosse
BG133	80833	400	Normal rates reported to WDNR	La Crosse
	80834	7	Normal rates reported to WDNR	La Crosse
	80835	69	Normal rates reported to WDNR	La Crosse
BG136	80836	67	Normal rates reported to WDNR	La Crosse
BG137	80837	200	Normal rates reported to WDNR	La Crosse
	80838	10	Normal rates reported to WDNR	La Crosse
CQ024	80841	122	Normal rates reported to WDNR	La Crosse
AD570	80843	14	Normal rates reported to WDNR	La Crosse
	80844	150	Normal rates reported to WDNR	La Crosse
	80933	83	Normal rates reported to WDNR	La Crosse
BH064	86851	153	Normal rates reported to WDNR	Trempealeau
BH072	86859	175	Normal rates reported to WDNR	Trempealeau
BH073	86860	175	Normal rates reported to WDNR	Trempealeau
BH088	87063	57	Normal rates reported to WDNR	Vernon
BH752	90182	8	Normal rates reported to WDNR	La Crosse
BH801	90237	5	Normal rates reported to WDNR	La Crosse

Table 4: Estimated travel time from surface water to municipal wells. Particle tracking simulations for travel time estimates used actual pumping rates based on annual averages or estimated pumping rates provided by well operators (table 2). The simulations indicate that at least 13 wells are capturing some portion of surface water. Although most of the particle traces for City of La Crosse wells #13 and #14 were blocked from extending northwards to the La Crosse River by the capture zones of wells #20, 21, and 15, model simulations showed a few particles able to edge through narrow paths between the capture zones northwards and reach the river, therefore travel times for these wells are included in the table. Travel times are purposely presented in ranges to reflect the uncertainty in the estimates related to uncertainty in model parameters.

Municipality Name	Wisconsin Unique No.	Well No.	Travel Time From Surface Water to Well	Surface Water Source
La Crosse	BG146	10	4 to 6 years	Mississippi River
La Crosse	BG148	13	10 to 12 years	La Crosse River
La Crosse	BG149	14	10 to 12 years	La Crosse River
La Crosse	AX019	15	10 to 12 years	La Crosse River
La Crosse	BG152	17	1 to 3 years	Mississippi River
La Crosse	BG154	19	7 to 9 years	Mississippi River
La Crosse	BG155	20	4 to 6 years	La Crosse River
La Crosse	BG156	21	4 to 6 years	La Crosse River
La Crosse	BG157	22	3 to 4 years	Mississippi River
La Crosse	BG158	23	less than 1 year	Black River
La Crosse	BG159	24	less than 1 year	Black River
La Crosse	BG178	25	less than 1 year	Mississippi River
La Crosse	AC716	26	2 to 4 years	Mississippi River
Holmen	BG144	4	1 to 3 years	Halfway Creek
Holmen	AY364	5	1 to 3 years	Halfway Creek