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Delineation of zones of contribution for municipal wells in Rock County, Wisconsin: Final report

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Delineation of Zones of Contribution for Municipal Wells in Rock County, Wisconsin

Final Report

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Introduction

Rock County is located in south-central Wisconsin and includes substantial urban and rural populations. The cities of Janesville and Beloit are located in the central portion of the county and are surrounded by small agricultural communities. Each of these municipalities relies on groundwater as its sole source of drinking water. In order to provide information necessary to protect these drinking water supplies, the Wisconsin Geological and Natural History Survey (WGNHS) conducted a study of the groundwater flow system in and around Rock County as a part of the Source Water Area Protection (SWAP) program of the Wisconsin Department of Natural Resources (WDNR) and the U.S. Environmental Protection Agency. The goal of the study was to define zones of contribution (ZOC's) for each of the municipal wells in the county for groundwater-travel times of 5, 50 and 100 years. These ZOC's illustrate those parts of the landscape in which water pumped from municipal wells originates as rainfall or snowmelt, and this information can be very useful to assist land management to protect the water supplies of Rock County.

Purpose, scope and data sources

The purpose of this report is to present the results of flow modeling of the groundwater system in Rock County and the resulting delineation of ZOC's for the municipal drinking water wells. The models described in this study represent simplifications of the actual hydrologic system, and their complexity is commensurate with the project objectives and the extent of available data. As a result, only regional features of the hydrologic system are included in the simulations. This level of detail is appropriate for delineation of ZOC's for travel times of 5 to 100 years, because long-term groundwater flow paths are controlled primarily by regional patterns in aquifer properties, groundwater recharge, and surface-water features. We used two-dimensional models, which are well suited for simulating regional flow in aquifers that are areally extensive. The simulations represent steady-state conditions, because available data do not show any trends in groundwater levels or streamflow over the past few decades.

This study relied primarily upon existing hydrologic and geologic data, although limited new data were collected during this project. Geologic data included well construction reports from the WDNR, geologic logs of well cuttings on file at WGNHS, interpretive maps of the soils, unlithified deposits and bedrock of Rock County and the surrounding region

(Alden, 1918; Hadley and Pelham, 1976; Clayton and Attig, 1997; Ham and Attig, in prep). We conducted limited mapping of surficial materials during this project to supply more detailed information needed for the modeling effort. These data were used to estimate hydraulic conductivity, groundwater recharge rates, aquifer thickness and water table elevation. We estimated mean long-term stream baseflow using data from several USGS gaging stations, partial record measurements on file at USGS and reported by a recent study of the Rock River watershed (Potter and others, 2000), and one streamflow measurement conducted during this study.

Methods

In order to improve our estimates of recharge rate and hydraulic conductivity, we compiled a map of the Pleistocene geology of Rock County from existing data and new observations (Figure 2). We refined the existing statewide Pleistocene geologic map (Hadley and Pelham, 1976) using (1) a recent stratigraphic study including western Rock County (Miller, 2000), (2) detailed Pleistocene maps of adjacent counties (Clayton and Attig, 1997; Ham and Attig, in prep.), (3) field mapping at a scale of 1:100,000 and (4) textural data from the digital soil survey for Rock County (NRCS, 2000). The most substantial revisions were made in the northern part of the county, where we identified numerous sand and gravel deposits. We compiled this information digitally in shapefile format.

We developed analytic element groundwater-flow models, using the computer program GFLOW (Haitjema, 1995), to delineate ZOC's for the municipal wells in Rock County. These models are two-dimensional representations of the groundwater flow system in the region including Rock County. Haitjema (1995) and Strack (1989) present detailed explanations of the analytic element method. The following brief description is adapted from Hunt and others (2000).

An infinite aquifer is assumed in analytic element modeling. The problem domain does not require a grid or involve interpolation between cells. To construct an analytic element model, features important to groundwater flow (such as wells) and surface-water features are entered as mathematical elements or a series of elements. The amount of detail used to represent the features depends on the distance from the area of interest; less detail is included for far-away features. Each element is represented by an analytic solution, and each of these individual solutions is added together to derive a solution for the entire flow system.

In the GFLOW models used in this study, elements are two-dimensional features and simulate steady-state solutions (not varying with time).

We calibrated the GFLOW models using automated parameter estimation techniques with the computer program UCODE (Poeter and Hill, 1998). The primary advantage of this technique over the trial-and-error approach is the ability to automatically calculate the parameters, such as hydraulic conductivity and recharge rate, that provide a quantified best fit to observed water levels and streamflows. The quality of the calibration is statistically quantified, and confidence intervals are provided for the estimated parameters. This method also allows for automated sensitivity testing to identify the parameters with the most impact on model results.

We used a more complex, three-dimensional groundwater modeling program to test the assumption that simple two-dimensional models are adequate for delineating ZOC's. Using the finite-difference code MODFLOW (McDonald and Harbaugh, 1988), we simulated three-dimensional features of the flow system in the Janesville area. Although existing data are insufficient to fully calibrate such a model, it was useful to examine the range of possible effects that variations in hydraulic conductivity of the layered aquifer system might have on vertical groundwater flow and ZOC's for the wells. Comparison of these results with the analytic element solutions provided greater insight into the groundwater flow system and increased our confidence in the ZOC's delineated with GFLOW.

Physical setting

Rock County, located in south-central Wisconsin (Figure 1), is near the edge of the area covered by ice sheets during the Pleistocene glacial periods. The most recent, or Wisconsin, glaciation terminated in the northern part of the county (Figure 2), resulting in pronounced hills and closed depressions in that area. To the south is an area covered by earlier ice sheets that is characterized by more subdued hills and valleys. The broad, flat valley of the Rock River bisects the county from north to south. Much of the course of the modern Rock River follows a deep valley eroded into the bedrock that has been filled with several hundred feet of glacial sediments.

The local bedrock consists of sedimentary layers that dip to the south at a very low angle, overlying relatively impermeable basement rocks. The sedimentary rocks have a total thickness of approximately 1500 feet in Rock County. Cambrian sandstones of the Elk Mound, Tunnel City and Trempeleau Groups account for most of this thickness. Above these sandstones are Ordovician aged rocks including the Prairie du Chien dolomite, sandstone and shale of the Ancell Group, and Sinnipee dolomite. A simplified stratigraphic nomenclature of Rock County is provided in Figure 3.

The population of Rock County is concentrated in Janesville and Beloit, located in the Rock River valley. Farms and small communities occupy the surrounding areas. Groundwater is the primary source for domestic and municipal drinking water supplies (Zaporozec, 1982), and it is used extensively for irrigation of the sandy soils along the Rock River and its major tributaries. Municipal water-supply systems are located in eight Rock County communities: the cities of Beloit and Janesville, and the villages of Clinton, Edgerton, Evansville, Footville, Milton and Orfordville (Figure 1). There are 28 operational municipal wells in the county, although several of them are currently inactive.

Conceptual model

Before simulating groundwater flow, it is essential to develop a conceptual representation the hydrologic system because this forms a framework for construction of the computer model. The conceptual model reduces the groundwater system into only its most important components. This simplification is necessary because including all of the real-world complexities in a model is impossible due to lack of available data and computational power. Steps in the development of the conceptual model include (1) definition of the aquifer(s), (2) identification of sources and sinks of water, and (3) identification and delineation of hydrologic boundaries present in the area of interest. Our conceptualization of the groundwater system in Rock County is shown in Figure 4.

The groundwater system includes three major aquifers: (1) unlithified sand and gravel in major river valleys, (2) shallow Galena dolomite and St. Peter sandstone, and (3) deep Cambrian sandstone (Zaporozec, 1982). Most of the municipal wells in Rock County pump water from the Cambrian sandstone aquifer, which consists of numerous rock layers with different capacities to transmit water. Many of these wells are also open to the overlying Galena – St. Peter aquifer, which is an important source of water for private wells. Several municipal wells in Janesville and Beloit pump exclusively from the sand-and-gravel aquifer.

Groundwater moves from higher to lower potentials (areas of higher groundwater levels to areas of lower groundwater levels). As a result, groundwater generally discharges to surface-water features and is recharged in the surrounding upland areas. The Rock River is one of the most significant surface water features in the region, and groundwater generally flows toward it from both the east and west.

Development of the GFLOW models

We developed two separate groundwater models to simulate flow in the two major aquifer systems tapped by municipal wells in the county. One model, called the comprehensive model, includes all of the aquifers and extends downward to the impervious crystalline basement rock at an elevation of 700 feet below sea level. Because the model combines all of the aquifer systems into one layer, it simulates average water levels and flows through the system. The Cambrian sandstone aquifer makes up the vast majority of the saturated thickness, and, as a result, this comprehensive model simulates the behavior of that aquifer more closely than the thinner aquifers. Because the hydraulic properties of the sand-and-gravel aquifer are very different than those of the underlying bedrock, the comprehensive model is not suitable to simulate flow to shallow wells pumping only from the sand and gravel. A second model simulates flow in the upper few hundred feet of the groundwater system, and it includes the sand- and-gravel aquifer and the Galena-St. Peter aquifer. The bottom of this model is at an elevation of 600 feet above sea level, which is near the top of the Cambrian sandstone. Although some groundwater certainly must flow downward into the Cambrian sandstone aquifer, rocks of the Tunnel City Group near the top of the Cambrian sequence probably act as a partial barrier to vertical movement of groundwater (Young, 1992).

We developed the comprehensive model first to determine regional water-level patterns and groundwater fluxes to surface-water features. The model includes a global recharge rate and a zone of increased recharge representing the sand-and-gravel deposits (

Figure 5).

We set the hydraulic conductivity and recharge rates to reasonable initial values and determined final values through the calibration process. High-capacity wells that are present in the WDNR database are included in the model, with pumping rates set to their reported normal averages. For municipal wells, this was calculated based on pumping reports from one entire recent year. Pumping rates for other high capacity wells are the normal discharges reported in WDNR high-capacity well records.

The groundwater flow model includes "far-field" and "near-field" elements (Figure 5). The far-field elements are distant lakes and rivers that are simulated with coarse linesinks for the purpose of explicitly defining the regional groundwater-flow field around Rock County (the “near field”). These far-field elements are regionally significant features that act as hydraulic boundaries and provide locations were the potential in the aquifer is known with a large degree of confidence. The near field is the primary area of interest and is simulated with much greater detail, and it includes all of the area inside and within a few miles of Rock County.

Streambed sediment resistance in the near and far fields was set to 1 day. Resistance is calculated by dividing the streambed sediment thickness by its vertical hydraulic conductivity. A value of 1 day corresponds to a1-ft sediment thickness and a vertical hydraulic conductivity of 1 ft/d. The width of the stream was assigned based upon field observations and stream order and ranges from 10 to 50 ft. Sensitivity analysis within UCODE demonstrated that the model results are affected very little by changes in streambed resistance, within a reasonable range, so the values were fixed for all model runs.

In the near field, the model tabulates the amount of water captured from and lost to the groundwater system by the stream network, allowing simulated fluxes to be compared to measured streamflows during model calibration. Near-field linesinks are linked so that surface water is routed from high elevation linesinks to low elevation linesinks. This not only allows easy determination of the flux of any linesink, but it also ensures that the amount of water a stream loses to the groundwater system cannot be greater than the amount available (that is, water delivered from upstream linesinks).

The model of the shallow flow system (Figure 6) is a refinement of the comprehensive model that includes greater detail for the sand and gravel and St. Peter – Galena aquifers. Recharge rates are fixed to the values used for the comprehensive model, because the models simulate the same area and must therefore have equal recharge. A zone of higher hydraulic conductivity represents areas of sand and gravel greater than approximately 50 feet thick. Both the global hydraulic conductivity and that of the sand and gravel were determined by model calibration, starting with reasonable values determined by analysis of well construction reports. Downward flow into the underlying sandstone aquifer is simulated by specifying a negative rate of 1 in/yr, which is approximately the difference in recharge rates between the comprehensive and shallow models indicated by preliminary parameter optimization runs. Sensitivity testing demonstrated that the model results are not sensitive to this leakage rate, so it was fixed at this value for all model runs. Flux targets in the linesink network include only streams that are likely to receive groundwater from the shallow system; major streams, such as the Rock River, are not used as flux targets because much of their groundwater inflow probably is supplied by the Cambrian sandstone aquifer (which is not represented in this model). The model includes municipal and other high capacity wells that are open to the sand and gravel or Galena – St. Peter aquifers, with the same pumping rates used in the comprehensive model.

Model calibration

In order to make the models represent the aquifer systems as realistically as possible, we followed a calibration procedure to determine the closest fit between model results and measured values of groundwater levels and streamflows ("calibration targets"). The calibration procedure involved repeatedly running the models with different parameter values and statistically analyzing the results to find the "best fit" to the target data. We coupled the GFLOW models to UCODE (Hill and Poeter, 1998) to automate this process.

For groundwater-level targets, we used existing field measurements of depth to water reported on well construction reports and high-capacity well records, as well as records from groundwater-monitoring wells. The comprehensive model includes 72 targets that are typically deep wells open to a thick portion of the aquifer system (to provide an accurate estimate of the average potential throughout the entire thickness of the aquifer). The 103 wells used as targets for the shallow model are generally not as deep (to provide a more accurate estimate of the water-table elevation).

Streamflow targets are important for constraining the groundwater recharge rate. Our streamflow targets are based on measurements made at long-term gaging stations and sites with a small number of measurements made with current meters (Table 1 and Table 2). We relied primarily on exiting streamflow data from the U.S.G.S. and a previous study of the lower Rock River Basin (Potter and others, 2000), although we measured the flow of one additional stream (Spring Brook in Janesville) to help estimate the recharge rate in sand and gravel deposits. Target values represent average conditions (here defined as the median base flow) over the past few decades. To determine this value, we separated base flow from storm flow for the long-term gaging station records using the Lynne-Hollick digital recursive filter (Lyne and Hollick, 1979; Nathan and McMahon, 1990, 1991; Chapman, 1991). For sites with only a few measurements, we estimated the long-term median flow by comparing the field measurements with flow at a nearby gaging station (Potter, 2001; Potter and Gaffield, in press).

One of the most important steps in using a parameter optimization technique, such as used in UCODE, is assigning each observation a weight that reflects its relative importance. We assigned weights based on the uncertainty in the field measurements, with lower weights given to targets with higher uncertainty. Weights for groundwater level are expressed as a standard deviation, and weights for streamflow are given in terms of coefficient of variation. Hill (1998) gives a detailed explanation of the use of these statistics to compute target weights. Choosing appropriate weights for streamflow at long-term gaging stations is not straightforward. Although these records consist of hundreds of measurements, they are highly correlated in time, effectively reducing the value of any given observation. Furthermore, the reported streamflow values are computed by converting daily river stage measurements to flows using a rating curve. This step probably introduces the greatest uncertainty, because the rating curve is based on only a few annual streamflow measurements. For this reason, we based our weights for stream gaging stations on the assumption that the rating curves have an accuracy of 5% (or that there is a 95% chance that the actual discharge is within plus or minus 5% of the reported value). For partial-record stations with only a few measurements, we assumed that measurement errors were up to 10%.

During calibration of the comprehensive model, global hydraulic conductivity, global recharge, and recharge in the sand and gravel were adjusted to obtain the best fit to the observed water levels and streamflows. Because the model was not sensitive to aquifer thickness or streambed resistance, these parameters were fixed at reasonable values. Initial model runs included a zone of increased hydraulic conductivity to account for the effect of the sand and gravel aquifer. The hydraulic conductivity of a comprehensive model represents a thickness-weighted average of the horizontal hydraulic conductivities of all of the units simulated by the model. Assuming values of hydraulic conductivity and thickness of 5 ft/d and 1300 ft, for the bedrock aquifer, and 250 ft/d and 300 ft, for the sand and gravel aquifer, the average conductivity would be 51 ft/d. We also tested more detailed recharge distributions in preliminary model runs. However, parameter sensitivity evaluations with UCODE demonstrated that the field data did not support this level of complexity, and that the model could be adequately calibrated using one global hydraulic conductivity and two recharge rates.

The optimization for the comprehensive model determined values of 6.5 ft/d for global hydraulic conductivity, 6.9 in/yr for global recharge, and 12.7 in/yr for recharge in the sand and gravel (Table 3). Unweighted statistics comparing measured groundwater levels to calibrated model results include an average difference of 6.6 ft and a mean absolute error of 20.1 ft. These errors are within the range of uncertainty in measured groundwater levels, which were measured in different years and have uncertainty in the location of the well, the land-surface elevation of the well, and the reported depth to water. The flux targets were also well simulated, with a mean error of –0.5% and a mean absolute error of 12.2%. The optimized hydraulic conductivity value of 6.5 ft/d is similar to the value of 4.0 ft/d determined from well construction reports using the TGUESS computer program (Bradbury and Rothschild, 1985), and it is consistent with values reported by Young (1992). The global recharge rate is nearly the same as the value of 6.7 in/yr determined for part of Waukesha County in southeastern Wisconsin by Hunt and others (2000).

The shallow model was calibrated by adjusting the global hydraulic conductivity and the hydraulic conductivity of the sand and gravel, with the recharge rates fixed at the values determined for the comprehensive model. The aquifer base and streambed resistance were fixed at 600 ft and 1 d, respectively, because the model was insensitive to these parameters. The optimization determined hydraulic conductivity values of 24.5 ft/d (global) and 457 ft/d (sand and gravel) (see Table 3). The model fits the observed groundwater levels reasonably well, with a mean difference of 8.4 ft and a mean absolute difference of 19.6 ft. The model also matches streamflow targets well, with a mean difference of –1.0% and an absolute mean difference of 22.3%. The optimized global hydraulic conductivity value of 24.5 ft/d is similar to the estimate of 31.6 ft/d for the Galena - St. Peter aquifer determined using TGUESS. Although the optimized hydraulic conductivity value of 457 ft/d for the sand and gravel aquifer is greater than the value of 217 ft/d determined with TGUESS, it is reasonable because values determined from well tests represent a small volume of aquifer and hydraulic conductivity typically increases with scale.

Impact of three-dimensional effects

The use of two-dimensional models may introduce substantial errors near prominent three-dimensional features, where vertical groundwater flow may be significant. GFLOW assumes that there is no vertical flow within the aquifer, and this is generally a reasonable assumption for distances of greater than two or three times the aquifer thickness away from three-dimensional features. For a similar study in Indiana, Haitjema (1995) concluded that vertical flow effects were significant only where a low-hydraulic-conductivity layer was present between the open interval of a pumping well and a nearby surface-water feature. In Rock County, this situation occurs in Janesville and Beloit, where low-conductivity units are present within the Cambrian sandstone.

We tested the importance of three-dimensional effects by constructing a three-dimensional model of the Janesville area using the computer program MODFLOW (McDonald and Harbaugh, 1988). This is a three-dimensional numerical model that simulates layers with contrasting hydraulic properties and traces groundwater-flow paths in three dimensions. The model domain is divided into 50 rows and columns of 1000-foot-square grid cells. Layers simulated include the sand and gravel aquifer, the Galena – St. Peter aquifer, the Tunnel City confining unit, and the Cambrian sandstone aquifer. The bottom elevation of the sand and gravel varies throughout the model domain to simulate its configuration in the buried bedrock valley along the Rock River. The horizontal hydraulic conductivities for the three aquifers are the same as in the calibrated GFLOW models, but we reduced the vertical hydraulic conductivity by a factor of 10 to be consistent with field measurements reported by Young (1992). For the Tunnel City confining unit, we used horizontal and vertical hydraulic conductivities of 1 ft/d and 0.01 ft/d, respectively, based on existing field data (Young 1992). We performed several simulations with vertical hydraulic conductivities ranging from 0.01 to 1 ft/d to assess the sensitivity of the model results to this parameter. We used the comprehensive GFLOW model to specify constant flux boundary conditions by extracting the MODFLOW grid from the GFLOW model (Figure 7). The MODFLOW model uses the same recharge rates and zones as the GFLOW models. Although the number and distribution of groundwater-level observations is insufficient to fully calibrate the MODFLOW model, simulated heads match the observations reasonably well.

The model demonstrated that three-dimensional effects are important for deep wells open to the sandstone aquifer below the sand and gravel, such as Janesville well 10. These wells capture water from both aquifers; water moves primarily along horizontal flow paths in the sand and gravel aquifer, then downward through the low-conductivity Tunnel City Group into the sandstone aquifer and into the well (Figure 8).

Although three-dimensional effects are important for wells such as Janesville well 10, combined use of the two analytic element models can adequately simulate their ZOC's. Simulations of flow in the sand and gravel are very similar for the shallow GFLOW model and the MODFLOW model (Figure 9). For short travel times (e.g. 5 years), the comprehensive GFLOW model predicts similar, but slightly larger ZOC's than the MODFLOW model (Figure 9). ZOC's for longer travel times in this two-aquifer setting are best simulated with the shallow GFLOW model to represent capture of water in the sand and gravel aquifer (Figure 8). Combined use of the comprehensive model to delineate 5-year ZOC's and the shallow model for the 50 and 100-year ZOC's accounts for the different sources of water that are important over different time scales and yields results very similar to the three-dimensional model. Considering the geologic data and groundwater-level observations necessary to develop and fully calibrate a three-dimensional model, we concluded that the analytic element models were sufficient for the purpose of delineating ZOC's for municipal wells in Rock County.

Delineation of zones of contribution

We delineated ZOC's for travel times of 5, 50 and 100 years for each municipal well in Rock County. Included in this analysis were all active wells and several inactive wells that have not been abandoned. A ZOC represents the land-surface area in which water entering the groundwater system at the water table reaches the pumping well in the designated time period. Its shape depends on many factors, including the pumping rate of the well, the hydraulic properties of the aquifer, the recharge distribution, and the location of surface-water features and other pumping wells.

We performed all ZOC delineations with the two GFLOW models. For wells pumping from the sand and gravel aquifer, we used the shallow model, and we used the comprehensive model for bedrock wells located outside the extent of the sand and gravel aquifer. For bedrock wells directly below the sand and gravel, we used the comprehensive model to delineate the 5-year ZOC and the shallow model to delineate the 50- and 100-year ZOC's (Table 4).

In order to produce conservative estimates of ZOC's, we increased the pumping rate of each well above its normal discharge. This accounts for potential increases in pumping in the future, and it helps compensate for the effects of uncertainty in our conceptual model and parameter values. For the delineations, we used the greater of the actual pumping rate plus 15%, or ½ of the operational capacity of the well (Table 5). Each delineation involved a separate model simulation, with the increased discharge for the well of interest and all other wells pumping at their normal rates.

We traced groundwater flow paths backward from the well for the travel time of interest. The groundwater model tracks the movement of imaginary particles that are useful for visualizing the movement of groundwater in the aquifer. We started 15 to 20 particles starting at each well, tracing their movement backward in time for 5, 50 or 100 years. We started these particles at the bottom of aquifer to compute the longest possible flow paths; particles starting higher in the system might intersect the water table in less than the designated travel time, giving the appearance of a smaller ZOC. Groundwater-flow velocity depends on the porosity of the aquifer, and we specified a typical value of 0.2 (Freeze and Cherry, 1979). For several wells, we compared the backward particle traces against the paths of particles originating away from the well and traced forward through time, and found that the two methods produced comparable results.

We constructed each ZOC with the particle tracking results, connecting the endpoint of each particle trace to form a polygon around the well (Figure 10 – 14). The polygons were exported from GFLOW in drawing interchange file (dxf) format and converted to shapefiles in a geographic information system program. We also converted the ZOC shapefiles from the universal transverse mercator projection (used by the models) to the Wisconsin transverse mercator 1983 projection.

Analysis of uncertainty

The ZOC's delineated with the calibrated models represent the configurations that are most likely, given all of the available information about the groundwater system. Because not all of the details of the flow system are known, there is uncertainty in the model design, parameter values and, therefore, the model results. The parameter estimation methods used in model calibration provided information on the uncertainty in each of the optimized parameters, such as recharge rate and hydraulic conductivity. For other parameters, such as porosity, we have information on the likely range of values that may occur in a groundwater system. It is possible to demonstrate the impact of this uncertainty in model input parameters on our ZOC delineations using a method known as a Monte Carlo analysis. The effects of other sources of uncertainty, such as errors in our conceptual model, are not captured by this technique.

The Monte Carlo method entailed performing many simulations (generally 50 to 200) for a well, with each simulation using a different set of input parameter values within realistic ranges. The results of all simulations were analyzed to determine the likelihood that water starting in any particular location would be captured by the well. We used this information to draw contour maps of the likelihood of capture (Figure 15 through Figure 22) that can be compared with the ZOC's predicted by the calibrated model. We made the common assumption that the logarithm of recharge rate and hydraulic conductivity are normally distributed, using the means and standard deviations determined by the UCODE optimizations. For additional realism, hydraulic conductivity and recharge rate were related by a correlation coefficient determined by UCODE. We also included streambed resistance and porosity in the Monte Carlo analysis, assuming simple uniform distributions between 0.1 and 0.3 for porosity, and between 0.1 and 10 days (in log space) for streambed resistance. Using these statistical distributions, we randomly generated different values for the input parameters for each simulation. The error between simulated and observed groundwater levels was calculated for each model run. We discarded simulations with very high errors, because they probably resulted from unrealistic combinations of input parameters. By including correlation between hydraulic conductivity and recharge, we reduced the number of such unrealistic simulations.

The Monte Carlo analysis demonstrated that the impact of uncertainty in the model input parameters is substantial in the sand and gravel aquifer but minor in the sandstone aquifer. The outer boundaries of the ZOC's delineated with the calibrated models generally correspond to a likelihood of capture between 20 and 60%. For the sandstone aquifer, there is generally a 5% likelihood of capture at a distance of only 100 m beyond the boundary of the ZOC delineated with the calibrated model. For the sand and gravel aquifer, this distance is typically 500 to 1000 m, but up to 2000 m for Janesville well 9. It is important to remember that there are other potential sources of uncertainty that cannot be represented by this Monte Carlo analysis.

Model limitations

The models described in this report are representations of the regional groundwater system in Rock County and were developed specifically to delineate long-term ZOC's for high-discharge municipal wells; other uses of these models may be inappropriate. Only the near field areas of the models (inside or within a few kilometers of Rock County) include sufficient detail to simulate groundwater flow with a reasonable degree of confidence. The far field areas of the model include little detail and only serve to improve the simulation of groundwater levels in Rock County.

Summary and conclusions

The groundwater system in Rock County includes three major aquifers: the surficial sand and gravel, the Galena dolomite and St. Peter sandstone, and the Cambrian sandstone. Municipal wells primarily tap the Cambrian sandstone, however several municipal wells in Beloit and Janesville pump for the sand and gravel. There are a total of 28 operational municipal wells in the Rock County communities of Beloit, Clinton, Edgerton, Evansville, Footville, Janesville, Milton and Orfordville.

We developed groundwater flow models of Rock County and the surrounding region to delineate ZOC's for the municipal wells. We relied on the computer program GFLOW, a two-dimensional, analytic element model. Because the municipal wells pump from two distinct aquifer systems, we developed separate models for each aquifer system. A comprehensive model represents the entire thickness of the aquifer system, and it closely represents the sandstone aquifer because that aquifer comprises most of the thickness of the groundwater system. A second model simulates the shallower Galena – St. Peter and unconsolidated sand and gravel aquifers. The models were coupled to the parameter optimization program, UCODE, to analyze parameter sensitivity and assist with model calibration.

We verified that these two-dimensional models were adequate for delineating ZOC's by comparing them to a simple three-dimensional model of the Janesville area. We used the numerical modeling program MODFLOW to simulate both horizontal and vertical groundwater flow across layers with contrasting hydraulic properties, using the comprehensive GFLOW model to set boundary fluxes. This exercise suggested that the low hydraulic conductivity of the Tunnel City Group, near the top of the Cambrian sandstone aquifer, probably creates substantial vertical groundwater flow components below the sand and gravel aquifer. Wells open to the sandstone below the sand and gravel, such as Janesville well 10, pump water from both the sandstone and the sand and gravel. In the sand and gravel, groundwater flows primarily along horizontal flow paths, moving downward through the Tunnel City Group near the wells. This situation can be simulated adequately by using the comprehensive model for short travel times (during which water moves through the sandstone) and the shallow model for longer travel times (to simulate capture from the overlying sand and gravel).

We delineated three ZOC's each municipal well, for travel times of 5, 50 and 100 years. We traced groundwater movement backward through time from the wells, using these traces to manually draw the boundaries of the capture zones. Zones of contribution for wells pumping from the Cambrian sandstone are much smaller than those for wells in the sand and gravel, due to the greater hydraulic conductivity and small thickness of the sand and gravel.

A Monte Carlo analysis demonstrated the impact of uncertainty in the model input parameters on the ZOC's. Parameters included in this analysis were hydraulic conductivity, recharge rate, porosity, and streambed resistance. The impact of this uncertainty is small in the sandstone aquifer, but it is considerable in the sand and gravel aquifer. Other sources of uncertainty, such as errors in our conceptual model, probably exist but could not be represented in this analysis.

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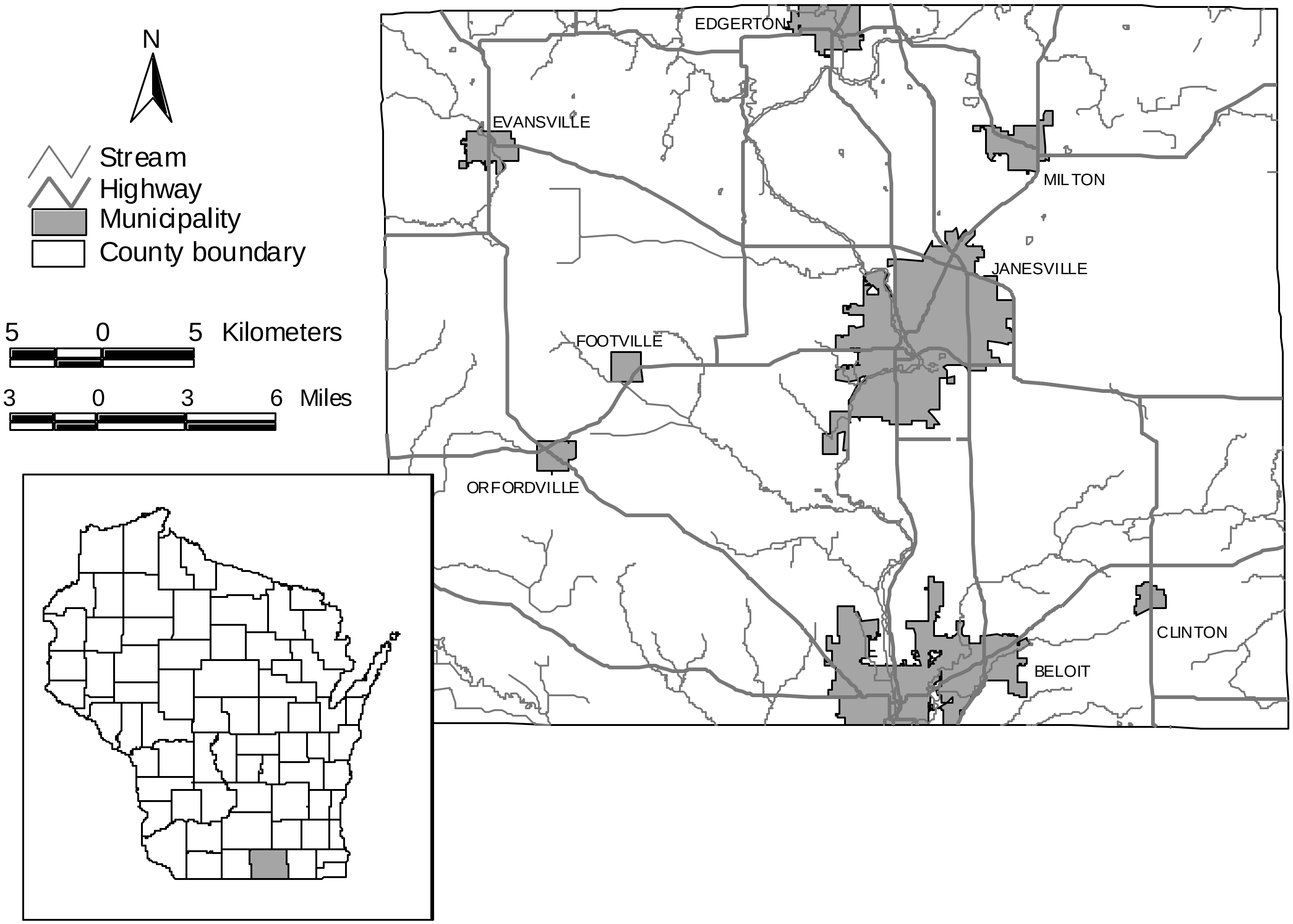

Figure 1. Location of Rock County, Wisconsin and municipalities included in this study.

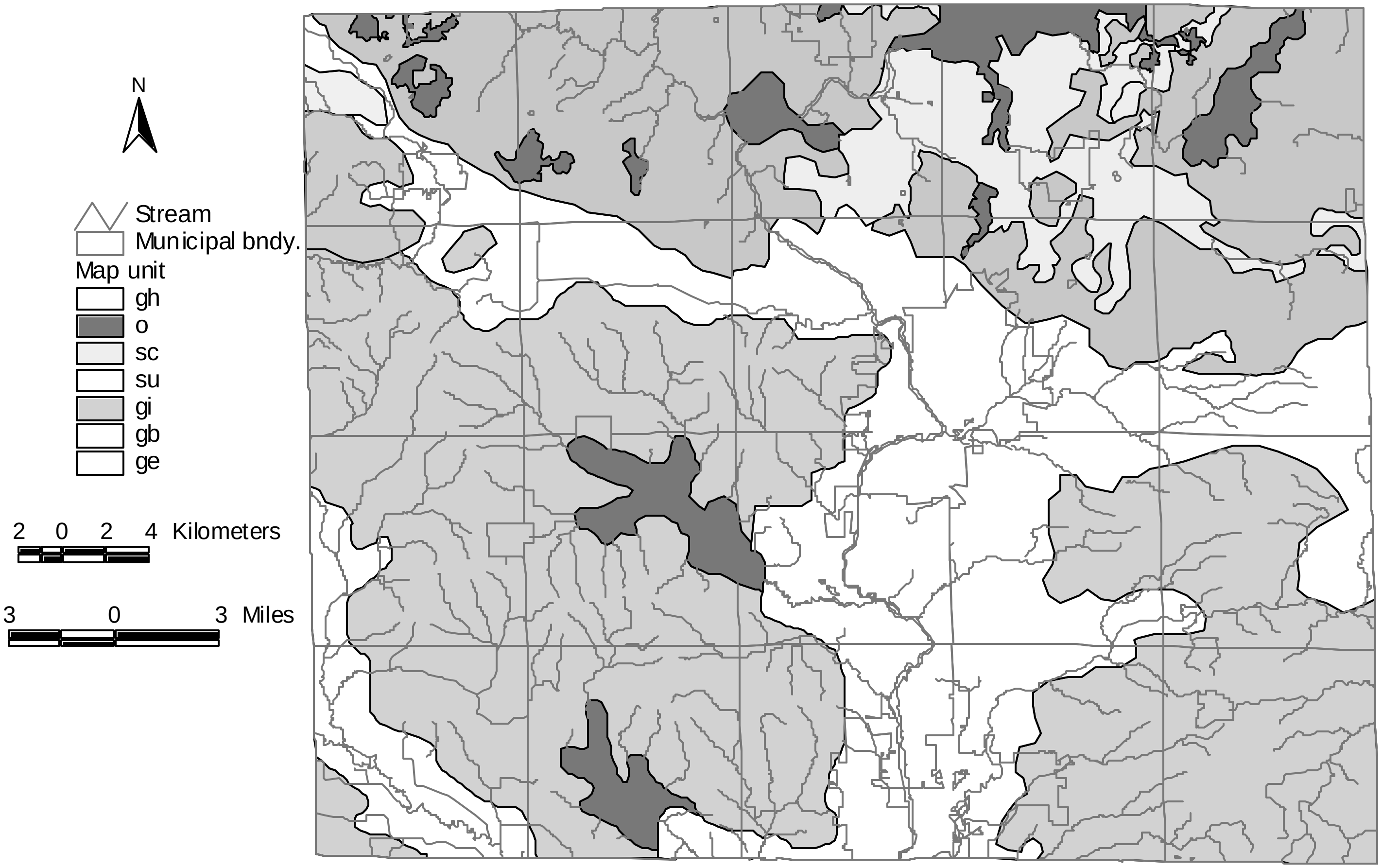

Figure 2. Pleistocene geology of Rock County.
Unit gh: till deposited during the last part of the Wisconsin Glaciation. Unit o: offshore lake sediment. Unit sc: collapsed meltwater-stream sediment. Unit su: uncollapsed meltwater-stream sediment. Unit gi: till deposited during the Illinois Glaciation. Unit gb: till deposited during the Brooklyn Phase of the Wisconsin Glaciation. Unit ge: till deposited during the Evansville Phase of the Wisconsin Glaciation.

Age	**Group**	**Formation**	**Description**
Ordovician	Sinnipee	Galena	Dolomite
		Decorah	
		Platteville	
	Ancell	Glenwood	Shale and sandstone
		St. Peter	Sandstone
	Prairie du Chien	Shakopee	Dolomite
		Oneota	
Cambrian	Trempealeau	Jordan	Sandstone
		St. Lawrence	Siltstone and dolomite
	Tunnel City	Lone Rock	Sandstone with fine layers
		Mazomanie	
	Elk Mound	Wonewoc	Sandstone
		Eau Claire	Sandstone and shale
		Mt. Simon	Sandstone
Precambrian			Undifferentiated crystalline rocks

Figure 3. Simplified bedrock nomenclature for Rock County, Wisconsin.
(Adapted from Ostrom, 1967)

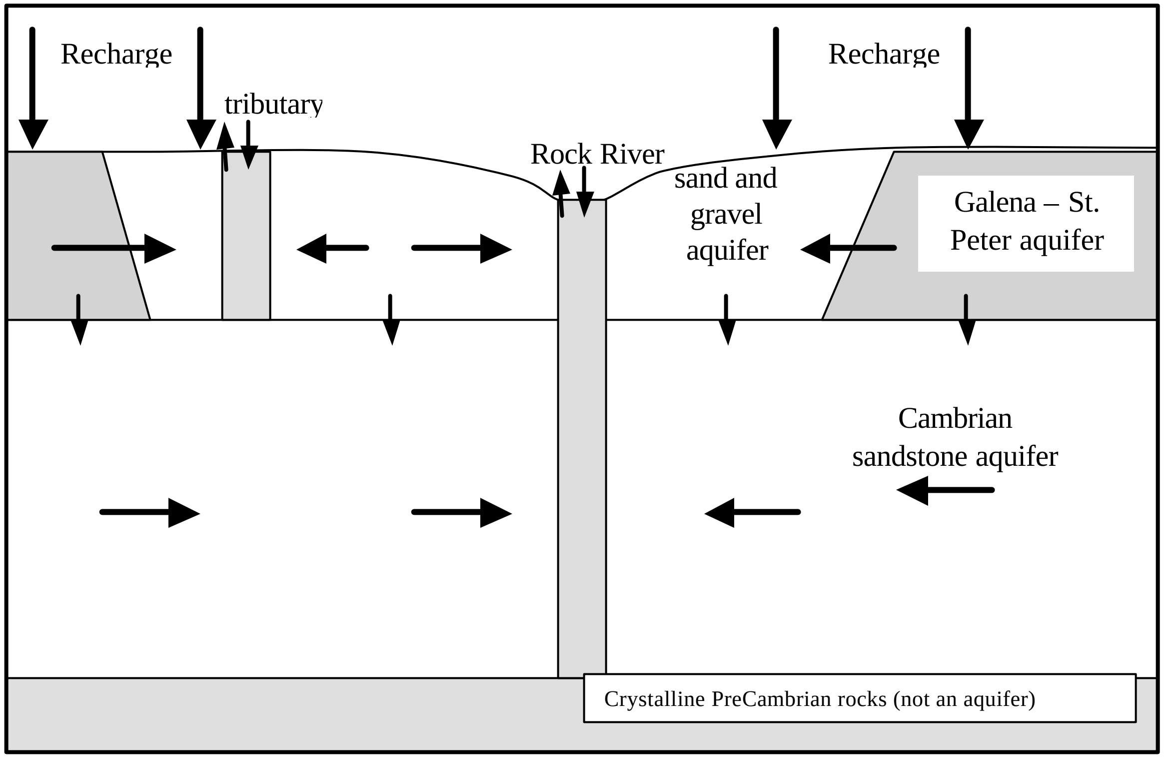

Figure 4. Schematic cross section showing conceptual model of the groundwater system in Rock County. Arrows indicate possible components of groundwater flow, and the size of the arrows represents the relative magnitude of flow. Surface-water features such as the Rock River and tributary streams can either contribute water to the groundwater system or receive water from it.

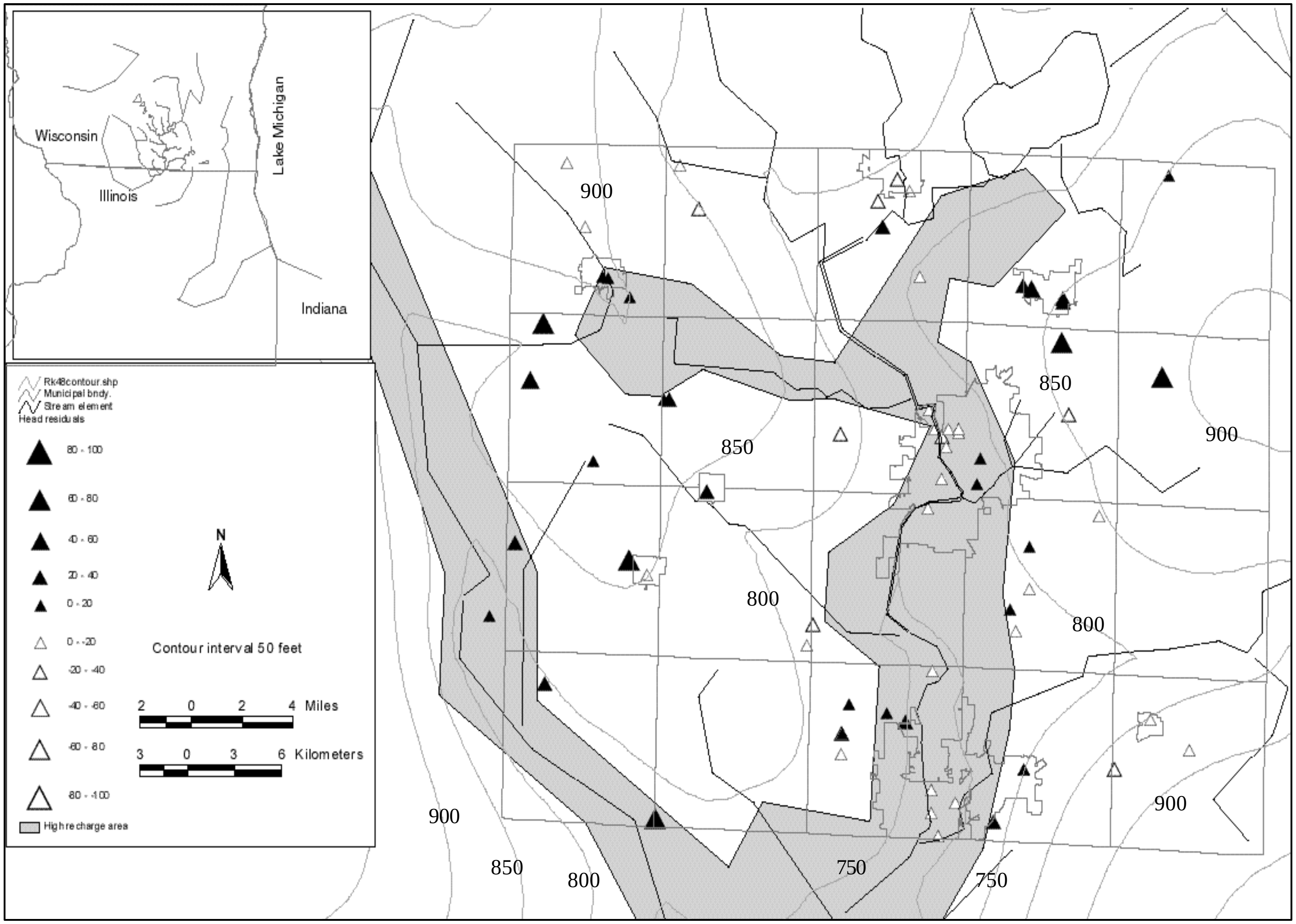

Figure 5. Simulated hydrologic features with analytic elements, potentiometric surface and calibration targets for comprehensive model. Inset map shows full extent of the model.

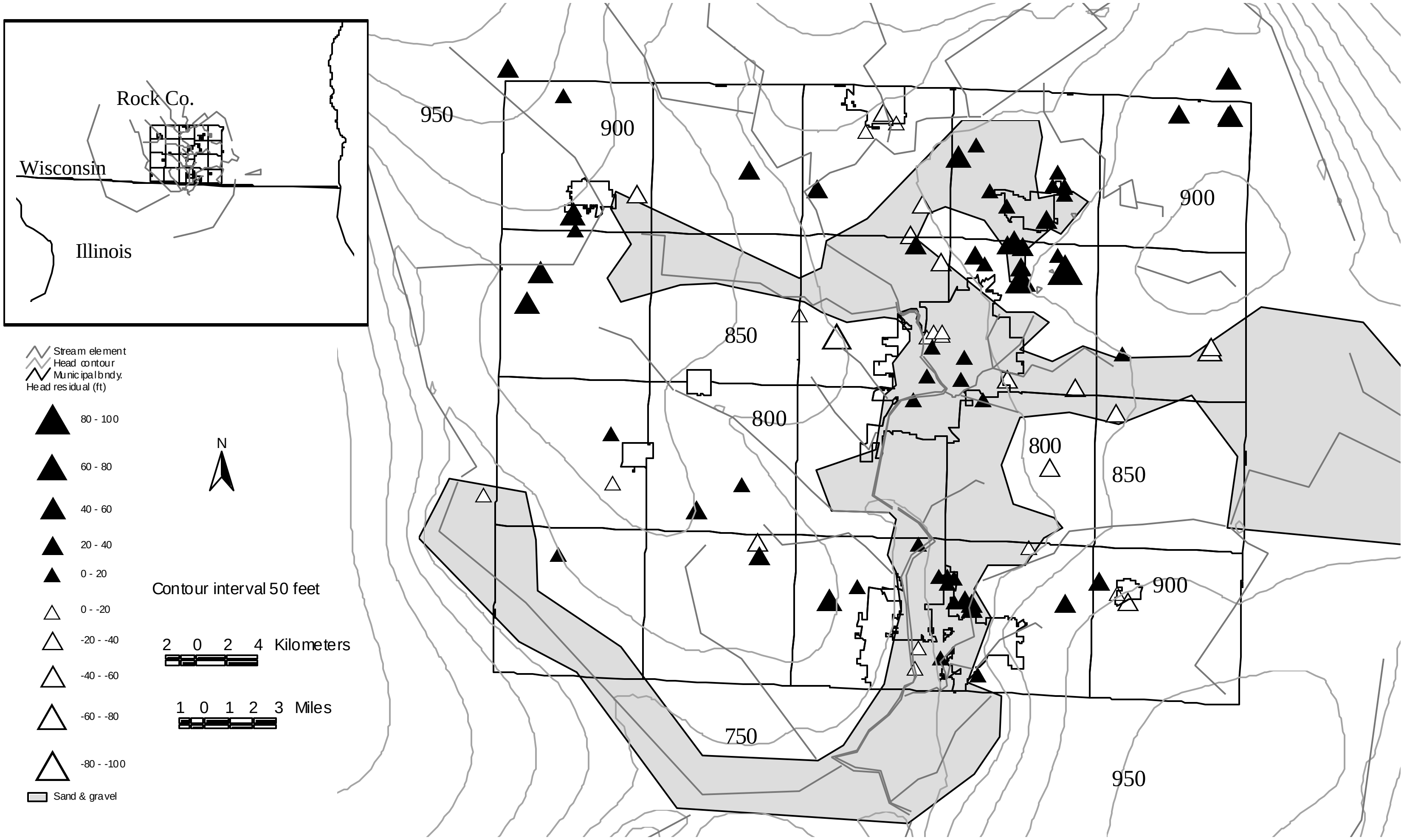

Figure 6. Simulated hydrologic features with analytic elements, water-table elevation and calibration targets for shallow model. Inset map shows full extent of the model. Additional recharge applied to same area shown in Figure 5.

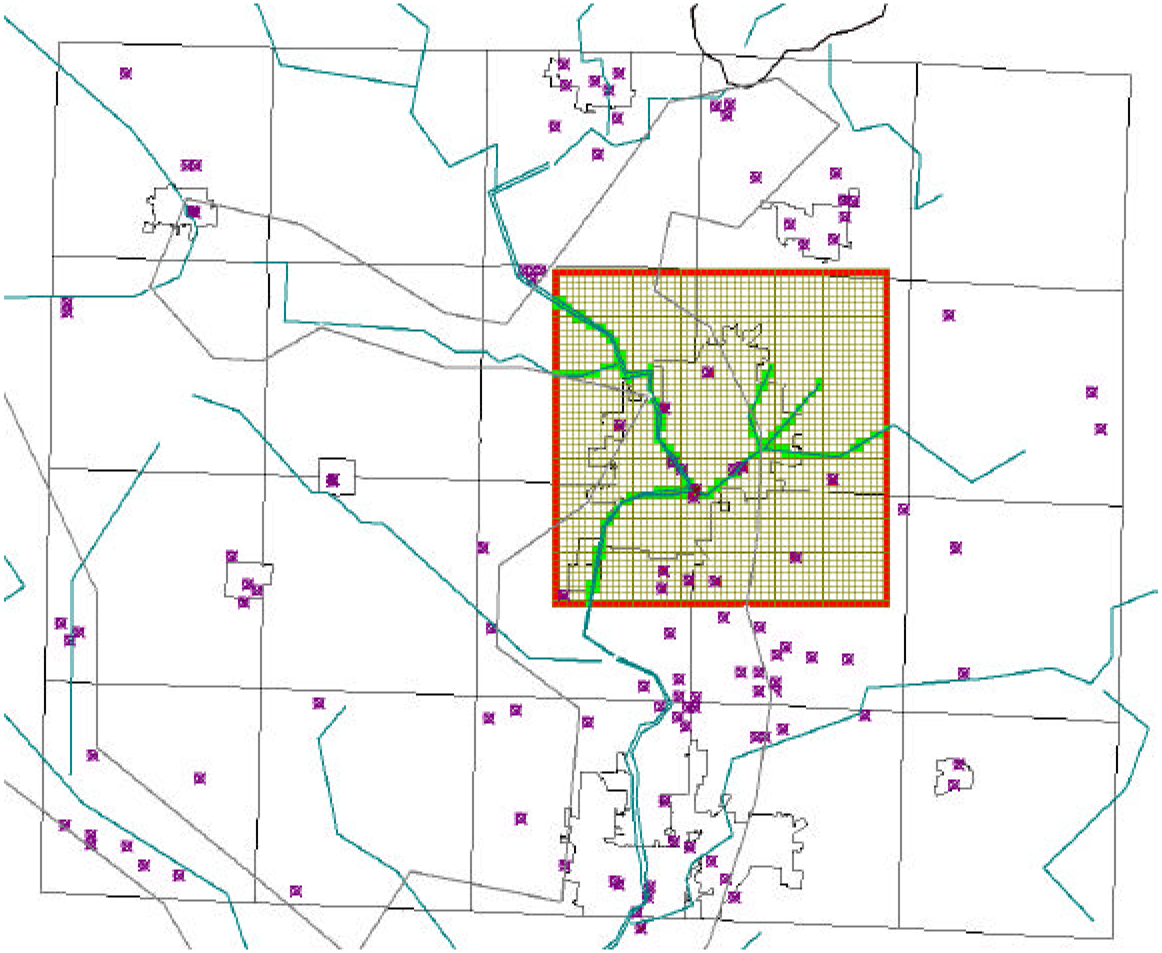

Figure 7. Extraction of boundary conditions for MODFLOW model of the Janesville area from comprehensive GFLOW model.

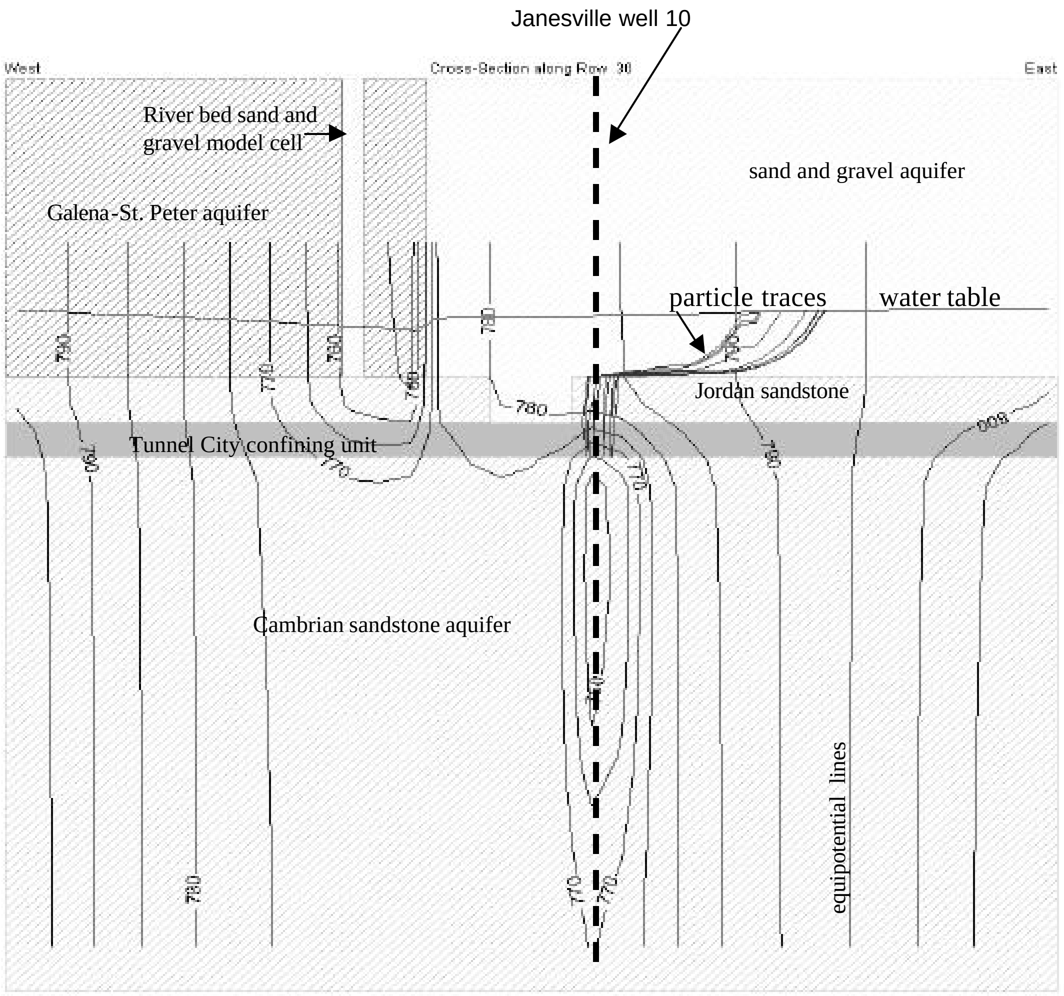

Figure 8. Cross section through MODFLOW model showing particle traces to Janesville well 10.
The well is open to the sandstone aquifer and also receives water originating in the sand and gravel aquifer.

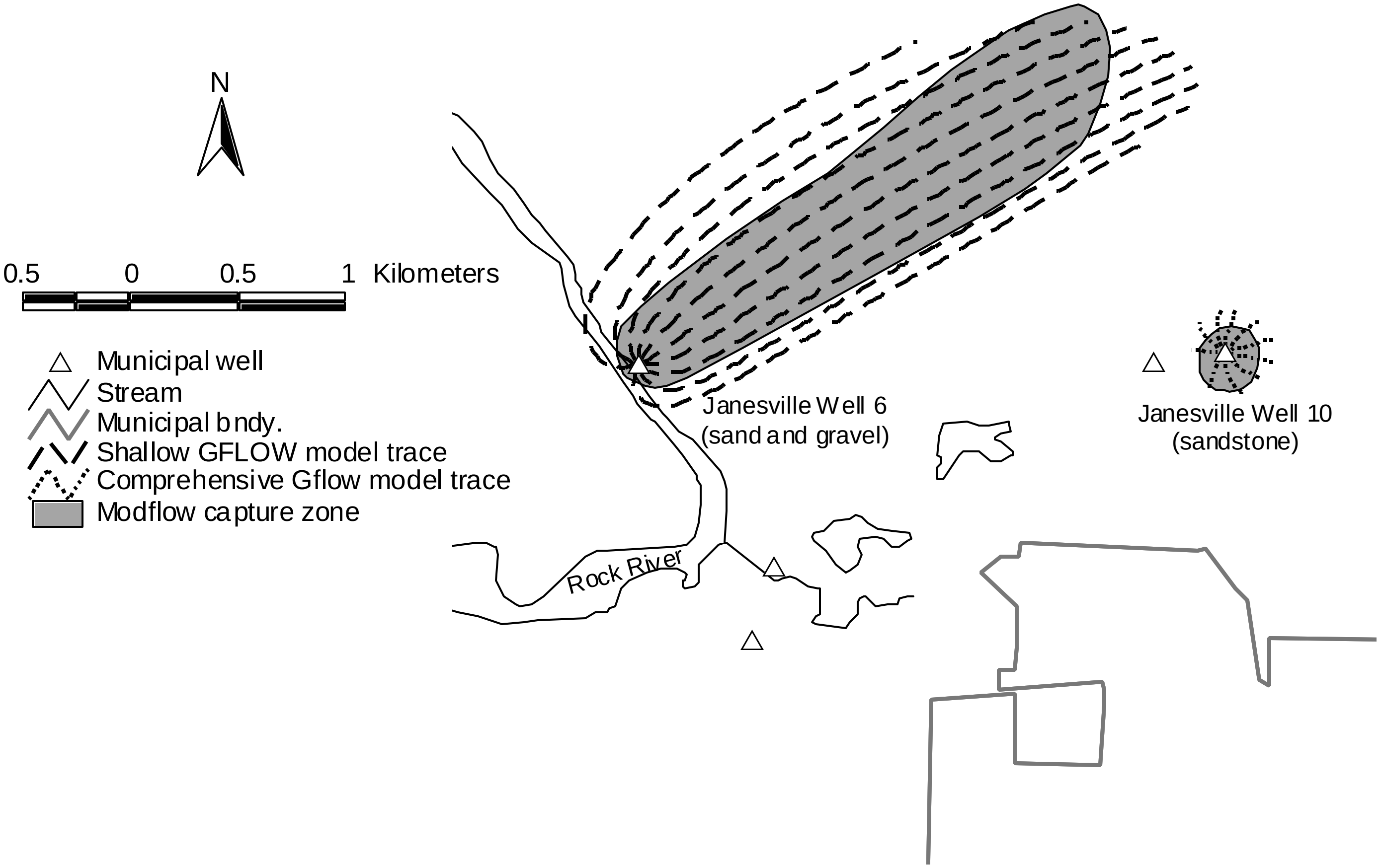

Figure 9. Comparison of particle tracking results from GFLOW and MODFLOW models.
Time of travel is 5 years. GFLOW particle traces computed with comprehensive model for Janesville well 10 and shallow model for well 6.

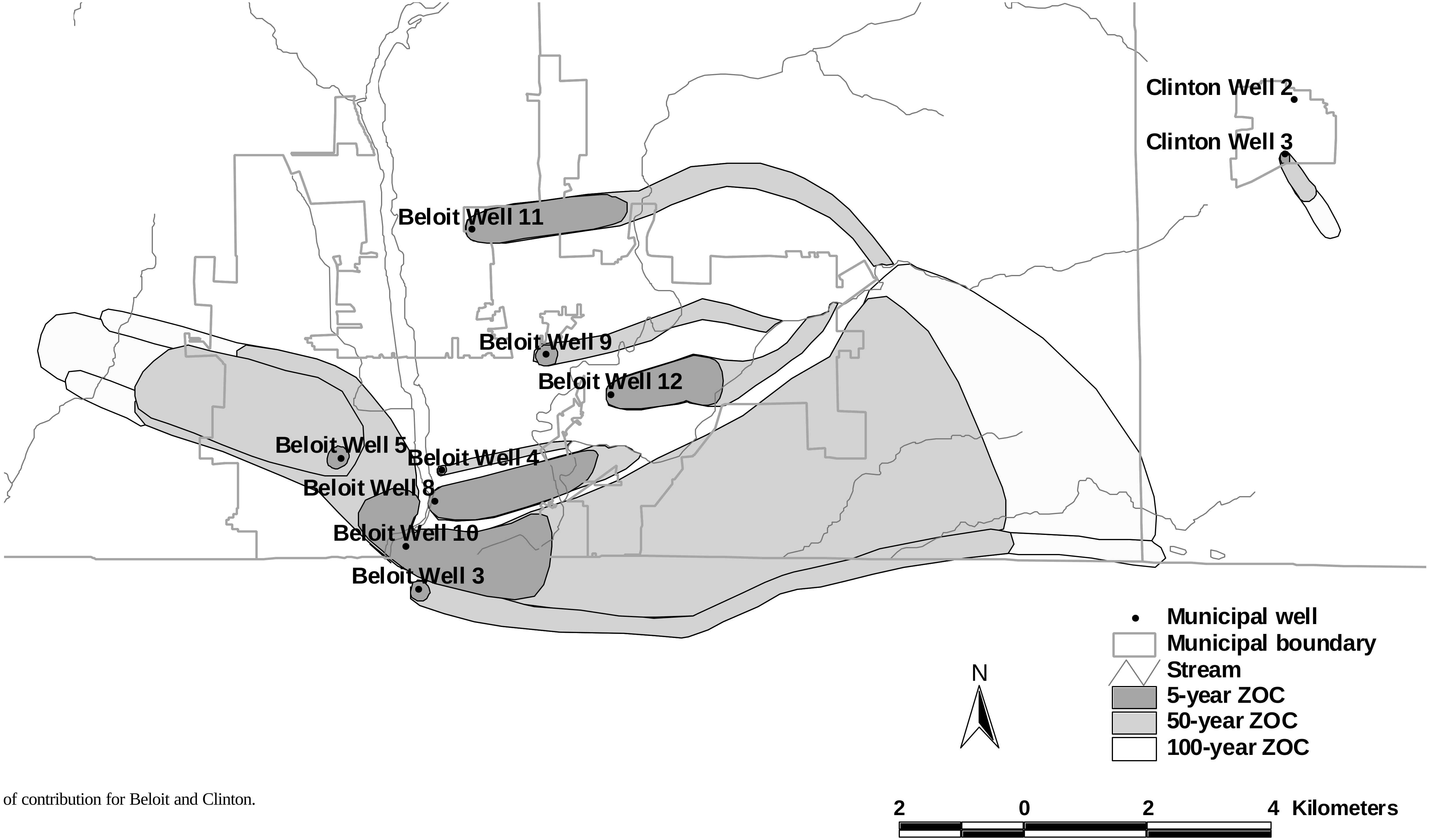

Figure 10. Zones of contribution for Beloit and Clinton.

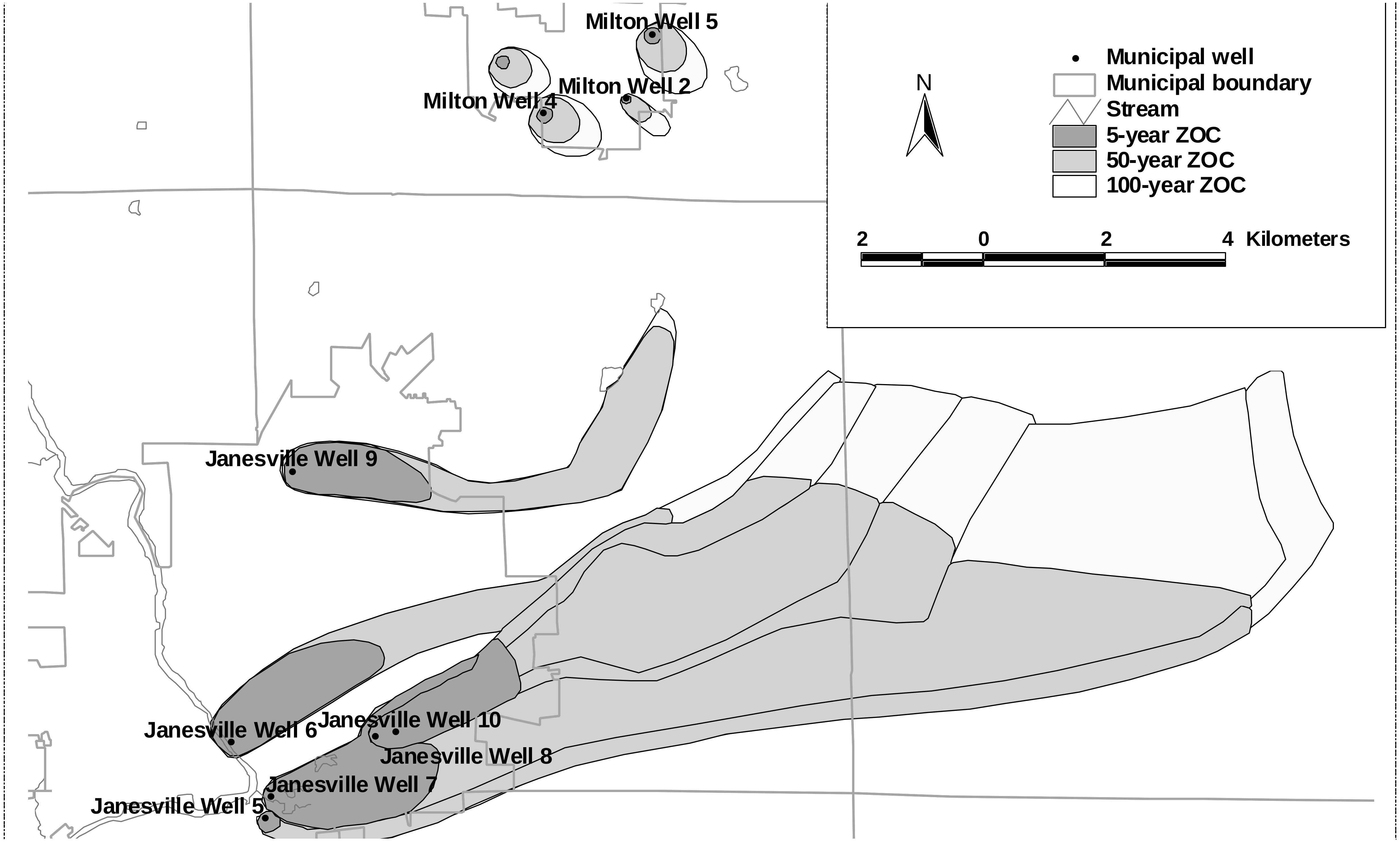

Figure 11. Zones of contribution for Janesville and Milton.

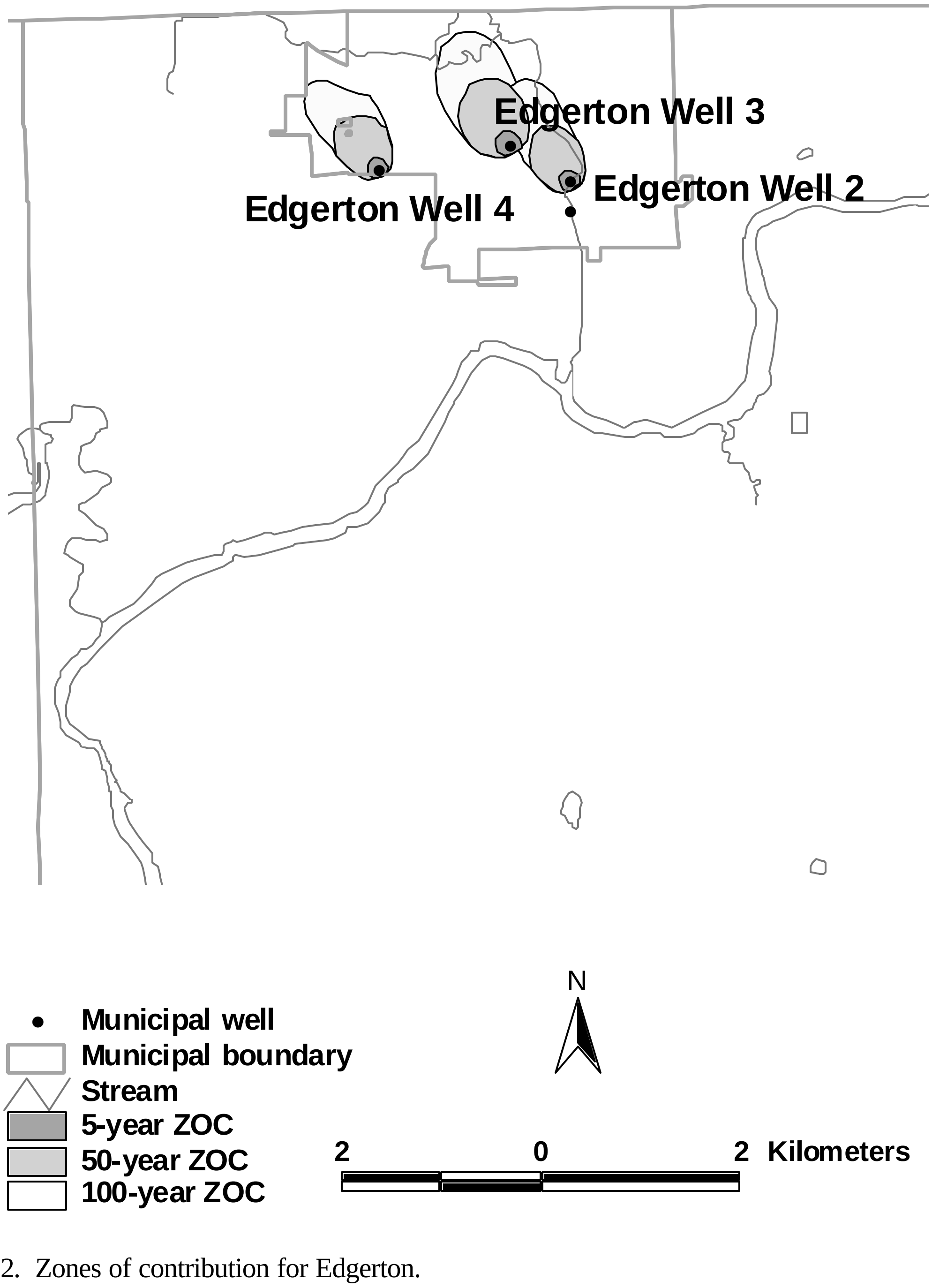

Figure 12. Zones of contribution for Edgerton.

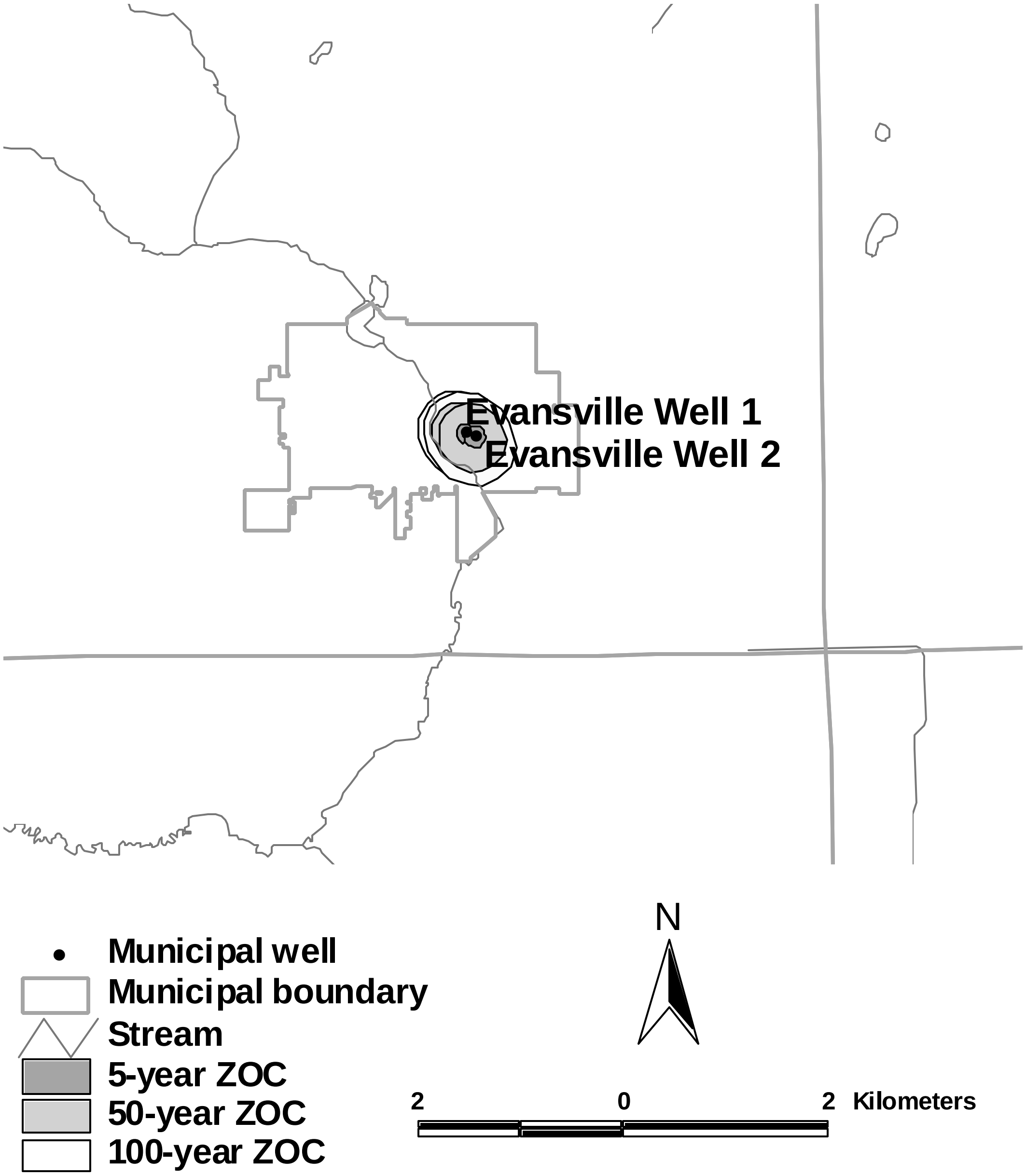

Figure 13. Zones of contribution for Evansville.

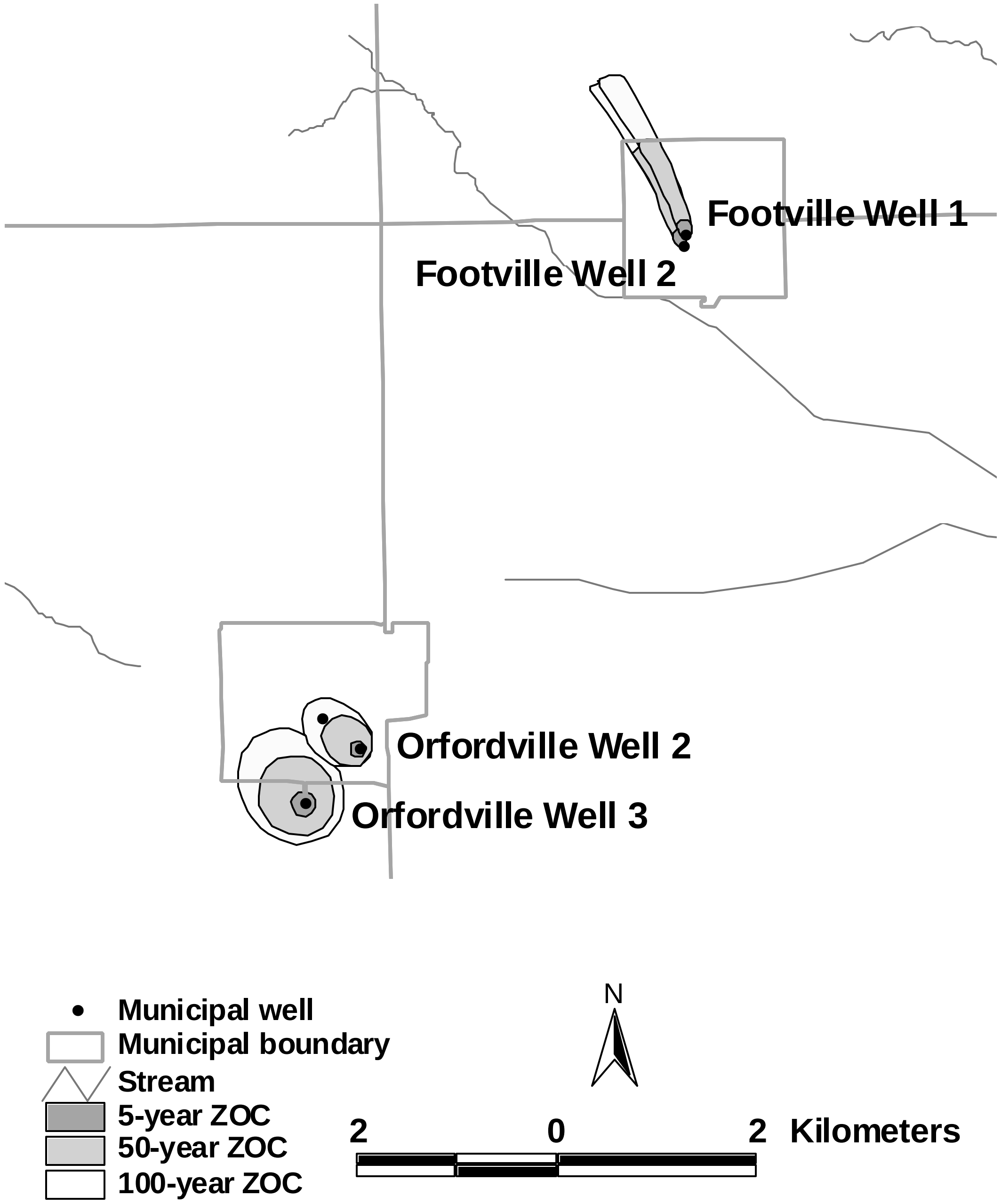

Figure 14. Zones of contribution for Footville and Orfordville.

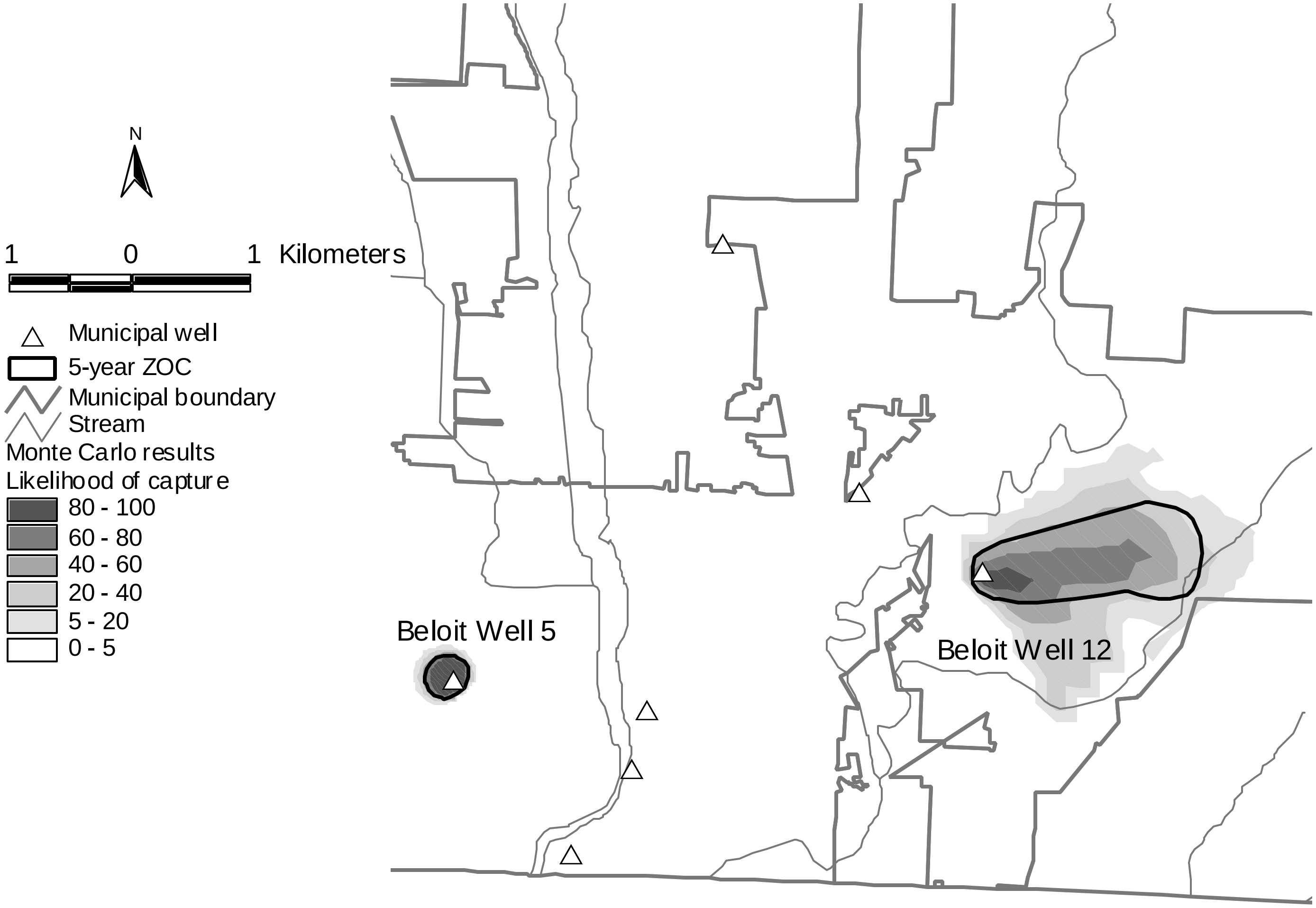

Figure 15. Monte Carlo analysis results for Beloit.

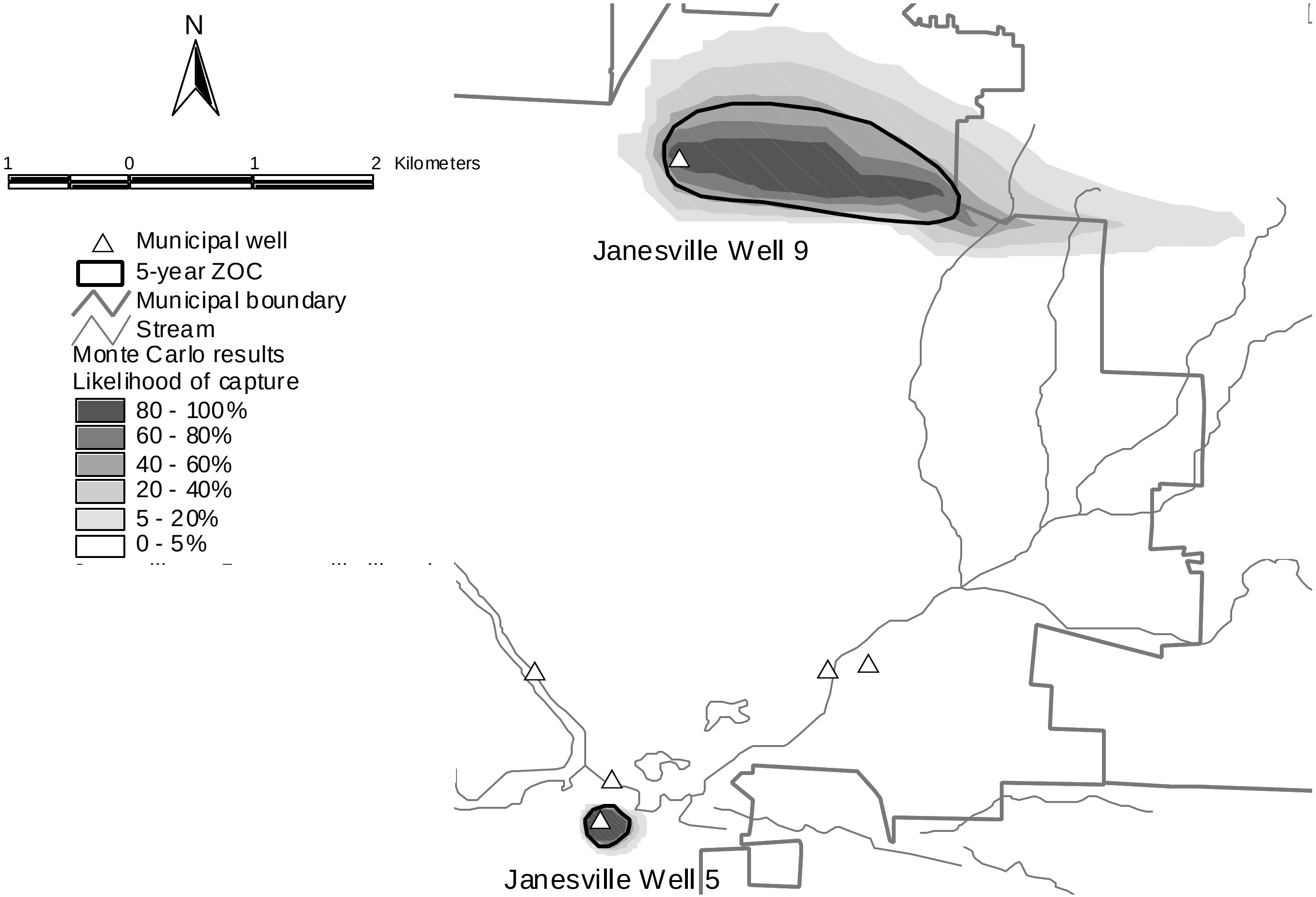

Figure 16. Monte carlo analysis results for Janesville.

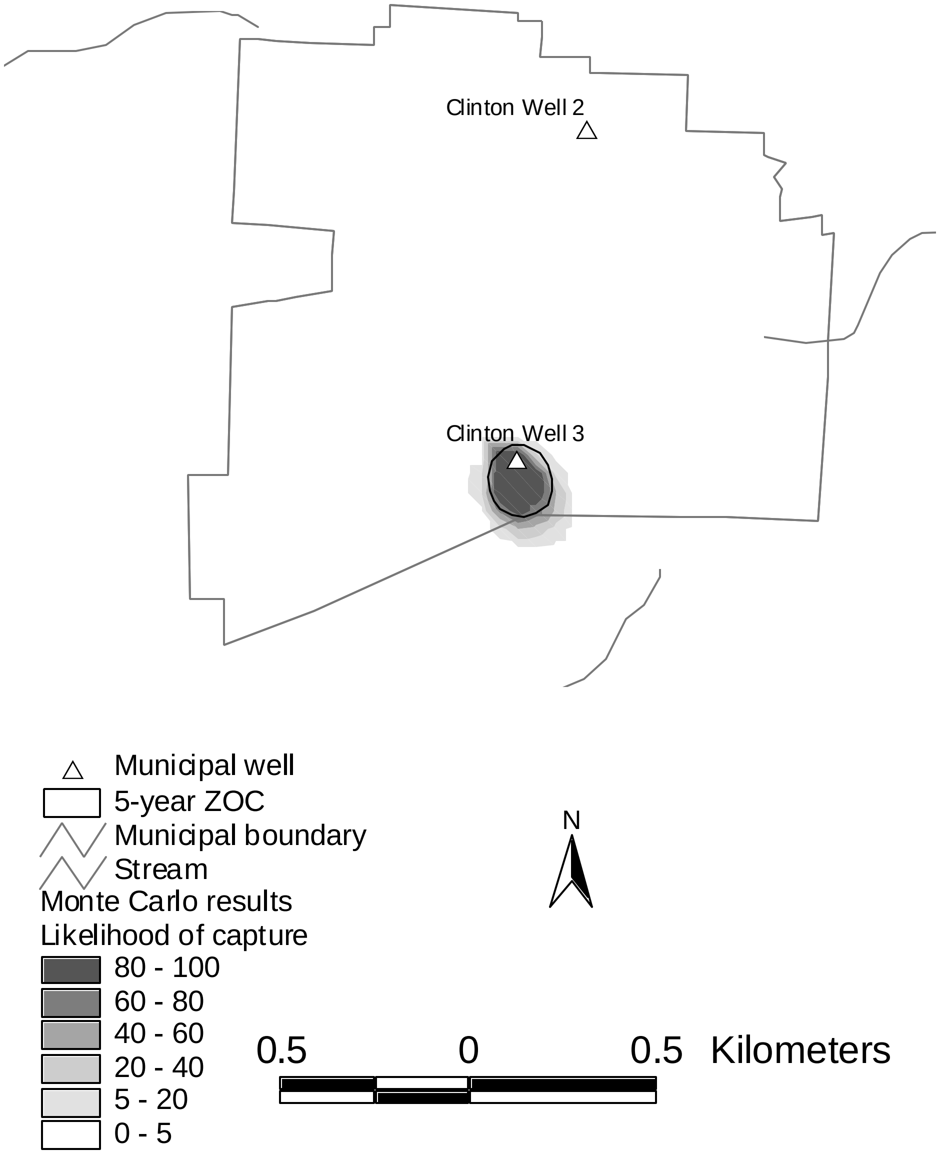

Figure 17. Monte Carlo analysis results for Clinton.

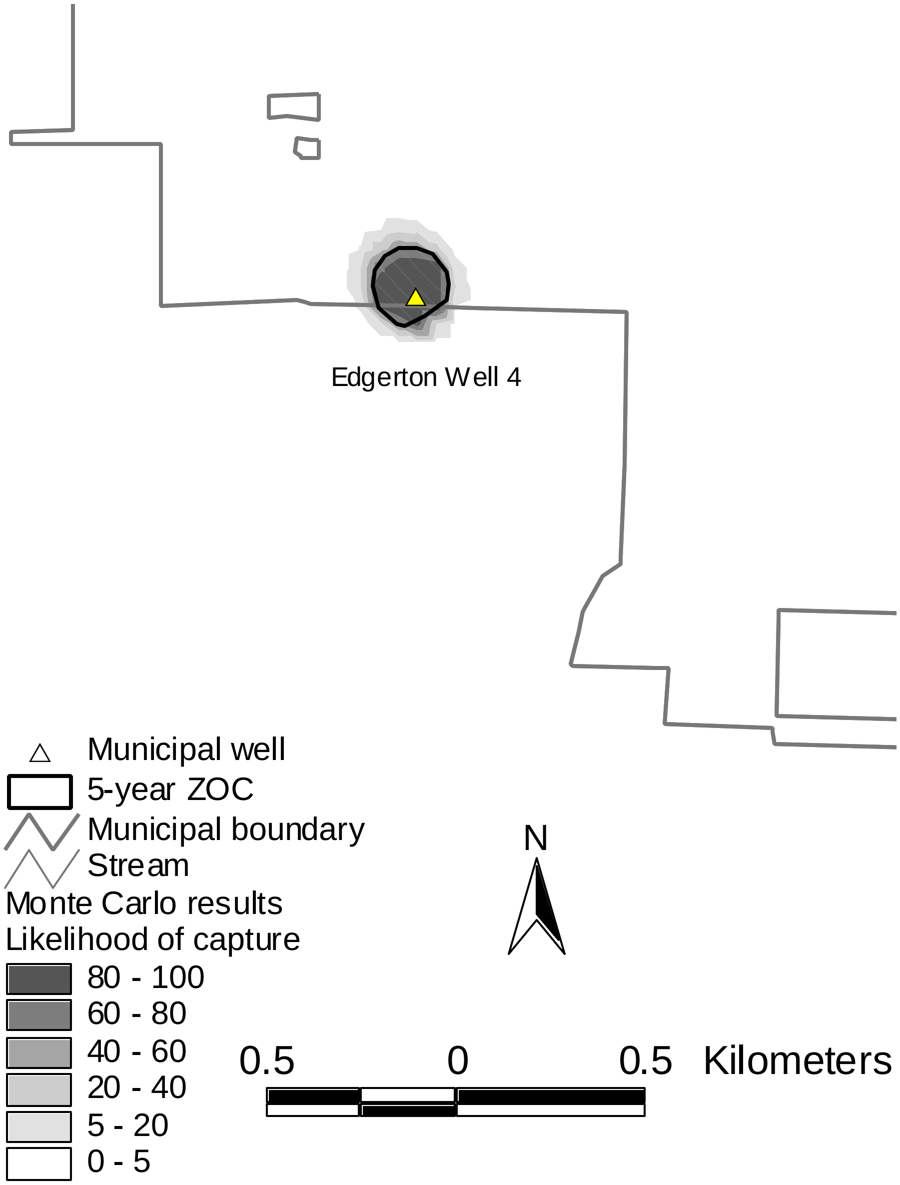

Figure 18. Monte Carlo results for Edgerton.

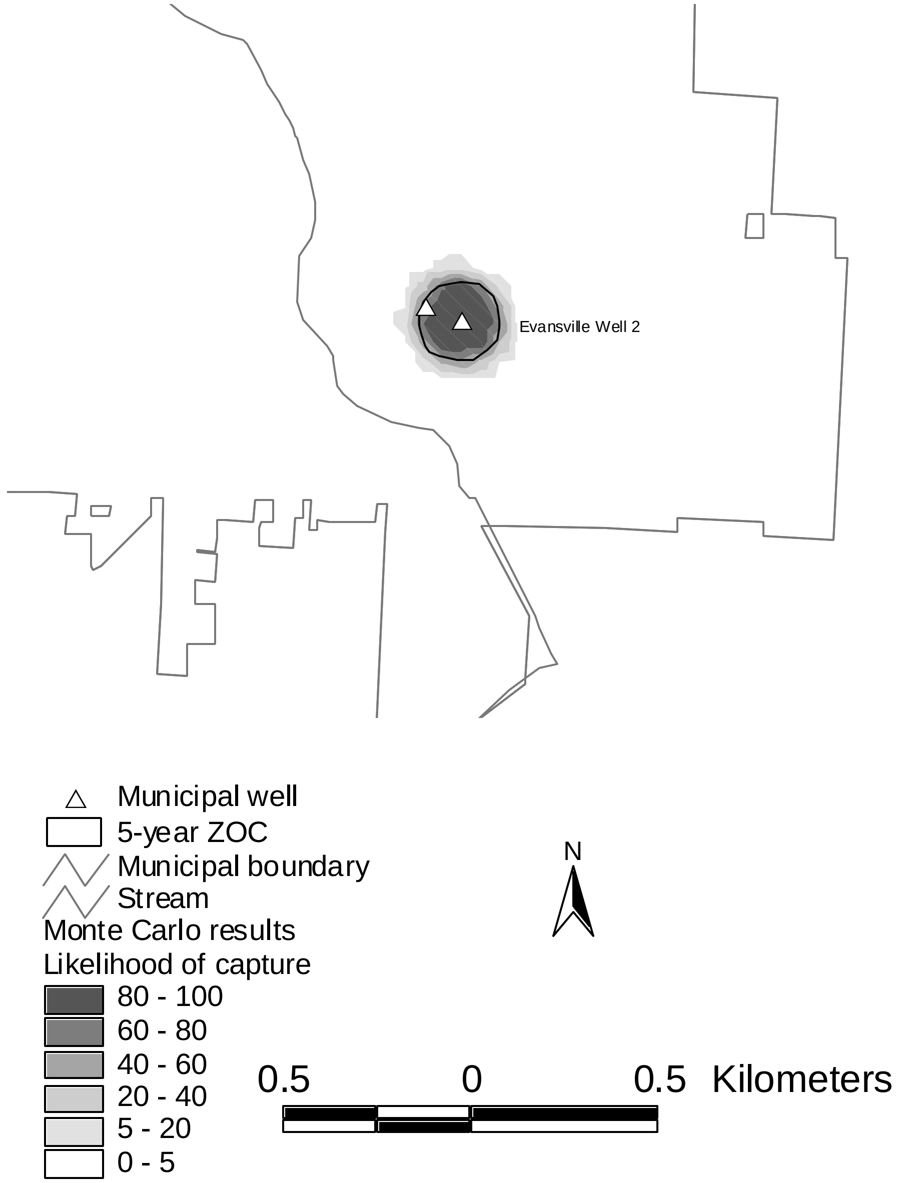

Figure 19. Monte Carlo analysis results for Evansville.

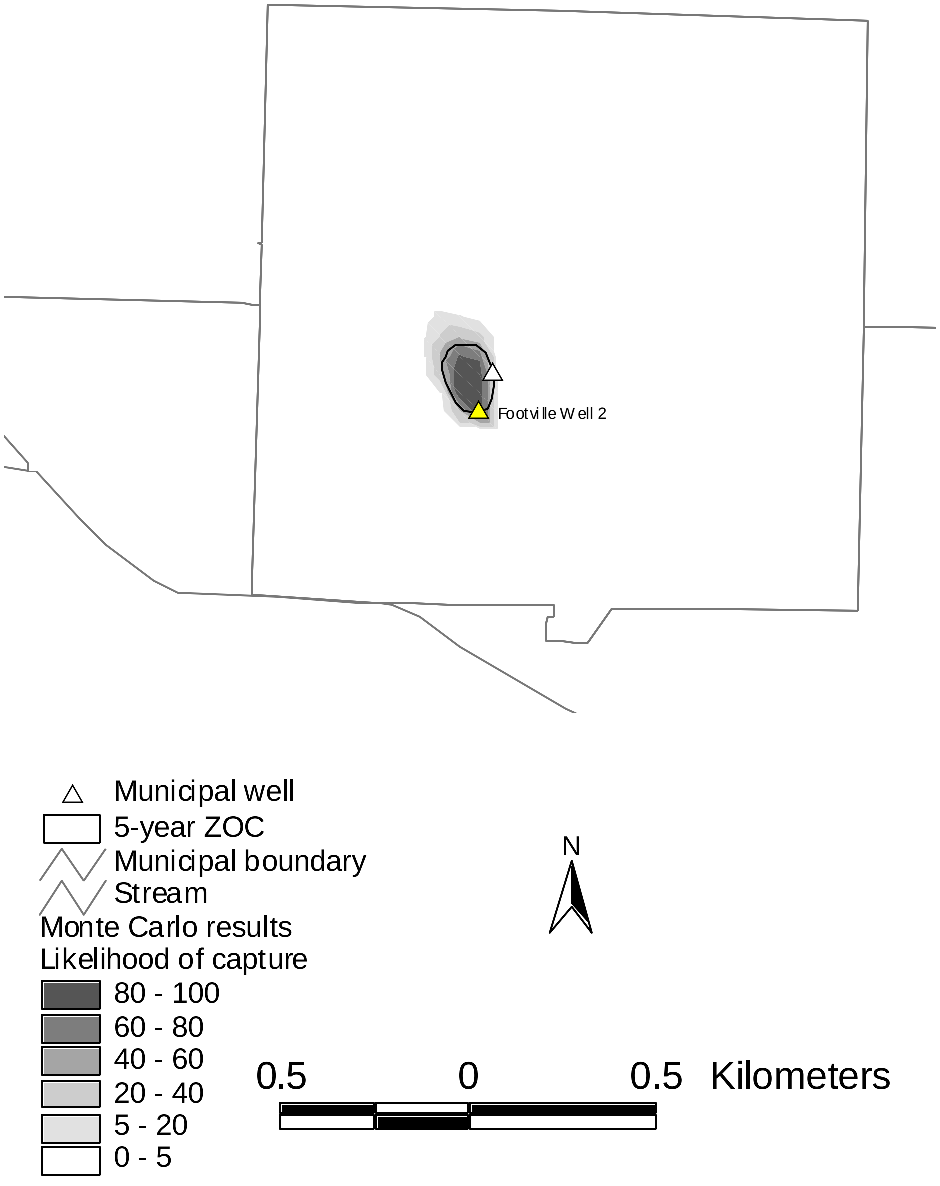

Figure 20. Monte Carlo analysis results for Footville.

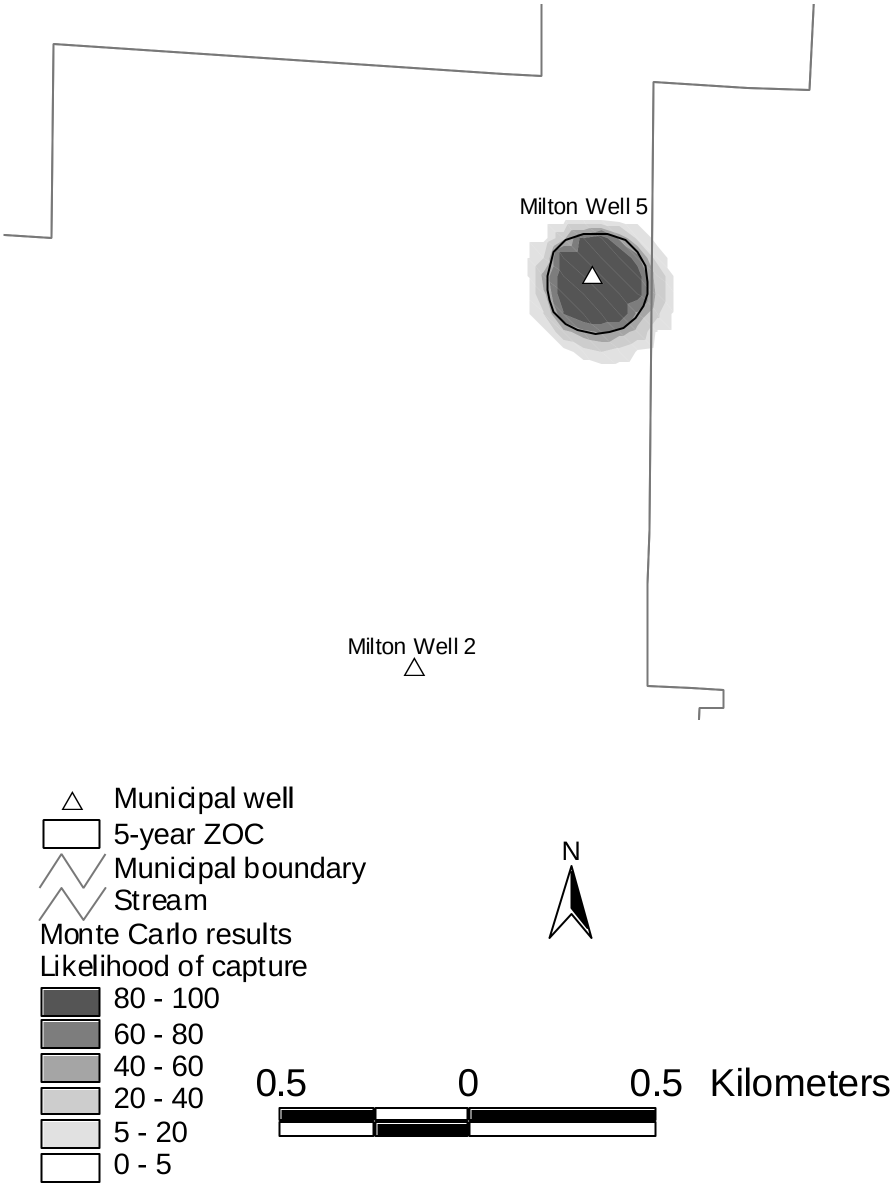

Figure 21. Monte Carlo analysis results for Milton.

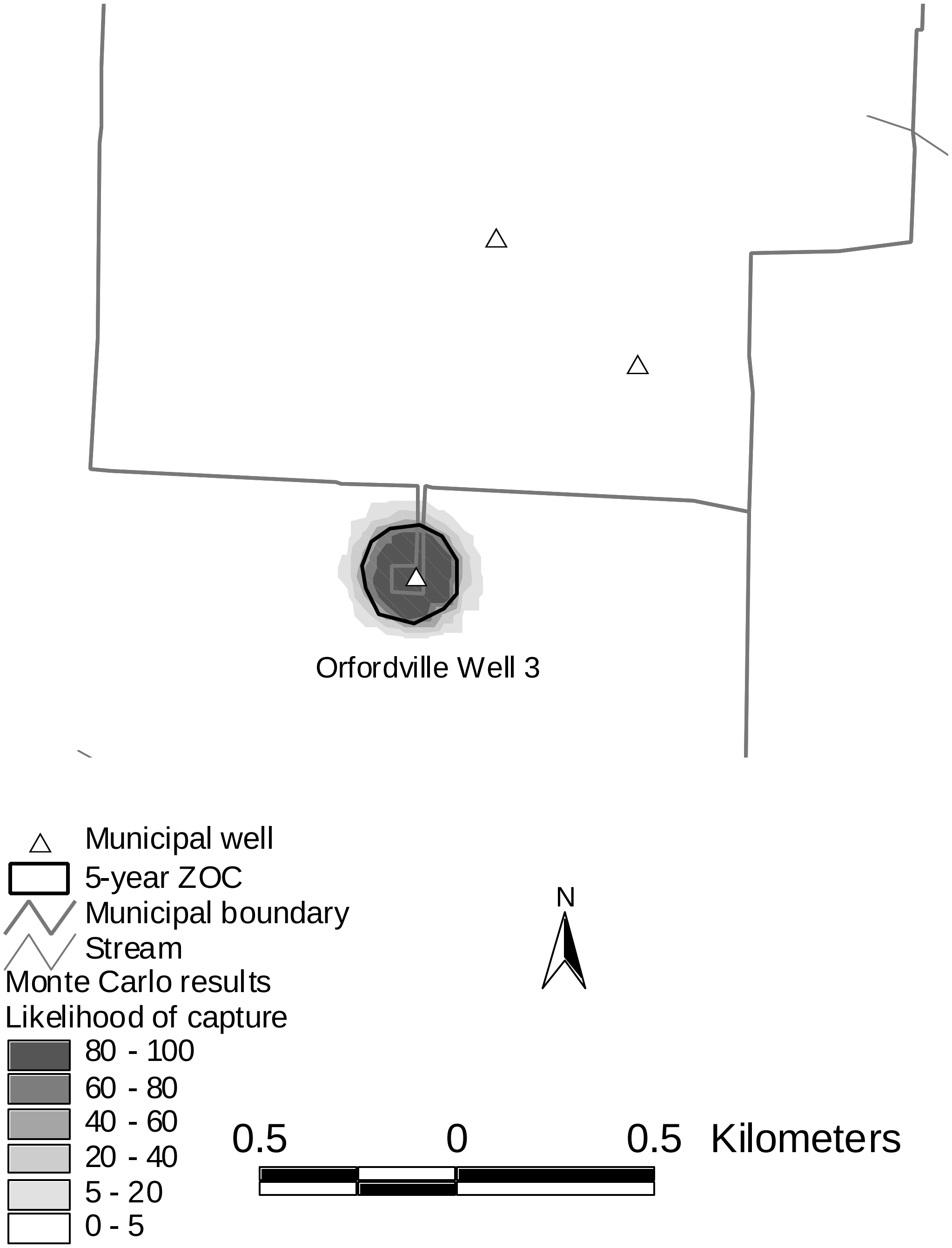

Figure 22. Monte Carlo analysis results for Orfordville.

Observation	Measured value	Simulated value	Residual	Weight
Streamflow targets				
Rock R. gain 1	9.7	7.5	2.2	0.14
Rock R. gain 2	29.1	28.8	0.3	0.27
Bass Cr.	2.2	3.0	-0.8	0.1
Sugar R.	23.8	22.7	1.2	0.03
Spring Br.	0.3	0.3	0.01	0.1
Turtle Cr.	8.0	8.1	-0.2	0.03
Little Turtle Cr.	1.0	0.8	0.1	0.1

Table 1. Streamflow targets for comprehensive GFLOW model, in ft^3/day x 10^6.
Weight is coefficient of variation (dimensionless).

Observation	Measured value	Simulated value	Residual	Weight
Bass Cr.	2.2	2.0	0.1	0.1
Rock R. trib. at Beloit	0.1	0.1	0.02	0.1
Markham Cr.	0.1	0.06	0.05	0.1
Fisher Cr.	0.02	0.02	0.004	0.1
Little Turtle Cr.	0.9	1.4	-0.04	0.1
Spring Br.	0.3	0.4	-0.008	0.1

Table 2. Streamflow targets for shallow GFLOW model, in ft^3/day x 10^6.
Weight is coefficient of variation (dimensionless).

Parameter	Initial estimate	Calibrated value
Comprehensive model		
Hydraulic conductivity (ft/d)	4	6.5
Global recharge (in/yr)	7	6.9
Sand and gravel recharge (in/yr)	15	12.7
Aquifer base elevation (ft)	- 700	--
Streambed resistance (d)	1	--
Shallow model		
Global hydraulic conductivity (ft/d)	32	24.5
Sand and gravel hydraulic conductivity (ft/d)	217	457
Global recharge (in/yr)	7	6.9
Sand and gravel recharge (in/yr)	15	12.7
Aquifer bottom leakance (in/yr)	- 1	--
Aquifer base elevation (ft)	600	--
Streambed resistance (d)	1	--

Table 3. Calibrated parameter values for analytic element models.

Well	5-year ZOC	50-year ZOC	100-year ZOC
Clinton 2	comprehensive	comprehensive	comprehensive
Clinton 3	comprehensive	comprehensive	comprehensive
Edgerton 1	comprehensive	comprehensive	comprehensive
Edgerton 2	comprehensive	comprehensive	comprehensive
Edgerton 3	comprehensive	comprehensive	comprehensive
Edgerton 4	comprehensive	comprehensive	comprehensive
Evansville 1	comprehensive	comprehensive	comprehensive
Evansville 2	comprehensive	comprehensive	comprehensive
Footville 1	comprehensive	comprehensive	comprehensive
Footville 2	comprehensive	comprehensive	comprehensive
Janesville 5	comprehensive	shallow	shallow
Janesville 6	shallow	shallow	shallow
Janesville 7	shallow	shallow	shallow
Janesville 8	shallow	shallow	shallow
Janesville 9	shallow	shallow	shallow
Janesville 10	comprehensive	shallow	shallow
Milton 2	comprehensive	comprehensive	comprehensive
Milton 3	comprehensive	comprehensive	comprehensive
Milton 4	comprehensive	comprehensive	comprehensive
Milton 5	comprehensive	comprehensive	comprehensive
Orfordville 2	comprehensive	comprehensive	comprehensive
Orfordville 3	comprehensive	comprehensive	comprehensive
Beloit 3	comprehensive	shallow	shallow
Beloit 4	comprehensive	shallow	shallow
Beloit 5	comprehensive	shallow	shallow
Beloit 8	shallow	shallow	shallow
Beloit 9	comprehensive	shallow	shallow
Beloit 10	shallow	shallow	shallow
Beloit 11	shallow	shallow	shallow
Beloit 12	shallow	shallow	shallow

Table 4. Models used to perform ZOC delineations.
All delineations performed with GFLOW.

Well Name	Pump rate (ft3/d)	Pump Rate Plus 15% (ft3/d)	1/2 pump capacity (ft3/d)	Rate used for ZOC delineation (ft3/d)
Clinton Well 2	inactive			
Clinton Well 3	28278	32520	50535	50535
Edgerton Well 1	abandoned			
Edgerton Well 2	24846	28573	62567	62567
Edgerton Well 3	27368	31473	93850	93850
Edgerton Well 4	10690	12294	62567	62567
Evansville Well 1	0	0	40428	40428
Evansville Well 2	28278	32520	71230	71230
Footville Well 1	0	0	38503	38503
Footville Well 2	14871	17102	38503	38503
Janesville Well 10	246387	283345	240642	283345
Janesville Well 5	26942	30983	168449	168449
Janesville Well 6	660059	759068	336898	759068
Janesville Well 7	442283	508625	423529	508625
Janesville Well 8	492202	566032	404278	566032
Janesville Well 9	492202	566032	452406	566032
Milton Well 2	0	0	30321	30321
Milton Well 3	0	0	67380	67380
Milton Well 4	41843	48119	96257	96257
Milton Well 5	30543	35124	105882	105882
Orfordville Well 2	3359	3863	38503	38503
Orfordville Well 3	11169	12844	93850	93850
Beloit Well 10	0	0	356150	356150
Beloit Well 11	285437	328253	269519	328253
Beloit Well 12	214620	246813	264706	264706
Beloit Well 3	97402	112012	141497	141497
Beloit Well 4	344	396	28877	28877
Beloit Well 5	87481	100603	168449	168449
Beloit Well 8	139147	160019	365775	365775
Beloit Well 9	78084	89797	163636	163636

Table 5. Actual and simulated pump rates for municipal wells.