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

A final report prepared for the Wisconsin Department of Natural Resources

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2002

Open-File Report 2002-05

74 p. + 2 plates

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WISCONSIN DEPARTMENT OF NATURAL RESOURCES

Submitted to

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WGNHS Open-file Report 2002-05

October 11, 2002

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Introduction

Background

This report documents the groundwater flow modeling and delineation of zones of contribution (ZOCs) for municipal wells in Sauk County, Wisconsin, carried out in 2001 as part of a countywide groundwater study (the Regional Hydrogeologic Study of Sauk County). The study is a joint project of the Wisconsin Geological and Natural History Survey (WGNHS) and the United States Geological Survey (USGS) under contract to the Wisconsin Department of Natural Resources (WDNR) and the Sauk County Board of Supervisors. In addition to this report on the ZOC modeling, products of the study will include water table elevation and depth to bedrock maps and a more general report describing the hydrogeology of Sauk County.

The WDNR Bureau of Drinking Water and Groundwater is currently carrying out its Source Water Assessment Program (SWAP), which is required by the 1996 Amendments to the Safe Drinking Water Act. The SWAP will eventually include a delineation of assessment area boundaries for all public water systems, a potential contaminant inventory within those boundaries, a susceptibility determination for each system and publication of the assessment results. The delineation of ZOCs reported here is an important part of determining the assessment areas.

The ZOC of a well includes the land surface over which recharging precipitation enters a groundwater system and eventually flows to a well. While the ZOC is a technically defined area based on groundwater hydraulics, here we have used a method of presenting our results that in some cases includes more land surface in the ZOC than that over which recharging precipitation flows to the well. This is caused by projecting the results of a three-dimensional model to a two-dimensional map of the land surface. For deeply-cased municipal wells common in Sauk County, the actual land surface contributing recharge may be physically distant from the well itself, and may not encompass the well. Franke et al. (1998) provide a thorough discussion of this issue. For the purposes of wellhead protection and this report, the ZOC includes the land surface over which precipitation that recharges the well enters the groundwater system plus the surface projection of the three-dimensional flow paths between the recharge area and the well. Methodologies typically used for ZOC delineation vary widely in their level of sophistication, from a fixed-radius method to numerical groundwater flow models (Born et al., 1988, Franke et al., 1998). In the work presented here, we have used numerical modeling methods to identify the ZOCs and to evaluate uncertainty in the results.

Objectives

The objective of the work presented here was to delineate the 5-, 50- and 100-year ZOCs for municipal wells in Sauk County based on numerical models of groundwater flow. This information can be used by the WDNR to determine appropriate assessment area boundaries and by water resource managers, planners and educators to protect groundwater resources.

Acknowledgements

YuFeng Lin of the WGNHS aided in model construction and carried out modeling runs. Lee Clayton and John Attig of the WGNHS provided review of geologic interpretation used in model development. Randy Hunt and Jim Krohelski of the USGS and Ken Bradbury of the WGNHS provided model review. The Sauk County Groundwater Committee has provided long-term support for model development and other aspects of this study.

Methods

Data sources and database development

This study relied primarily upon existing hydrologic and geologic data. Geologic data were compiled from WDNR well construction reports (WCRs), geologic logs of high-capacity wells on file at WGNHS, interpretive maps of the soils (SSRGO soils data), unlithified deposits and bedrock of Sauk County (Clayton and Attig, 1990). Data collected during the study include borehole geophysical logs (natural gamma radiation, electric, caliper) at wells of opportunity in Baraboo and Lake Delton. Two resistivity surveys were conducted in western Sauk County to evaluate thickness of geologic strata and water table elevation. These geologic data were used to identify the lateral extent and top and bottom elevations of hydrostratigraphic units.

Existing hydrologic data was compiled from WCRs, records of pumping tests and specific capacity tests on file at the WGNHS, and stream gauge records contained in the USGS files. During this project, we conducted limited field surveys of stream headwaters and performed some stream gauging to provide additional information for the modeling effort. The pumping test and specific capacity test data were analyzed with the TGUESS computer program (Bradbury and Rothschild, 1985) to estimate horizontal hydraulic conductivity (K_h) of aquifer sediments. Model calibration targets (groundwater levels and stream fluxes) for the groundwater flow models were also selected from these data sets.

A large portion of the data used in this study was placed in a GIS coverage and database. The database includes over 1200 municipal, high-capacity, irrigation and private drinking water wells and contains information regarding well location, ground surface elevation, depth to bedrock and depth to water.

Hydrostratigraphy

Information in the project database was used to generate a hydrostratigraphic framework for the county. Regional-scale maps showing the elevation of the surface of significant hydrogeologic units were constructed, including the top of the Cambrian sandstone aquifer, the top of the Eau Claire shale, and the top of the Pre Cambrian crystalline rock. Ground surface elevations were estimated from the National Elevation Dataset (USGS, 2001) digital elevation model (DEM), 30-meter grid. These maps were used to provide elevations and thicknesses for the groundwater flow model layers.

Water Table Map

Groundwater elevations were estimated from the elevations of surface-water features such as streams, lakes, and wetlands and from the depth to water recorded on over 1100 WCRs. USGS digital data for hydrography (derived from USGS, 2001)**,** topographic quadrangles (7.5-minute series; USGS, 1996–97), and the National Elevation Dataset (USGS, 2001) were used as aids in estimating these elevations and contouring the data. The accuracy of the map varies throughout the study area, increasing near surface-water bodies and where there is a greater density of wells. The water-table elevation is inferred from topography where data were scarce.

The use of water levels recorded on WCRs to create this map may be a source of inaccuracy. Water-supply wells are not ideal measuring points for determining the water-table elevation because most of these wells are open to the aquifer over long intervals that extend far below the top of the saturated zone. In low-lying areas, such as the outwash plains, this well design provides a good measurement of depth to groundwater because groundwater flow is predominantly horizontal. At higher elevations and in areas of steep terrain, groundwater flow may have a significant vertical component to its flow. In such areas, the water level measured in a well may be lower than the water-table elevation. For this reason, it is difficult to determine accurately the water-table elevation on ridgetops in the uplands.

Well Locations and Pumping Rates

Municipal well locations, monthly pumping rates from the year 2000, and operational pump capacities were provided by the WDNR. The locations and pumping rates were verified for a majority of the municipal wells by contacting water utility personnel from each town or city. The models were calibrated using the year 2000 municipal well average pumping rates (Table 1). The locations of other high-capacity wells included in the model were determined from information on file at the WGNHS and the WDNR. These wells were assigned pumping rates based on the information provided in high-capacity well permits (Table 2). The current pumping rates of these wells were not verified. This is significant because in the case of Reedsburg, as discussed in later sections of this report, the ZOC delineations are affected by the pumping rates assigned to nearby high-capacity wells.

Private well locations were determined by crosschecking information from the WCRs with plat maps, aerial photographs and USGS 7.5-minute series topographic maps. The depth to water recorded on the WCR was converted to a groundwater elevation using an estimate of land surface elevation from the DEM. Well records from 582 wells were used for head calibration targets in the regional model. Pumping from residential wells was not represented in the groundwater flow models because the relatively low water use of domestic wells is not expected to significantly affect the groundwater flow field at the model scale.

Groundwater Flow Models

A step-wise process was used to construct models of each municipal system. A two-dimensional analytic element model of the Sauk County region was developed using the GFLOW computer code (Haitjema, 1995). The regional model was calibrated (model parameters such as hydraulic conductivity and recharge adjusted to provide a reasonable match between simulated and observed head targets and stream fluxes) with the UCODE parameter estimation code (Poeter and Hill, 1998). In cases where the two-dimensional approach of the regional model was deemed to adequately represent local hydrogeologic conditions, the GFLOW model was further refined in the area of interest and then used to delineate ZOCs for municipal wells in that area. For municipalities located in more hydrogeologically complex settings, the regional GFLOW model provided a basis for developing three-dimensional finite difference models with the MODFLOW code (McDonald and Harbaugh, 1988). The use of analytic element models in conjunction with more complex finite difference models is discussed by Hunt et al. (1998). The various models constructed for this project are listed in table 3.

GFLOW assumes an aquifer infinite in aerial extent, whereby analytic solutions to the groundwater flow equation are superposed to approximate groundwater flow. The area of interest is represented in the near field of the model, where features that affect flow (wells, streams, lakes, local changes in K_h or recharge) are represented in detail by a series of various mathematical equations called analytic elements. The far field of the model includes a coarse representation of regional features that act as boundary conditions in the model by controlling the simulated regional flow field. Analytic solutions for each element in the model are superposed to produce a solution across the model domain. The method does not require a grid or cell descretization. Hydrologic features may be easily added or modified to test hypotheses or add complexity in the area of interest. Detailed descriptions of the mathematical and practical applications of the method are found in Haitjema (1995) and Strack (1989).

GFLOW includes a model extraction feature that allows the user to define a grid within the GFLOW model domain. The GFLOW results are subsequently written to MODFLOW input files. This feature was used to extract groundwater fluxes from the regional model for use as boundary conditions for inset MODFLOW models.

UCODE (Poeter and Hill, 1998) is a “universal” parameter estimation code that provides a statistically rigorous methodology for calculating parameter values (such as K and recharge) that result in a best fit between simulated and observed data (such as hydraulic heads and stream flows). UCODE may also be used to assess parameter sensitivity, correlation between parameters, and uncertainty in the model results. It is designed to link to other models, such as GFLOW or MODFLOW. In the work presented here, we have relied heavily upon the guidance in Hill (1998) and the example provided by Hunt (Hunt et al., 2000) in using UCODE to optimize the regional GFLOW model.

MODFLOW (McDonald and Harbaugh, 1988), the U.S. Geological Survey modular groundwater modeling code, was used to simulate three-dimensional steady-state flow to wells in areas of Sauk County where aquifer complexity was not sufficiently represented by the regional GFLOW model. Three MODFLOW models were developed, covering: 1) the Sauk Prairie/Prairie du Sac area; 2) the Baraboo, North Freedom and Rock Springs area; and 3) the villages of Spring Green and Plain (table 3). Results of the regional GFLOW model, including the model-simulated location of water table divides and particle tracking to wells, were used to determine appropriate boundaries for these MODFLOW inset models. Groundwater fluxes at the boundaries, wells, and rivers were extracted from the GFLOW model as described above and incorporated into the MODFLOW datasets. The calibration and sensitivity testing of each inset model is described in the appendices to this report.

<u>Delineation of Zones of Contribution</u>

ZOCs were determined for 5, 50 and 100 year time of travel for each municipal well. Included in this analysis were active wells and inactive wells that have not been abandoned. Pumping rates used in the ZOC simulations were determined by a formula developed by the WDNR: the average 2000 pumping rate was assigned to each municipal well with the exception of the well for which the ZOC was delineated. For the well of interest, whichever was the greater of ½ operational pump capacity or the year 2000 average rate plus a factor of 15% was used. In most cases, the use of a rate equal to half of the operational capacity leads to a simulated ZOC that is larger than the simulated ZOC for the actual pumping rate of the well. Actual and modeled pumping rates are presented in table 1.

The ZOCs were determined from steady-state model simulations because groundwater withdrawal in Sauk County is relatively limited and does not cause significant deceases in water levels over time. This conclusion was reached on the basis of historical and current water level records, and on long-term hydrographs from two monitoring wells in Sauk County. Backwards particle tracking was used from the wells to determine the flow paths for 5, 50 and 100 years travel times. The endpoints of the flowpaths (which in some cases defined a three-dimensional, irregularly shaped volume) were projected to a map of the ground surface. The endpoints were connected to define a polygon; this two-dimensional shape is the ZOC. Forwards particle-tracking runs were performed to verify the results of the backward method. Particles were started at the top and bottom of the open interval of the well in order to determine the starting elevation that would yield the largest ZOC.

Physical Setting

Sauk County is located in south central Wisconsin and encompasses three geologically and geographically distinct regions (fig. 1). The Baraboo Hills are located in the east-central part of the county, a glaciated region covers the eastern portion of the county, and a non-glaciated "Driftless Area" includes the northern, western and southern parts of the county. These regions have distinct topographic and geomorphic features that are the result of the complex geologic history of the area. This report provides a summary of these features relevant to the hydrogeologic framework developed for the study area; the reader is referred to Clayton and Attig (1990) and Dalziel and Dott (1970) for a complete description of the geologic history of the area.

<u>Geology</u>

The Baraboo Hills consist of Precambrian quartzite that forms a complex arrangement of doubly plunging synclines and anticlines, trending east-northeast and exposed at the surface over a distance of about 15 miles. The anticlines are expressed as the North and South Ranges, where the Precambrian Baraboo quartzite is exposed. The intervening syncline, the Baraboo basin, is at a lower elevation and contains sandstones of the Elk Mound Group overlying the quartzite. The South Range rises over 800 feet above the surrounding land, is fairly continuous, and has relatively flat summit plateaus. The North Range is smaller and more discontinuous. A thin soil layer covers the Hills; the depth to bedrock is generally less than 25 feet. A shaded relief map (inset on Plate 1) illustrates the varied and distinct topographic regions within the county.

The Driftless Area consists of narrow uplands with thin soil cover surrounded by steep-sided valleys. In the uplands, the thickness of unlithified material is typically less than 25 feet, although in isolated areas the depth to bedrock ranges up to 100 feet. These areas of thicker deposits in the non-glaciated uplands are probably the result of increased mineral weathering (clay and soil formation) or windblown deposition of glacial loess. Nearly flat lying, Paleozoic sand, sandstone and dolomite are exposed along the valley walls. The valley bottoms contain tens of feet of Pleistocene sediment overlying layers of sandstone and dolomite.

The glaciated portion of the county is covered by material deposited during the last part of the Wisconsin glaciation. The Johnstown moraine marks the maximum extent of the glacial ice, and the area to the east of this consists of thick deposits (up to 400 feet) of glacial and stream sediments. Glacial lake and outwash sediments cover a significant portion of the land surface west of the moraine (fig. 1). The outwash deposits, which range up to about 250 feet in thickness, consist primarily of sand and gravel and extend in broad terraces along the Wisconsin River. The lake sediments, which typically underlie modern stream valleys, consist primarily of sand with interbedded silt and clay. The complex layering of moraine, lake, outwash and other glacial deposits found in Sauk County is illustrated in cross sections provided by Clayton and Attig (1990) and Dalziel and Dott (1970).

The bedrock geology of Sauk County is as complex as the surficial geology. A generalized stratigraphy and cross section are presented in figures 2 and 3. In the Baraboo Hills region, the uppermost bedrock is Precambrian Baraboo quartzite, which is bounded by sandstone and conglomeratic beds of the Parfrey's Glen Formation. Sandstones of the Elk Mound Group are present in the valley between the North and South ranges of the Baraboo Hills, and local deposits of sandstone and dolomite are found in smaller valleys and at lower elevations within the Baraboo Hills. In uplands of the Driftless area, Ordovician sandstones and dolomites cap thick sequences of Cambrian sandstone. In the valleys of the Driftless area, a thin sequence of the Tunnel City typically overlies sandstone of the Elk Mound Group. In the deep bedrock valley followed by the Wisconsin River, the bedrock surface is formed by older Cambrian sandstone and shale of the Eau Claire and Mt. Simon Formations.

Hydrologic Features

The Wisconsin and Baraboo Rivers are the major rivers in Sauk County (fig. 4). The Wisconsin River basin extends along the northeast, southeast and southern borders of the county. To the north, in the Wisconsin Dells area, the river valley is narrow and is steeply down-cut into the sandstone formations. To the south and southeast, the river valley broadens significantly as it passes through flat, outwash plains. The river stage drops approximately 38 feet across the hydroelectric dam at Lake Wisconsin, approximately one mile north of Prairie du Sac.

The Baraboo River traverses the width of Sauk County, flowing from the northwest through the City of Baraboo, eventually discharging to the Wisconsin River in Columbia County. Four dams that once spanned the Baraboo in Sauk County were removed between 1997 and 2001.

Modern stream systems occupy glacial lakebeds and the valleys of the Driftless area, including Honey Creek, Narrows Creek, Seeley Creek, and Dell Creek. Several large lakes are present in the northern portion of the county, including Lake Redstone, Lake Delton and Devils Lake.

Population and Pumping Centers

The population of Sauk County is centered in Reedsburg, Baraboo and Sauk City/Prairie du Sac, with smaller communities scattered throughout the County (fig. 5). Groundwater is the primary source of water for commercial, domestic and municipal drinking water supplies. Groundwater is also used for agricultural irrigation in the broad terraces along the Wisconsin River Valley. The Wisconsin Dells/Lake Delton area is host to several large resort hotels and water parks that place a seasonal demand on water use.

There are fourteen municipal water supply systems in Sauk County, with a total of 34 wells (fig. 5 and table 1). The City of Wisconsin Dells, which spans the Wisconsin River, also operates four wells located on the east side of the river in Columbia County (Wisconsin Dells wells 4 and 5 are in Sauk County and wells 1,2, 3 and 6 are in Columbia County). The results of our hydrogeologic characterization of Sauk County were extended to model the ZOCs of the four wells located in Columbia County. Total pumping from municipal wells represented in the calibrated regional GFLOW model is 5,433 gpm.

In addition to these municipal wells, 116 high-capacity wells are represented in the groundwater flow models of the county, including irrigation, hotels, water parks, schools, hospitals, mobile home parks, commercial establishments, and groundwater remediation wells at the Badger Army Production Plant (BAPP). The pumping rates assigned to these wells in the groundwater models (table 2) were estimated based on the high-capacity well permits on file with the WDNR. These pumping rates were not verified and may not reflect current water use patterns. Total pumping from the non-municipal high capacity wells represented in the calibrated regional GFLOW model totals 10,910 gpm.

Regional Hydrogeologic Conceptual Model

This conceptual model is a simplified representation of the hydrologic system that includes components critical to the groundwater system. The purpose of the conceptual model is to simplify the hydrogeologic and hydraulic information and data sets into a representation of the regional setting that can be numerically modeled (Anderson and Woessner, 1992). We have simplified our interpretation of the system as much as possible while retaining sufficient complexity to adequately simulate groundwater flow to municipal wells. This conceptual model served as a framework for development of the numerical models, and it was refined throughout the numerical modeling process as insight into the hydrogeologic regime was gained through the process of model development and calibration. The regional conceptual model was further refined in particular areas of interest as inset models were developed to represent local pumping centers. Our conceptual model includes interpretation of the regional hydrostratigraphy and groundwater recharge regimes across the county.

<u>Aquifers and Aquitards</u>

For the purpose of describing and simulating regional groundwater flow patterns in Sauk County, we have defined three aquifers and one aquitard: the unlithified aquifer, the sandstone aquifer, the quartzite aquifer, and the Eau Claire aquitard. While the delineation of aquifers and aquitard presented here is appropriate for the scale of this study, site-specific studies may require further consideration of local conditions. The aquifers and aquitard are described below and are illustrated in a series of cross sections (figures 6 through 11).

Unlithified Aquifer

The upper aquifer is made up of unlithified glacial and alluvial materials, and varies in composition from sand and gravel outwash to clayey tills and lake sediments. The extent and thickness of these deposits is shown in figure 12, and areas where it is commonly used as an aquifer is illustrated in figure 13. This aquifer is absent in the uplands of the Driftless area, where the unlithified deposits are thin and unsaturated and consist primarily of sandy clay of the Rountree Formation. The aquifer is thick and very permeable in outwash plains and the major river valleys (figs. 6, 7 and 8). The permeability of the unlithified aquifer decreases in areas where it consists of glacial lakebed sediments or moraine deposits. Several municipal wells located in outwash plain or alluvial valleys pump exclusively from the unlithified aquifer, as indicated in table 1.

Sandstone aquifer

The sandstone aquifer underlies the unlithified deposits and consists of all saturated bedrock units above the Precambrian crystalline rocks, with the exception of some portions of the Eau Claire Formation (discussed below). Where the water table is in bedrock, the water table defines the top of the aquifer. Where the water table is in unlithified materials, the bedrock surface defines the top of the sandstone aquifer. The thickness and top elevations of the bedrock above the Precambrian crystalline rock are shown in figures 14 and 15. In many areas of the county, such as Spring Green, there is no confining unit present between the unlithified and sandstone units and they are in good hydraulic connection (fig. 6). Areas of Sauk County where the sandstone is the primary aquifer are illustrated in figure13.

Most high-capacity wells in Sauk County are drilled through and open to the multiple geologic formations that constitute the Cambrian sandstone sequence (table 1). In general, lithologic descriptions on geologic logs from the municipal wells indicate that the Cambrian sandstones in this aquifer are fairly uniform across Sauk County, consisting primarily of fine to medium grained sandstone. However, several geologic logs from northwest Sauk County describe approximately 10 feet of shale at the base of the Tunnel City Formation, and thin (5 to 15 feet) layers of siltstone and dolomite are noted in logs of several of the municipal wells. While these heterogeneities within the sandstone indicate that the aquifer is not isotropic and homogenous on a local scale, we consider it a single aquifer with uniform properties for the purposes of this project because hydraulic data on individual formations is not available.

Similarly, there is a lack of hydraulic information about the Ordovician Prairie du Chien dolomites that overlie the Cambrian formations in the uplands of the Driftless area (fig. 2). While many domestic wells are completed in the Oneota Formation of the Prairie du Chien group, all municipal wells in the county are located in areas stratigraphically below this unit, in valleys where the Ordovician and younger Cambrian formations are absent. The relative low permeability expected of the Oneota (and evidenced by specific capacity of wells completed in the unit) may have a significant impact on regional groundwater recharge patterns (discussed below) and may also be a significant control on runoff of precipitation to streams high in the landscape. For the purposes of this modeling effort, the saturated thickness of Ordovician units is included in the sandstone aquifer hydrostratigraphic unit.

Eau Claire aquitard

The Eau Claire aquitard is present in the southeast portion of Sauk County; its extent and thickness are illustrated in figure 16. We have identified the aquitard by correlating WGNHS geologic logs showing siltstone, shale and interbedded shale and dolomite within the upper portion of the Eau Claire Formation. Hydraulic information also indicates the confining properties of this unit: Sauk City and Prairie du Sac municipal wells that are cased through the siltstone/shale facies and open to the lower Eau Claire Formation and Mount Simon Formation have static water levels at or very near land surface. This interpretation is consistent with the hydrostratigraphic interpretation offered by Bradbury and others (Bradbury et al., 1999) in northwestern Dane County.

Where the Eau Claire aquitard is present, there is little to no sandstone above it. The aquitard typically constitutes the uppermost bedrock and separates the unlithified aquifer from the sandstone aquifer (figures 8 and 9). Where the aquitard is absent, the Eau Claire Formation consists primarily of sandstone that is largely indistinguishable from other sandstones of the Elk Mound Group (Clayton and Attig, 1990).

Quartzite aquifer

In the Baraboo Hills region, where the unlithified and sandstone aquifers are very thin or absent, the relatively impermeable Precambrian quartzite rock is used to supply water for domestic and park wells (Plate 1, fig. 13). In this area, flow to wells is mostly through fractures and overall hydraulic conductivity (K) is low. Within the extent of quartzite aquifer depicted on figure 13, wells completed in sandstone indicate local, discontinuous deposits of sandstone (Parfrey's Glen Formation) within the Baraboo Hills that are also used to supply water to wells. Where the sandstone aquifer is present (fig. 14) the quartzite or other Precambrian crystalline rock units form the base of the sandstone aquifer. This Precambrian surface is highly irregular, ranging from less than 200 to over 1,400 feet above sea level (fig.17).

<u>Groundwater Recharge and Discharge</u>

Many variables, such as soil properties, vegetation, ground surface slope, soil type, and the timing and magnitude of precipitation events, affect the recharge of groundwater by precipitation and snowmelt. For the purpose of this modeling project, we estimated the rate of groundwater recharge by calibrating to estimates of stream flow (further described below). Areas of increased groundwater recharge were delineated based on the aquifer type. For instance, we assumed that recharge is greater where the unlithified aquifer consists of thick deposits of sand and gravel (e.g., outwash plains and alluvial valleys), but is likely more restricted where finer grained glacial lake sediments are present. Little groundwater recharge is expected to occur on the crystalline rock of the Baraboo Hills. Based on observations of Otter Creek, precipitation generally drains off of the Hills through the thin soil cover or surficial deposits, or discharges to local, ephemeral stream systems high up in the landscape. This runoff recharges groundwater where the unlithified or sandstone aquifers occur at the base of the Hills.

Groundwater flows from areas of higher head to lower head, and the water table is typically a subdued reflection of the topography. In this part of the humid Midwest, groundwater generally discharges to surface water bodies and groundwater wells. The water table map of Sauk County (plate 1), illustrates major groundwater discharge features, such as the Baraboo and Wisconsin Rivers, Honey Creek and Dell Creek. The map also indicates that groundwater discharge occurs along many smaller stream systems. In upland areas, flow to these small stream systems may be from groundwater discharge from shallow, local portions of the unlithified aquifer, and not necessarily discharge from the bedrock aquifer. At higher elevations, some surface water features recharge groundwater. For example, in the Baraboo Hills region, Devils Lake recharges the groundwater system (Krohelski and Batten, 1995).

Regional Model Development, Calibration and Results

The purpose of the regional GFLOW model is to provide a single-layer model that can be refined in the areas of interest (municipal wells ZOCs), provide a screening tool to develop appropriate boundary conditions for three-dimensional inset models of complex hydrogeologic areas, and provide an educational tool to illustrate concepts of groundwater flow. The regional model simulates comprehensive groundwater flow in the sense that in some areas of the model domain it represents flow in both the unlithified and sandstone aquifers. In these areas, where the model represents both aquifers in one layer, it simulates an average of the properties of the two aquifers. Over the portions of the model domain where the unlithified aquifer is absent or very thin, the regional model simulates only the sandstone aquifer. The regional model is isotropic, two-dimensional, and does not simulate vertical flow within the aquifer. This simplifying assumption, that flow is predominantly horizontal, is reasonable where the aquifer is regionally isotropic and away from boundaries that induce significant vertical gradients. The Eau Claire aquitard is not explicitly represented in this model. This model does not simulate flow in the quartzite aquifer; the Baraboo Hills are represented as a no-flow area using the horizontal barrier element of GFLOW.

The regional model includes “far-field” and “near-field” elements (Haitjema, 1995). The far-field elements are distant rivers that are simulated with coarse linesinks for the purpose of explicitly defining the regional groundwater-flow field around Sauk County (the near field) (figure 18). Far-field elements are regionally significant features that act as hydraulic boundaries and provide locations where the potential in the aquifer is known with a large degree of confidence. The near field, which includes all of Sauk County, is the primary area of interest and is simulated with much greater detail than the far field.

The GFLOW code requires that "global" parameters, such as model base elevation, K_h and recharge, be defined. These values apply to the entire model domain with the exception of "inhomogeneities", which are parts of the domain that are assigned a unique value for a particular parameter. This regional model is assigned a global base elevation of 450 feet, which is the average elevation of the base of the Cambrian sandstones, estimated from cross-sections provided by Clayton and Attig (1990). Global recharge and K_h values were assigned during model calibration, as described below.

Four parameters are specified for linesinks that represent surface water features: beginning and ending head (stage) elevations, streambed resistance, and width. Streambed sediment resistances in the near field were set within the range of 0.25 to 5 days. Resistance is calculated by dividing the streambed sediment thickness by its vertical hydraulic conductivity (K_v). A value of 1 day (ft / ft/day) corresponds to a 5-foot sediment thickness and a K_v of 5 ft/d. The width of the stream was assigned based upon field observations and stream order, and ranges from 2 to 25 feet with the exception of the Wisconsin River, which was assigned a width of 500 feet. Sensitivity analysis within UCODE demonstrated that model results are affected very little by changes in streambed resistance, so these 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 stream flows to be compared to measured stream flows during model calibration. Near-field linesinks are linked so that surface water is routed from high elevation linesinks to low elevation linesinks. This allows easy determination of the flow in any line sink (reach of stream) and ensures that the amount of water a stream loses to the groundwater system is not greater than the amount available (that is, water delivered from upstream linesinks).

Inhomogeneities, areas within the model that are assigned K_h and recharge values that differ from global values, were added to the model where necessary to achieve a reasonable simulation of the water table. These areas were defined on the basis of mapped geologic units (Clayton and Attig, 1990) and include alluvial and outwash deposits in the Wisconsin River Valley and south of the Baraboo range, and glacial and melt-water deposits north of the Baraboo range (fig. 19 and table 4). A K_h inhomogeneity was also assigned to the Driftless area uplands northwest of the Wisconsin Dells, where water levels reported on WCRs suggest that the K_h of the sandstone aquifer is lower than in other regions.

The crystalline rock of the Baraboo Hills is represented as a series of "horizontal barriers" in the GFLOW model. The horizontal barriers extend to the base model elevation, are assigned a K_h of zero, and act as no-flow boundaries in the model. Two large polygonal barrier elements represent the south limb of Baraboo Hills, and 17 smaller polygons represent the north limb of the Hills (fig. 19). Line sink strings are placed around the exterior perimeters of the barriers and are assigned a negative discharge value to represent focused recharge that occurs at the base of the Baraboo Hills due to runoff of precipitation. The line sink strength (rate of recharge to the aquifer) assigned to these strings was calculated by applying a runoff coefficient of 0.30 to the average precipitation rate (31.5 in/yr) to determine the volumetric runoff from each bluff area. The runoff coefficient and methodology were adapted from Krohelski and Batten (1995). The volumetric runoff was converted to a value for line sink strength based on the length of the perimeter of each barrier polygon.

An iterative process was used to develop and calibrate the regional model. As hydrologic detail was added to the GFLOW model, a UCODE optimization run was completed to determine if sufficient detail was included to obtain a good match to head and stream flow calibration targets. Head targets included depth to groundwater reported on 582 WCRs. The WCRs were selected from those used to construct the water table map (plate 1) based on our confidence in the accuracy of the well location and to provide a good spatial distribution across the county. Many of these WCR wells used as calibration targets are domestic or irrigation wells and are often constructed with a long open interval. Therefore, the reported depths to water represent the average head over which the well is open and are not precise measurements of piezometric head. This well construction design likely has a larger impact on measured water levels in the uplands of Sauk County, where there are strong downward gradients in the bedrock aquifer. Water levels reported in the uplands may be biased low relative to the true water table elevation.

The model was not specifically calibrated to the county water table map (plate 1) because the water table map honors water levels from many domestic wells completed in the Oneota dolomite and surface water elevations of upland streams. Although this is probably an accurate depiction of the water table in the uplands, the two-dimensional nature of the GFLOW code requires that either heterogeneities be put into the model to explicitly represent areas such as the uplands, where K_h of the shallow bedrock units may be different than the deeper sandstone units, or that the overall global K_h used in the model represent a composite of hydraulic conductivities expressed in the calibration targets. Because the purpose of this model was to simulate flow to the municipal wells, we chose to calibrate to head targets that would reflect more of the properties of the deeper sandstone units rather than calibrate to the shallow water table map. One implication of this decision is that the regional model may simulate groundwater flow patterns more accurately in the lower-lying areas of the county than in the uplands.

Seven stream flow targets were selected from existing stream flow data from the U.S. Geological Survey and included in the regional model calibration (table 5). (Additional miscellaneous measurements collected as a part of this project for the Wisconsin Dells inset model are reported in appendix 6 to this report.) Measured stream flow was used to estimate 50 and 80 percent flow duration (the flow rate that is equaled or exceeded 50 % [Q_{50}] or 80 % [Q_{80}] of the time) for each site. Baseflow is generally assumed to fall between the Q_{50} and Q_{80} (e.g. Krohelski and others, 2000). Because the GFLOW model is a steady state simulation, simulated stream flows are assumed to represent baseflow conditions. Q_{80} data were selected as the targets for the final optimization and calibration runs because initial results indicated that they could be simulated using rates of K_h and recharge that resulted in a better match to head targets.

For model optimization with UCODE, each calibration target was assigned a weight based on the uncertainty associated with the measurement. Lower weights are given to targets with higher uncertainty. Hill (1998) provides a detailed explanation of assigning target weights and the statistical methods used to evaluate model sensitivity to parameters. All groundwater level measurements were assigned a weight of 0.1 (expressed as a standard deviation). The stream flux targets were assigned a weight of 0.01, 0.05 or 0.2 (expressed as a coefficient of variation) (table 5).

Preliminary UCODE runs indicated that the model was not sensitive to aquifer base elevation or streambed resistance, so these parameters were fixed at the values cited above. UCODE was used to optimize K_h and recharge values because the statistics of model sensitivity calculated by UCODE demonstrated that there were sufficient calibration targets to support estimation of these parameters. Optimized values are reported in table 4. The same recharge value was assigned to the three heterogeneities that represent portions of the unlithified aquifer the UCODE runs to preserve the simple framework appropriate for this regional screening model. The optimized K_h values are within the range of values determined from specific capacity and pumping test data on record for high-capacity wells in Sauk County (table 6).

The regional recharge rate arrived at by UCODE optimization, 5.2 in/yr, is similar to the average recharge rate of 5 in/yr applied in a model of Dane County (Krohelski et al., 2000). The higher recharge rate of 10.2 in/yr applied to heterogeneities that represent the unlithified aquifer is comparable to the 12.7 in/yr determined for sand and gravel deposits in Rock County by Gaffield and others (2002).

Unweighted statistics comparing measured groundwater levels to calibrated model results include an average difference of 4.1 feet, with a root mean square (RMS) difference of 23.6 feet. Simulated water table elevations are generally well distributed about the measured values, however the model underestimates the highest water level measurements (figure 20). This may be due to the two-dimensional nature of this model, which represents the sandstone aquifer sequence as a single hydrogeologic unit. Although additional heterogeneities could be have been added to this regional model to more closely match observed water levels (for example, in the western uplands of Sauk County, most wells are completed in the Oneota dolomite, which may have a lower K than the underlying sandstones), this was not deemed necessary because the municipal wells of interest in this study are not located in these areas. The quality of calibration was also judged by the distribution of residuals across the model domain (fig. 20); positive or negative errors in the simulated values are not clustered within the domain. A good match between simulated and measured stream flows was also obtained for the flux targets (table 5). The match to stream flows may have been improved by an increase to recharge, however an increase in recharge would need to be off-set by a decrease in K_h in order to match head targets.

Municipal Well ZOCs

ZOCs for municipal wells in Sauk County were simulated using refined versions of the regional model for areas where the two-dimensional approach of the regional model was appropriate, or with three-dimensional MODFLOW models in more hydrogeologically complex settings (table 3). Documentation for each refined or inset model, including descriptions of development, calibration and results are presented in appendices to this report. Conclusions from the inset models are summarized below. The boundaries of the MODFLOW inset models and the area of the regional GFLOW model refined for the Wisconsin Dells / Lake Delton area are show on plate 2. Model domains for Merrimac and wells in the northwest are not shown on plate 2 because changes to the regional model for these wells were limited to refining stream linesinks in the areas of interest. 5-, 50- and 100-year ZOCs for all municipal wells are presented on plate 2. The ZOCs differ in shape and size as a result of the varied hydrogeologic setting, well construction and pumping rates at each location.

In the town of Merrimac (appendix 1), the model indicates that the primary source of groundwater to Well #1 is relatively recent recharge that falls to the northwest. It is very unlikely that Lake Wisconsin contributes water to the well. The 100-year and 50-year ZOCs are identical because the capture zone intersects the water table at a travel time of approximately 14 years.

Reedsburg, LaValle, Ironton, Loganville, the Sauk County Health Center wells have similarly shaped ZOCs because these wells are all completed in the sandstone aquifer in an area where is assigned uniform properties in the model (appendix 2). The size of these ZOCs varies because of the higher pumping rates assigned to some wells. The ZOCs for the Reedsburg municipal wells intersect in complex patterns because of their relative proximity to each other and to two industrial high-capacity wells located in Reedsburg.

In Plain and Spring Green, flow between the unlithified and sandstone aquifers is considered in simulating the ZOCs (appendix 3). The model shows that flow to the Plain wells is from the northwest (plate 2) and that there are strong upward gradients from the sandstone to the overlying alluvium. Both Plain wells, which are cased through the alluvium, receive all of their water within the 100-year travel time from the sandstone aquifer.

A majority of the flow to Spring Green #2, which is completed in the sand and gravel aquifer, originates from the sand and gravel. Some particles tracked from this well originate from the bedrock aquifer because of strong upward gradients from the bedrock to the unlithified aquifer in the Wisconsin River valley. The ZOC for Spring Green #1 is greatly affected by the half capacity pumping rate used in the simulation (which is large compared to the actual pumping rate); the higher pumping rate causes reversal of vertical gradients at the well so that the well, which is cased into the sandstone, receives some flow from the sand and gravel aquifer. This ZOC has a long tail to the north because of the rapid flow rates in the upper aquifer; particles that originate in the upper aquifer have much longer flow paths than particles that originate in the bedrock. The model does not simulate a reversal of vertical gradients when Spring Green #1 is assigned its actual average pumping rate. The model shows that the upper and lower aquifers are well connected, and that under the half-capacity pumping rates, both Spring Green wells receive some groundwater flow from both the sand and gravel and bedrock units.

Flow between the upper, unconfined aquifer, the Eau Claire aquitard and the Mt. Simon aquifer are considered in the Sauk City / Prairie du Sac inset model (appendix 4). Sauk City #5, which is cased through the aquitard, receives all of its water within the 100-year travel time from the Mt. Simon. Particle traces from Prairie du Sac #3 and Sauk City #4, which are open to part of the Eau Claire aquitard as well as the Mt. Simon aquifer, show that these wells are fed predominantly by the sandstone aquifer but receive a small portion of flow from the aquitard. The model demonstrates that the aquitard restricts upward flux of water from the Mt. Simon to the Wisconsin River, and groundwater in the Mt. Simon underflows the Wisconsin River.

The long and narrow ZOC simulated for Prairie du Sac #2, completed in the sand and gravel aquifer, shows that most of the recharge area for the well is to the northwest. Both the 50- and 100-year particle traces extend to the upper portions of Otter Creek, which is a losing stream. This ZOC also extends east of the well because some particle traces discharge vertically from the underlying aquitard to the unlithified aquifer.

A three-dimensional model was used to determine the ZOCs for Baraboo, North Freedom and Rock Springs (appendix 5) because the flow field is expected to be very complex where these municipal wells are located near the Baraboo Hills. The Baraboo quartzite is represented as a no-flow boundary in this model, and enhanced recharge to the aquifer from runoff from the Hills is simulated with injection wells along the boundaries. The ZOCs (plate 2) indicate that flow to these wells is generally from the west and southwest. The 50- and 100-year ZOCs for some of these wells are strongly influenced by the location of the no-flow boundaries in the model. For example, the capture zone of Baraboo #7 extends to the southern no-flow boundary of the model, implying that the enhanced recharge from the Hills reaches the well within 50 years. Similarly, the ZOCs of Baraboo #4 and North Freedom #2 are largely determined by the location of the Hills relative to the wells. These ZOCs are designated on plate 2 as having an increased level of uncertainty associated with them because the model results are constrained by the representation of the Baraboo Hills; this representation is based on limited data regarding the spatial extent of the Hills and the rate of runoff from them. The North Freedom ZOC should also be used cautiously because groundwater flow direction with respect to the well is very sensitive to the pumping rate assigned to the well.

The ZOC for Rock Springs well #1 is bifurcated; a portion of the flow to the well comes from the west, up the Narrows Creek valley, and a portion from the south of the creek. The model shows that the well receives groundwater from both the unlithified and sandstone aquifers. The extent of the ZOC is strongly influenced by the location of the no-flow boundary with respect to the Narrows Creek valley and the model representation of runoff from the bluffs.

The regional GLFOW model was refined in the vicinity of Wisconsin Dells / Lake Delton to simulate the ZOCs for wells in this area (appendix 6). A large proportion of the area of interest in this inset model is encompassed by the northern glacial inhomogeneity, representing glacial sediments to the east of the Dells, and an inhomogeneity representing the uplands west of the Dells. The inhomogeneity boundaries were refined in this model but the recharge and K_h values were not changed from those used in the regional model. All of the municipal wells in this inset model are completed in the sandstone aquifer in areas where the unlithified aquifer is thin or absent.

Only the 5-year ZOCs are shown on plate 2 for Wisconsin Dells wells located in Columbia County (wells #1, 2, 3, and 6) because the model was not calibrated to local conditions in Columbia County, and the quality of model simulations for 50- and 100-year travel times could not be evaluated. The 5-year ZOCs for these wells are shown here because their flow paths are relatively close to the Wisconsin River, where this model is expected to be a reasonable representation of hydrologic conditions.

Flow paths to Wisconsin Dells #4 originate from the northwest; the 100-year ZOC includes land in Juneau County. Flow to Wisconsin Dells #5, and Lake Delton #3 and #5 is from the west while flow to Lake Delton wells #1 and #2 is from the south. Backwards particle tracking from Lake Delton #4, located at the eastern end of Lake Delton, showed that flow paths originate from within the line sinks representing Lake Delton. This suggests that in addition to the sandstone aquifer underlying the lake, Lake Delton itself may be a source of water to this well. Field work would be necessary to confirm gradients between the lake and underlying aquifer prior to using the model to estimate the extent to which Lake Delton recharges the aquifer and ultimately provides water to the well. The 50- and 100-year ZOCs for this well also terminate within the aquifer underlying the lake.

Conclusions

This report summarizes development of groundwater flow models and the simulation of ZOCs for municipal wells in Sauk County, and leads to the following conclusions:

At a county-wide scale, a hydrogeologic conceptual model of Sauk County includes three aquifers and one aquitard. An unlithified aquifer consists of glacial and alluvial deposits that vary in composition from sand and gravel to clayey tills and lake sediments. This aquifer is absent in much of the uplands of western Sauk County, but consists of over 200 feet of permeable sand and gravel deposits in the Wisconsin River valley.

A sandstone aquifer consists of all saturated bedrock units above the Precambrian crystalline rock, with the exception of some portions of the Eau Claire Formation. The sandstone aquifer underlies the unlithified aquifer where the unlithified aquifer is present and is the uppermost aquifer in upland areas where the depth to bedrock is small and the surficial deposits are unsaturated. In the uplands, this aquifer includes some dolomite, such as the Oneota Formation, that is likely lower K than some of the underlying sandstone units. The Tunnel City Formation is also reported to contain some shale sequences that may restrict groundwater flow on a local scale. In areas of the county where the Eau Claire aquitard is not present, the sandstone aquifer is in good hydraulic contact with the overlying unlithified aquifer.

A relatively low-permeability, quartzite aquifer supplies small volumes of water to domestic and park wells in areas of the Baraboo Hills where there is no overlying sandstone or unlithified aquifer. The overall K of the quartzite is low and flow to wells is predominantly through fractures. This same geologic unit is characterized as the bottom boundary to the sandstone aquifer where the sandstone aquifer is present because of their relative difference in permeability.

The shale facies of the Eau Claire Formation is present at thicknesses ranging to over 200 feet in the southeast portions of Sauk County. The shale thins to the west and is not present over much of the county. Where present, this facies is an aquitard, restricting vertical flow between the unlithified and sandstone aquifers.

The two-dimensional regional groundwater flow model presented here is adequate for simulating groundwater flow to wells where path lines are predominantly horizontal, such as areas of the county where wells are completed in a thick sequence of the sandstone aquifer. This model may do a poor job of simulating flow to wells and streams in the uplands, where lower permeability units (e.g. the Oneota dolomite) that are located higher in the stratigraphic sequence of the sandstone aquifer are not explicitly represented in the two-dimensional model. Three dimensional inset models developed for hydrogeologically complex areas of the county are useful to simulate flow in the vicinity of Baraboo, Spring Green and Sauk City/Prairie du Sac.

Almost all of the groundwater pumped in Sauk County originates as recharge in the county. Steady-state ZOCs limited by travel times of 100 years show that most of the municipal wells produce water that originates as recharge within about 2 miles away. The ZOCs should be useful for delineating source water assessment areas and for wellhead protection planning.

References cited

Anderson, M. P. and W.W. Woessner (1992). Applied Groundwater Modeling. San Diego, Academic Press.

Born, S. M., D.A. Yanggen, A.R. Czecholinski, R.J.Tierney, and R.G. Hennings, 1988. Wellhead-protection districts in Wisconsin: an analysis and test applications, Wisconsin Geological and Natural History Survey Special Report 10, 75p.

Bradbury, K. R. and E.R. Rothschild, 1985. A computerized technique for estimating the hydraulic conductivity of aquifers from specific capacity data. Groundwater **23**(2): 240-246.

Bradbury, K. R., S.K. Swanson, J.T. Krohelski, and A.K.Fritz, 1999. Hydrogeology of Dane County, Wisconsin, Wisconsin Geological and Natural History Survey, Open File Report 1999-04, 66p.

Clayton, L. and J.W. Attig, 1990. Geology of Sauk County, Wisconsin, Wisconsin Geological and Natural History Survey Information Circular 67, 68p.

Dalziel, I. W. D. and R.H. Dott, Jr. (1970). Geology of the Baraboo District, Wisconsin: a description and field guide incorporating structural analysis of the Precambrian rocks and sedimentologic studies of the Paleozoic strata, Wisconsin Geological and Natural History Survey Information Circular 14, 164p.

Franke, O.L., T.E. Reilly, D.W. Pollock, and J.W. LaBaugh, 1998. Estimating areas contributing recharge to wells, United States Geological Survey Circular 1174, 14p.

Freeze, R.A. and J.A. Cherry, 1979. Groundwater. Englewood Cliffs N.J., Prentice Hall. 604p.

Gaffield, S., M. Gotkowitz, and K. Bradbury, 2002. Delineation of zones of contribution for municipal wells in Rock County, Wisconsin. Wisconsin Geological and Natural History Survey Open-File Report 2002-02, 48 p.

Haitjema, H. M., 1995. Analytic element modeling of groundwater flow. San Diego, Academic Press. 394p.

Hill, M.C., 1998. Methods and guidelines for effective model calibration, United States Geological Survey Water-resources Investigations Report 98-4005, 90p.

Hunt, R.J., M.P. Anderson and V.A. Kelson, 1998. Improving a complex finite-difference ground water flow model through the use of an analytic element screening model. Groundwater **36**(6): 1011-1017.

Hunt, R.J., Y.-F. Lin, J.T. Krohelski and P.F. Juckem, 2000. Simulation of the shallow hydrologic system in the vicinity of Middle Genesee Lake, Wisconsin, using analytic elements and parameter estimation, United States Geological Survey Water-Resources Investigations Report 00-4136.

Krohelski, J. T. and W.G. Batten, 1995. Simulation of stage and the hydrologic budget of Devils Lake, Sauk County, Wisconsin, United States Geological Survey Open-File Report 94-348. 22p.

Krohelski, J.T., K.R. Bradbury, R.J. Hunt, and S.K. Swanson, 2000. Numerical simulation of groundwater flow in Dane County, Wisconsin, Wisconsin Geological and Natural History Survey Bulletin 98. 31p.

Poeter,E.P. and M.C. Hill, 1998. Documentation of UCODE, a computer code for universal inverse modeling, United States Geological Survey water-resources investigations report 98-4080. 116p.

Strack,O.D.L. (1989). Groundwater mechanics. Englewood Cliffs, New Jersey, Prentice Hall.

U.S. Geological Survey, 2001, National elevation dataset. Online; available at URL: <http://gisdata.usgs.net/ned/>.

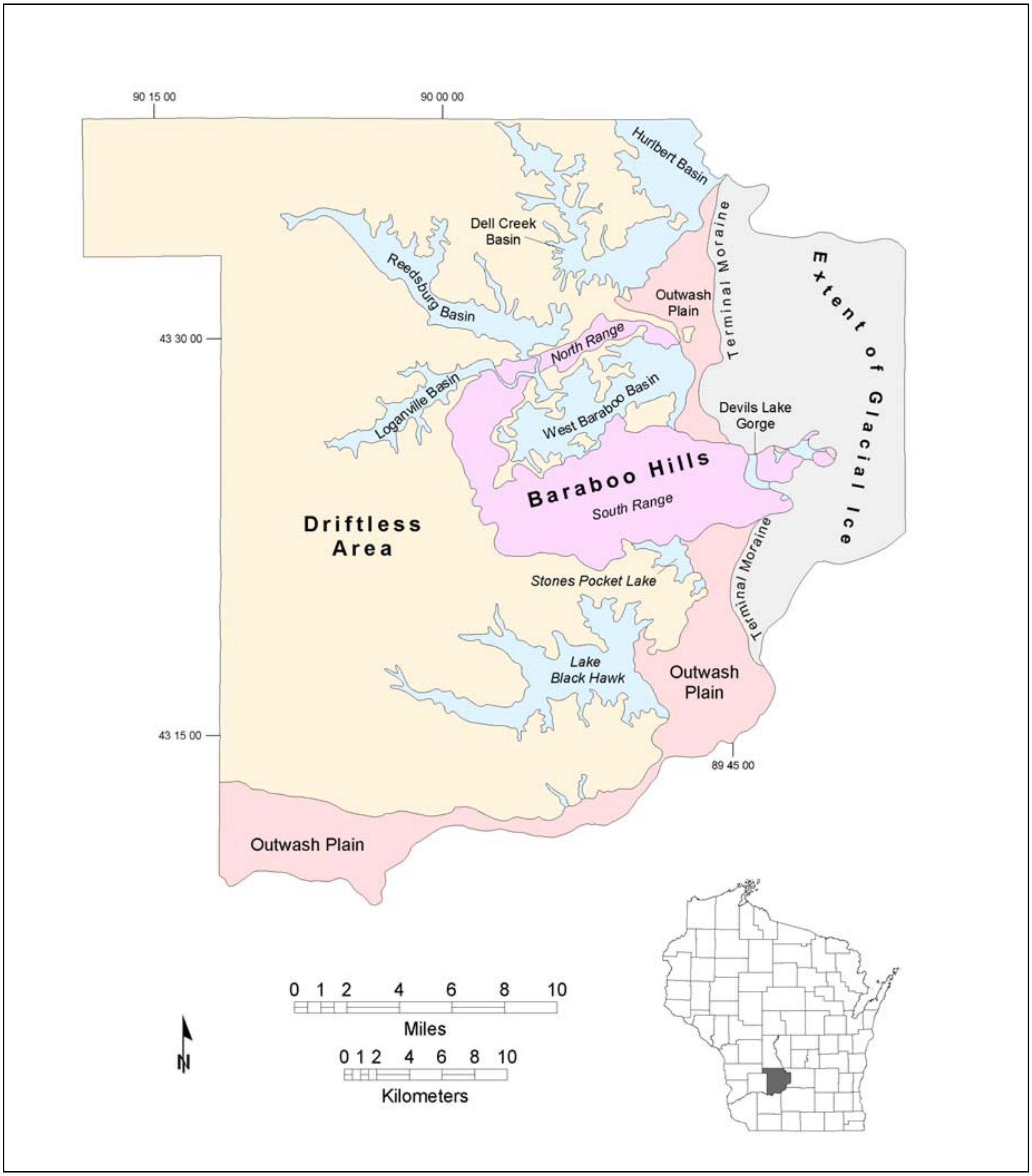

Figure 1. Location of Sauk County and its physiographic regions.

Age	Group	Formation	Description
Pleistocene		Rountree and others	Clayey sand
Ordovician	Ancell	St. Peter	Sandstone
	Prairie du Chien	Oneota	Dolomite
Cambrian		Jordan	Sandstone
		St. Lawrence	Siltstone, sandstone and dolomite
		Tunnel City	Sandstone
	Elk Mound	Wonewoc	Sandstone
		Eau Claire	Sandstone or shale
		Mt. Simon	Sandstone
Precambrian		Baraboo	Predominantly quartzite

Figure 2. Generalized geologic units in Sauk County showing relative position and age (modified from Clayton and Attig, 1990).

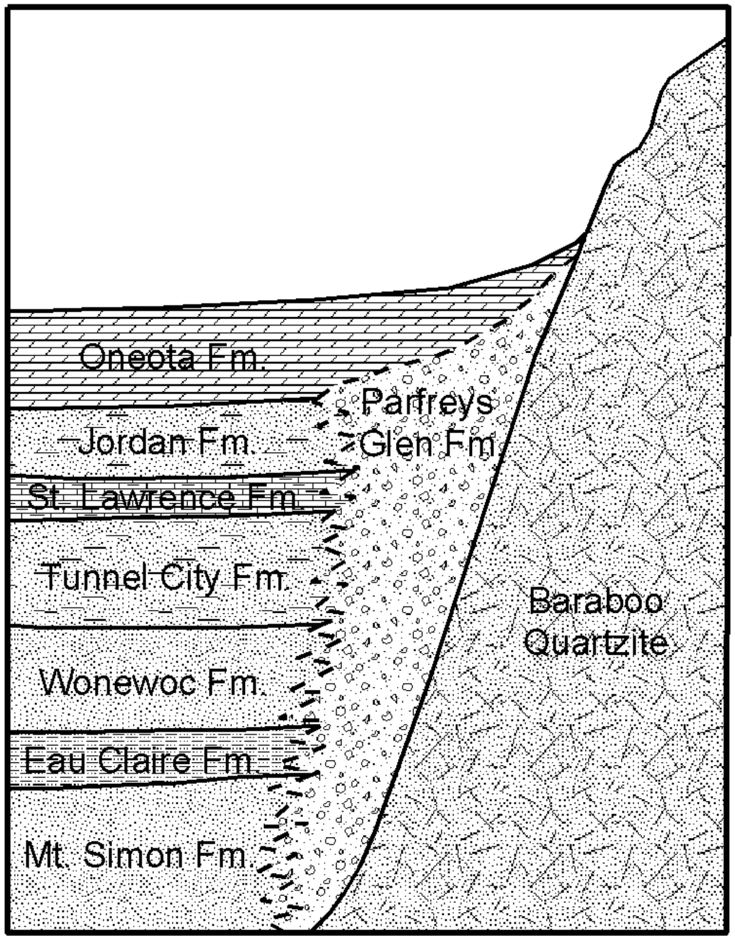

Figure 3. Generalized cross-section showing relationship between sandstone aquifer units and the Baraboo quartzite
(modified from Clayton and Attig, 1990.)

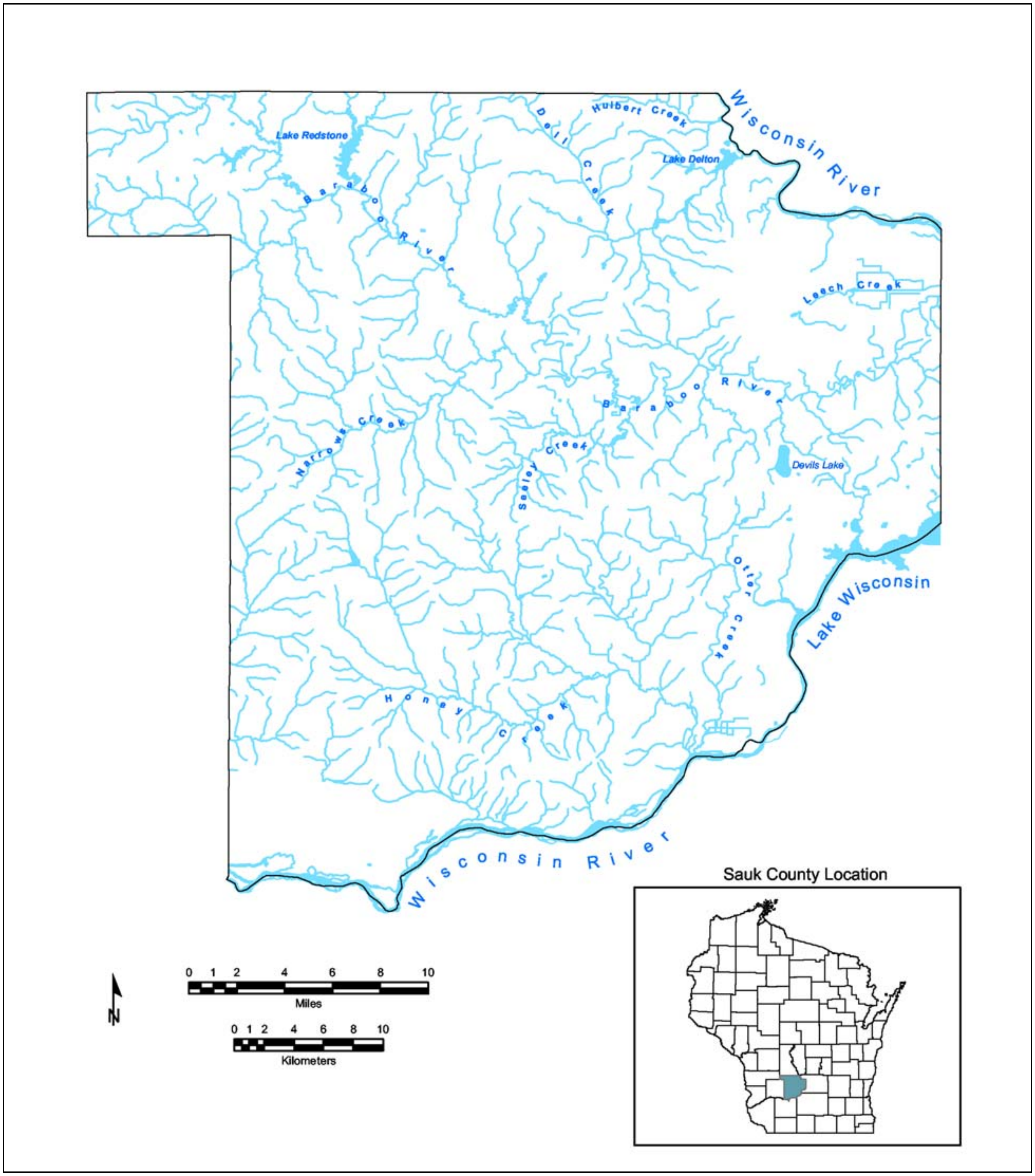

Figure 4. Major hydrologic features of Sauk County.

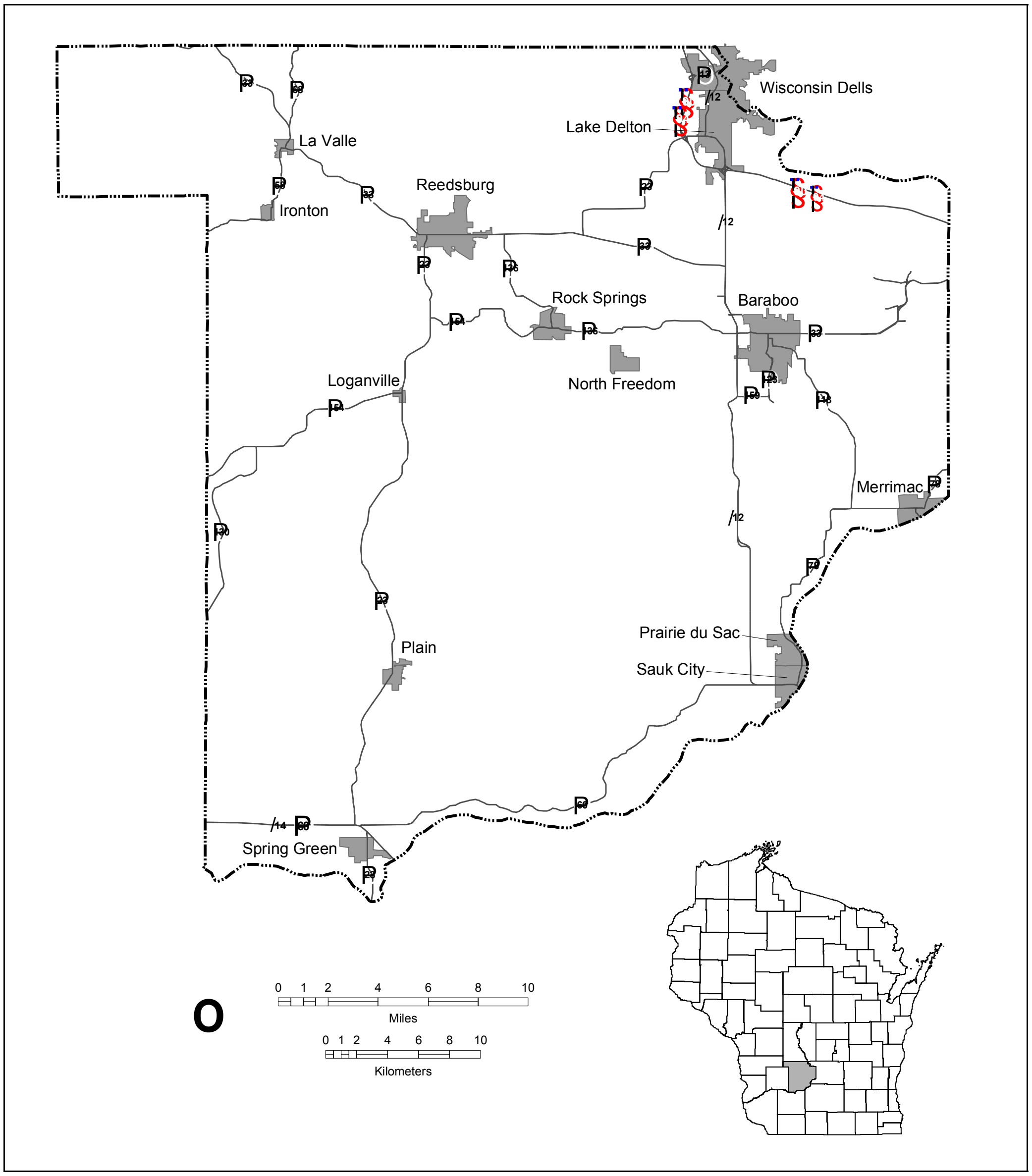

Figure 5. Locations of communities with municipal wells in Sauk County.

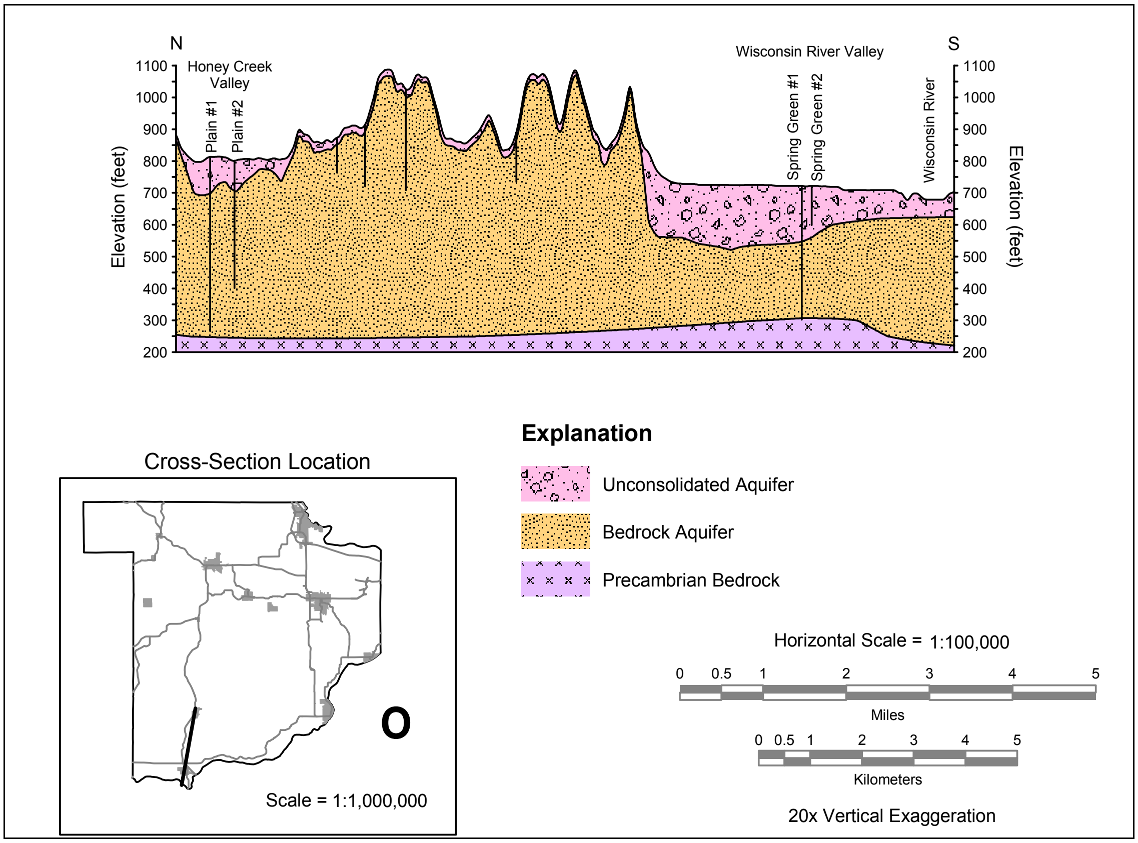

Figure 6. Cross-section from Plain through Spring Green.

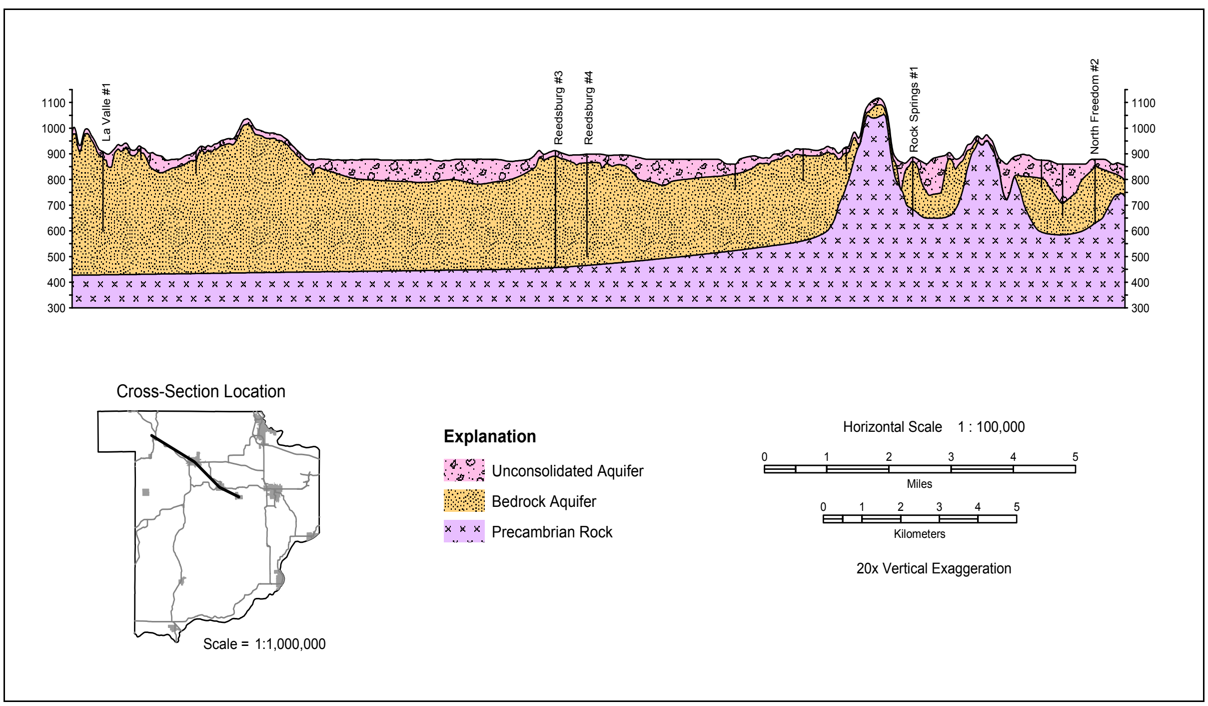

Figure 7. Cross-section from LaValle through North Freedom.

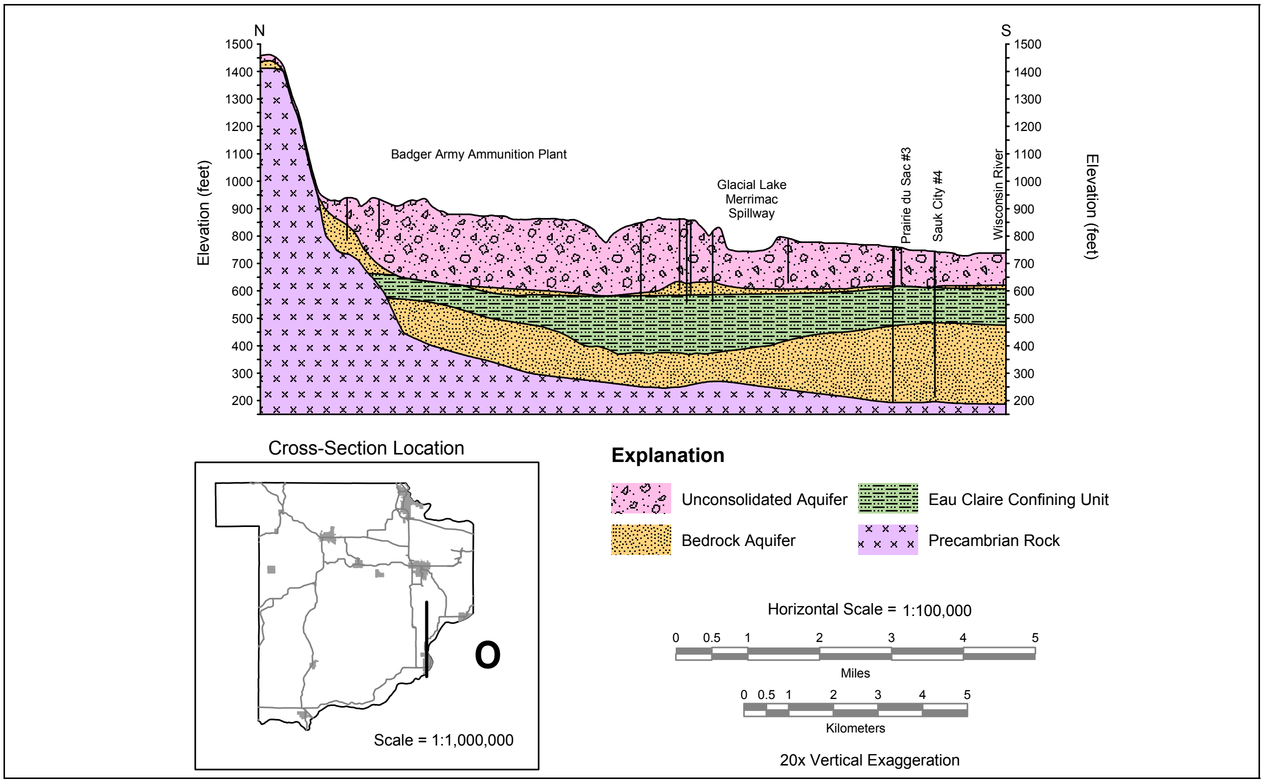

Figure 8. North-south cross section through Prairie du Sac area.

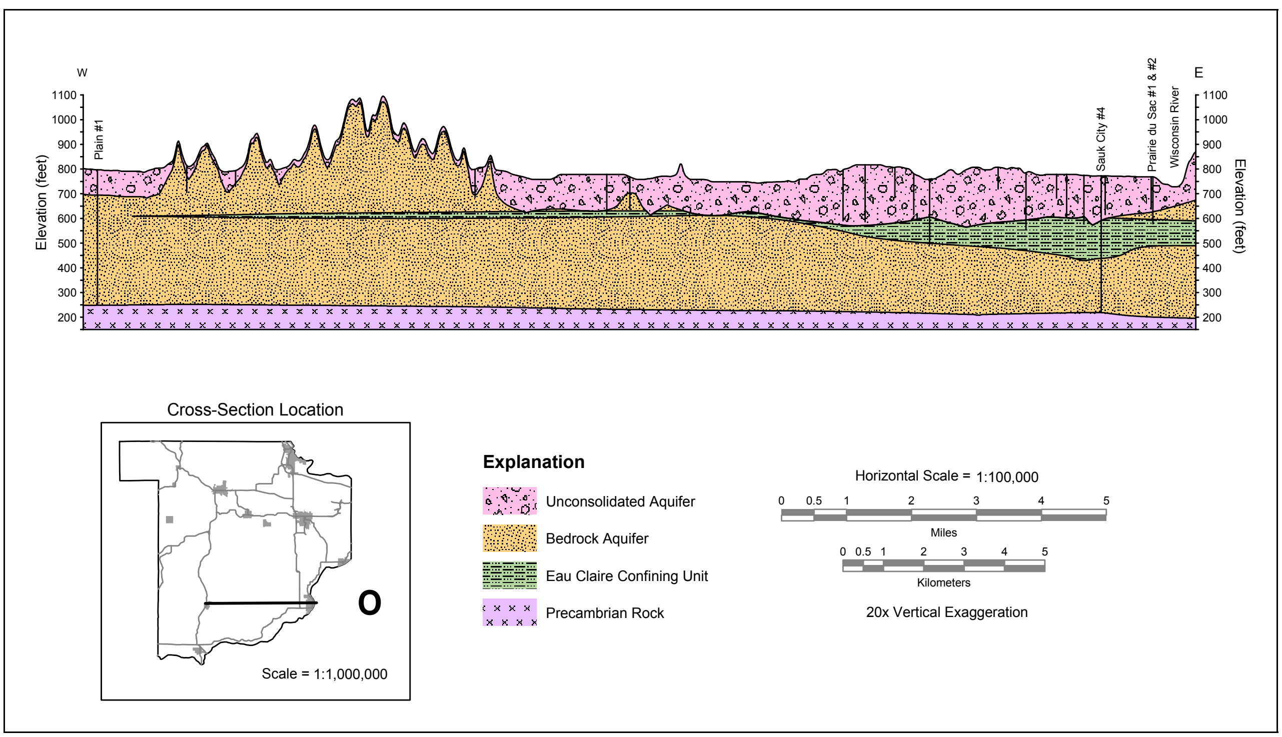

Figure 9. Cross-section from Plain to Prairie du Sac area.

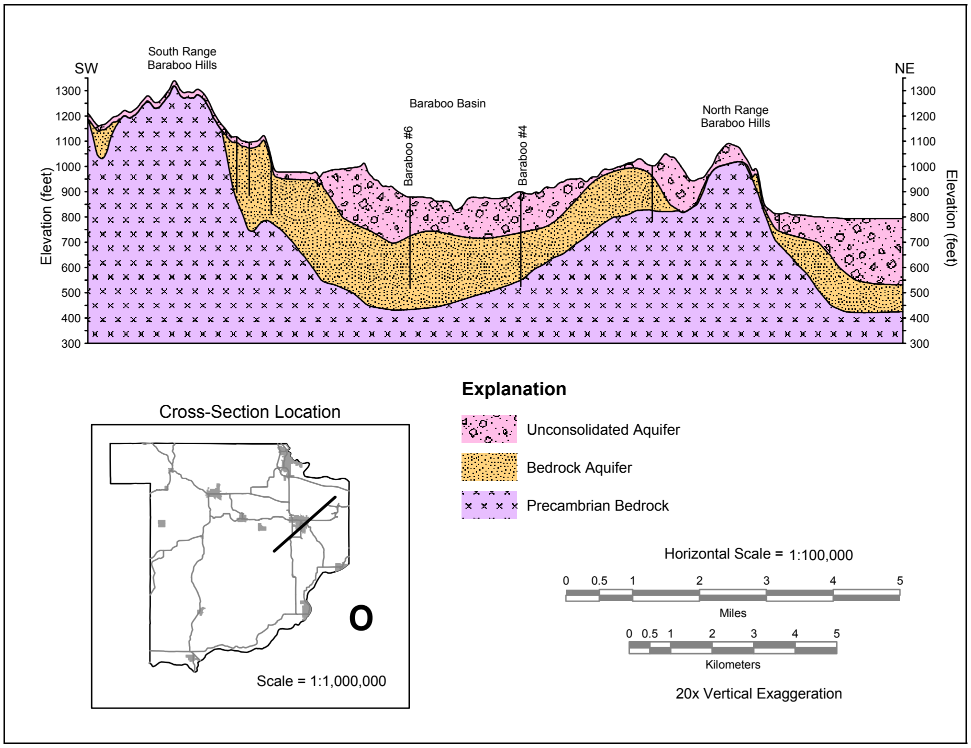

Figure 10. Cross-section through the Baraboo Basin, southwest to northeast.

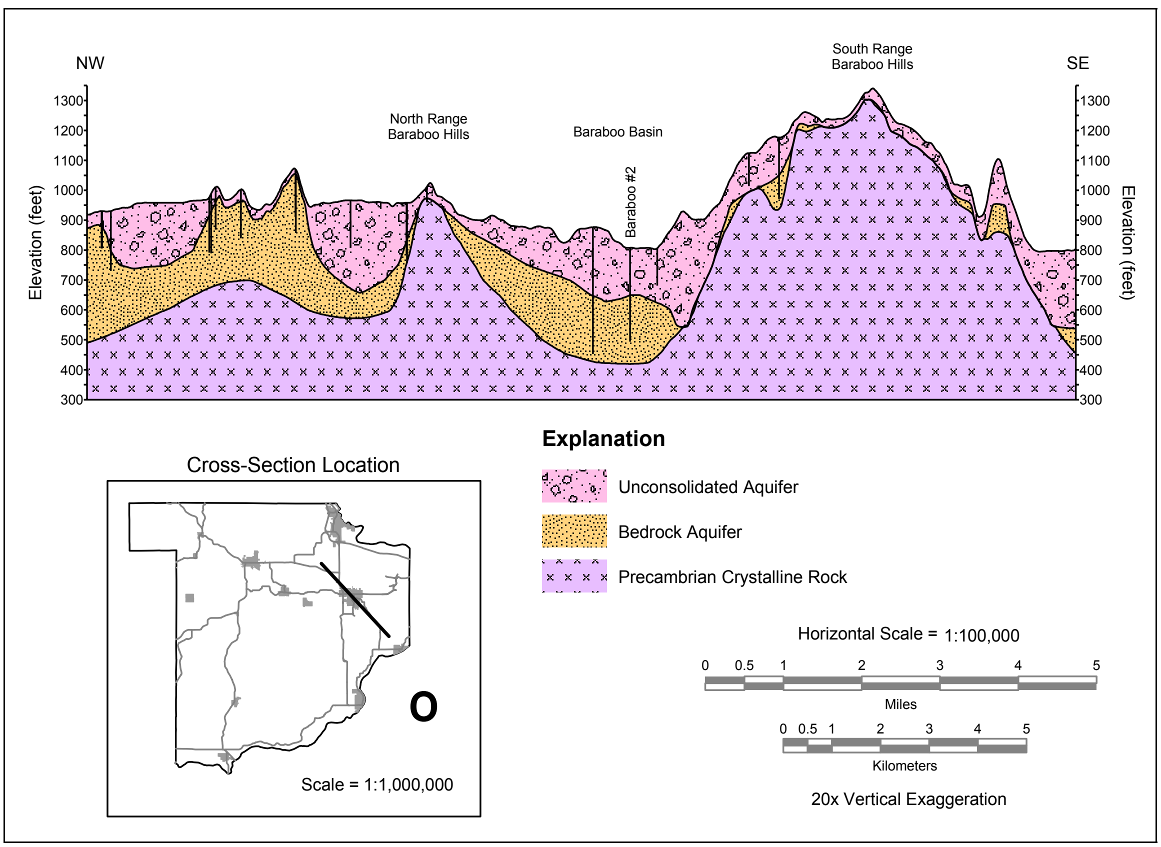

Figure 11. Cross-section through Baraboo Basin, northwest to southeast.

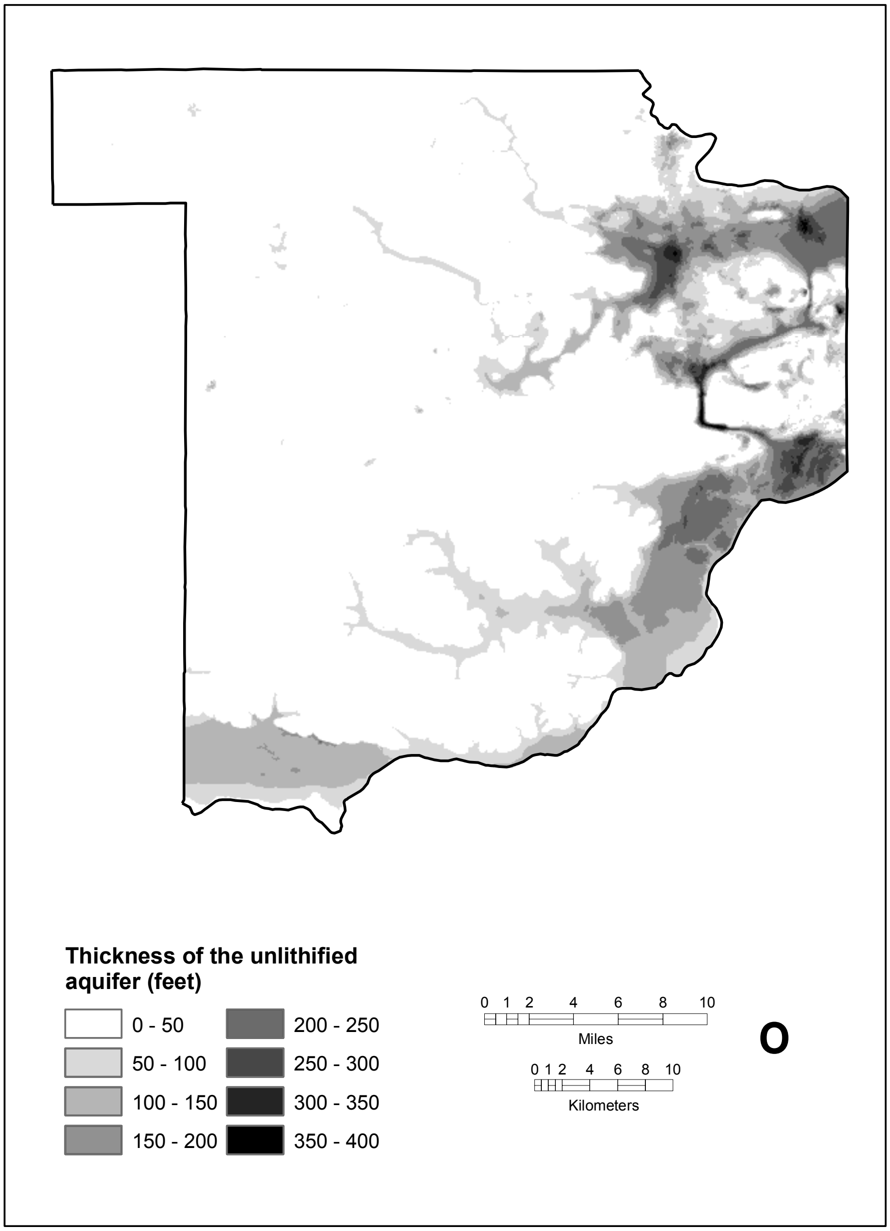

Figure 12. Thickness and extent of the unlithified aquifer.

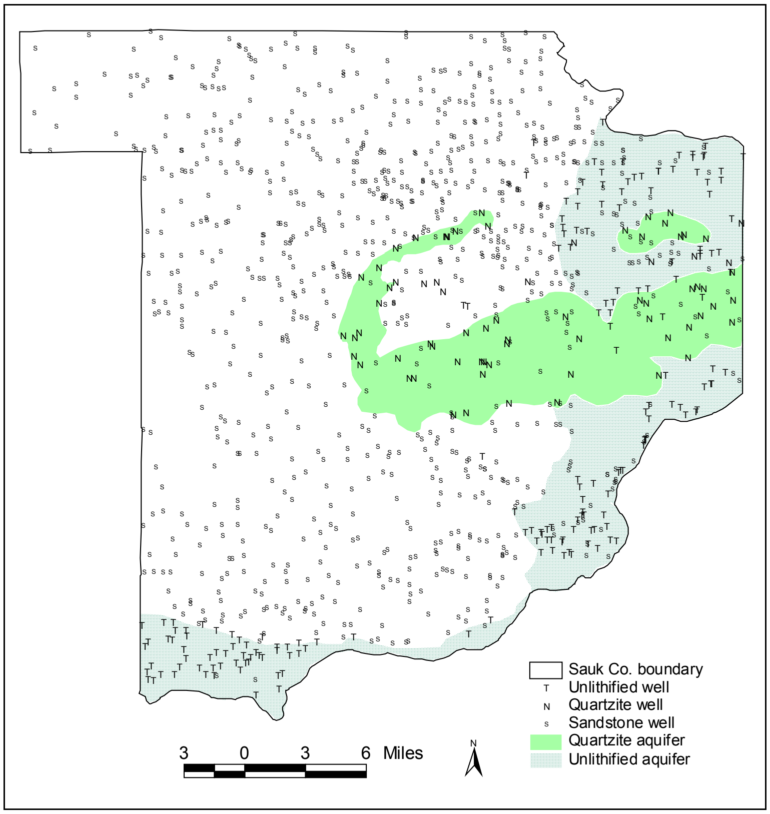

Figure 13. Aquifer and well type across Sauk County.
Area where sandstone is primary aquifer is shown in white. Extent of quartzite and unlithified aquifers are approximate. Where the unlithified aquifer is present, some wells are also completed in the underlying sandstone aquifer. Where the quartzite aquifer is shown, wells completed in the unlithified or sandstone aquifer indicate that the surficial deposits or sandstone are locally present at sufficient thickness to yield water to wells. .

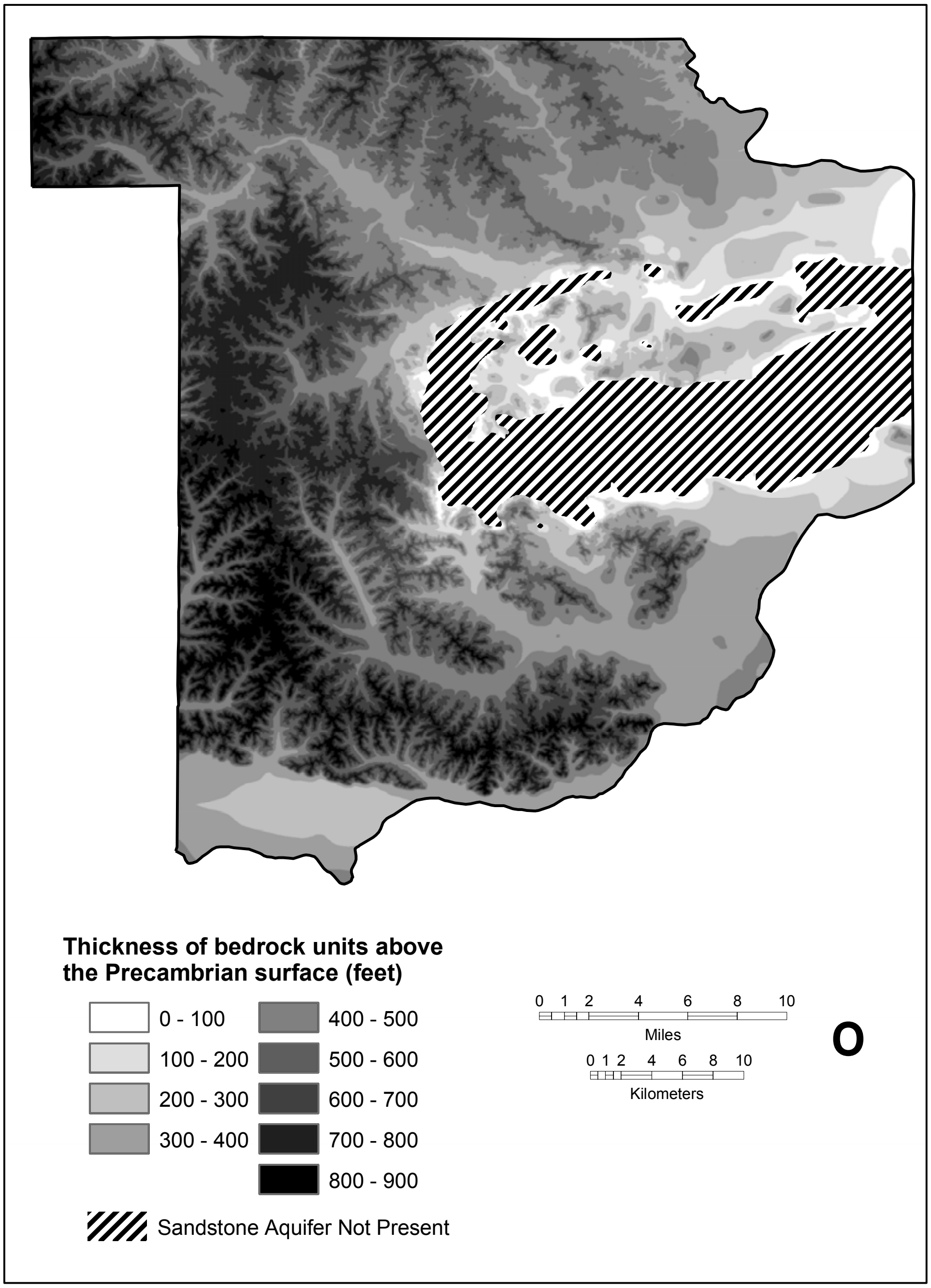

Figure 14. Thickness and extent of the bedrock above the Precambrian basement.

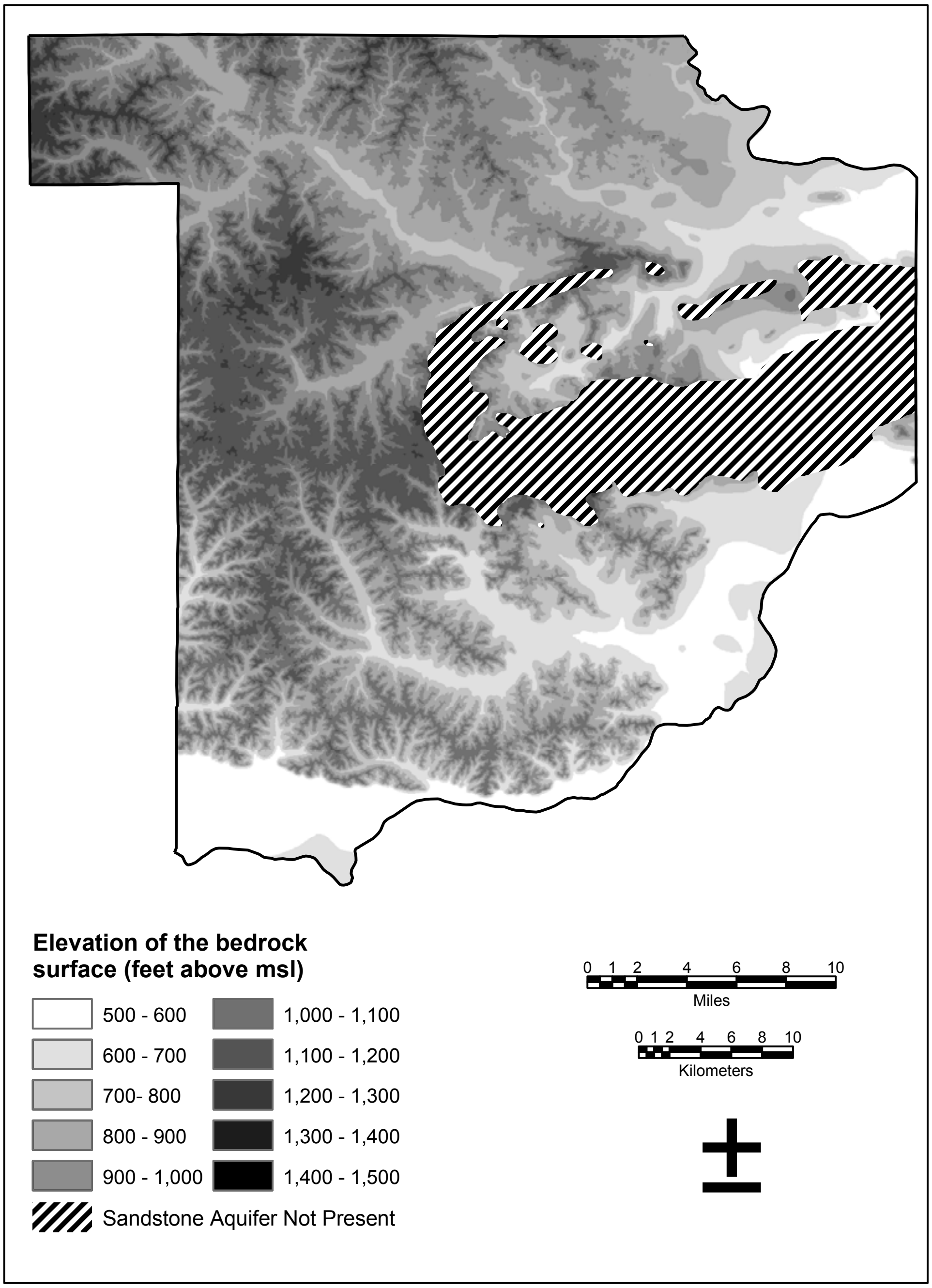

Figure 15. Elevation of the bedrock surface.

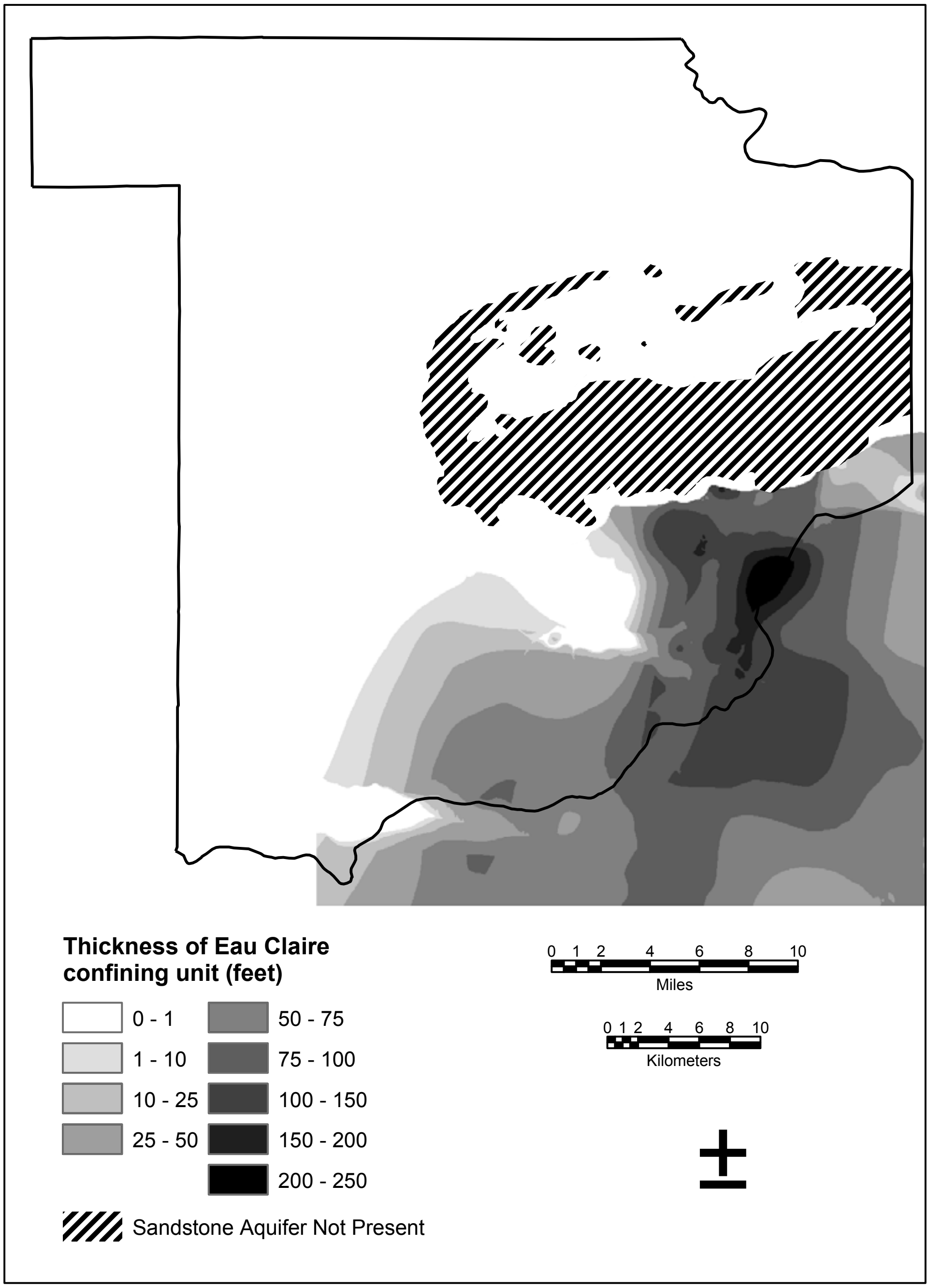

Figure 16. Thickness and extent of the Eau Claire Aquitard.

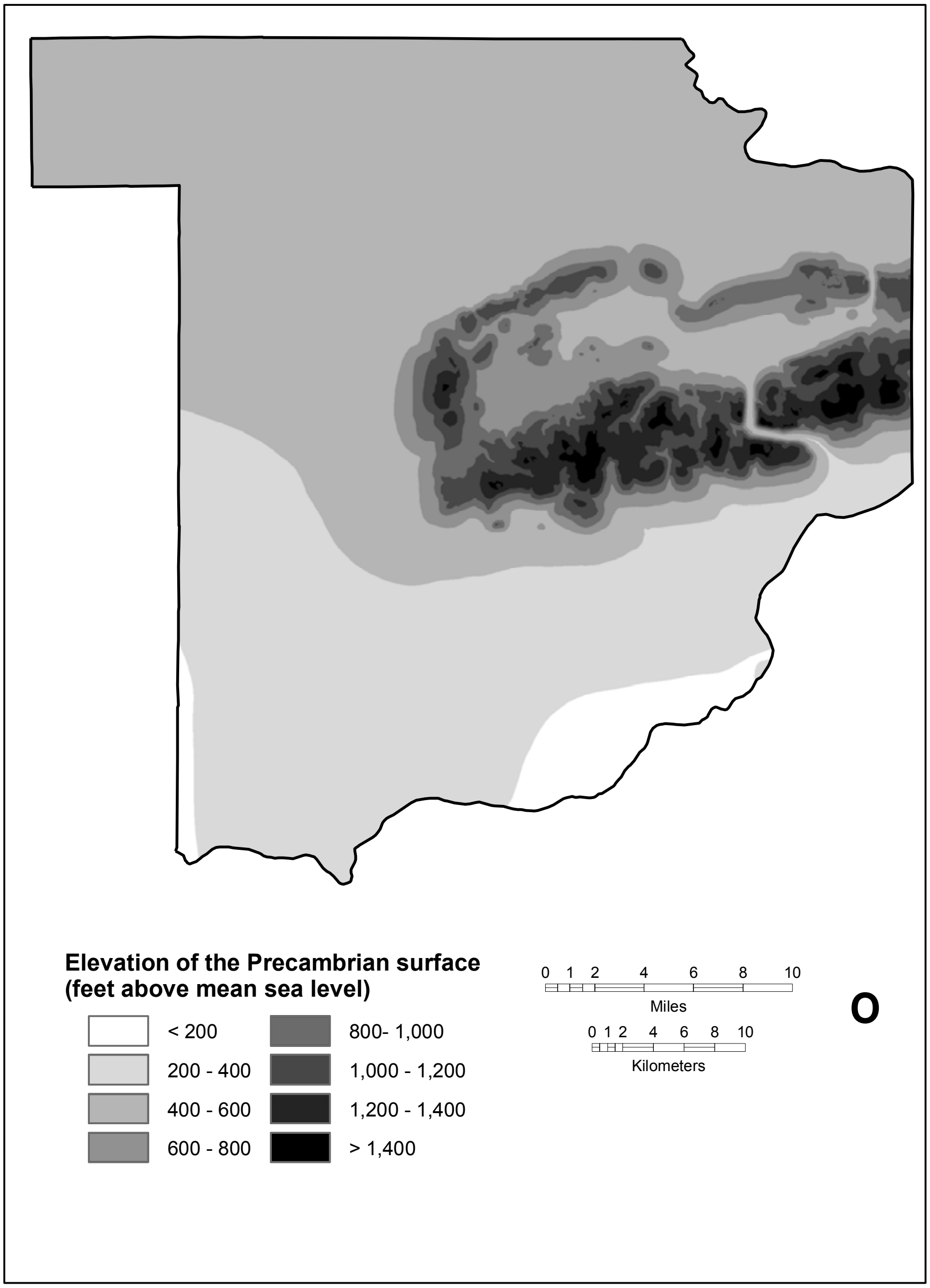

Figure 17. Elevation of the Precambrian surface.

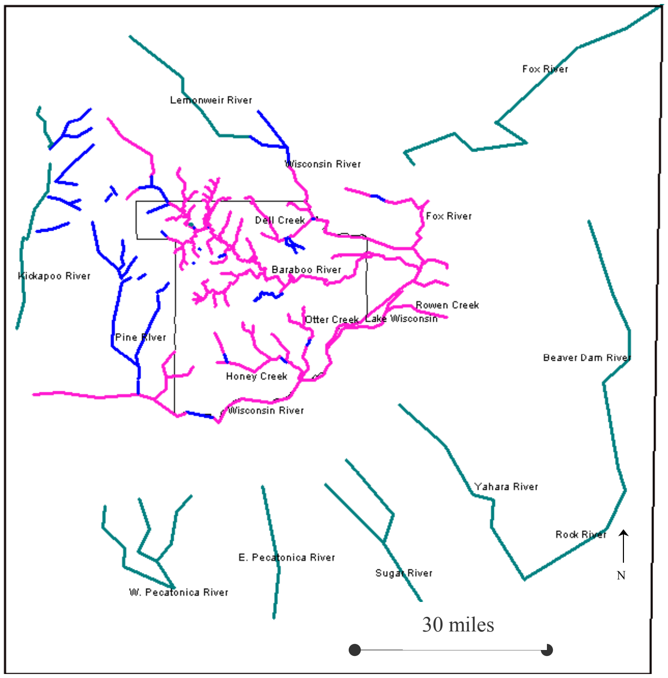

Figure 18. Far-field and near-field features in the regional flow model.

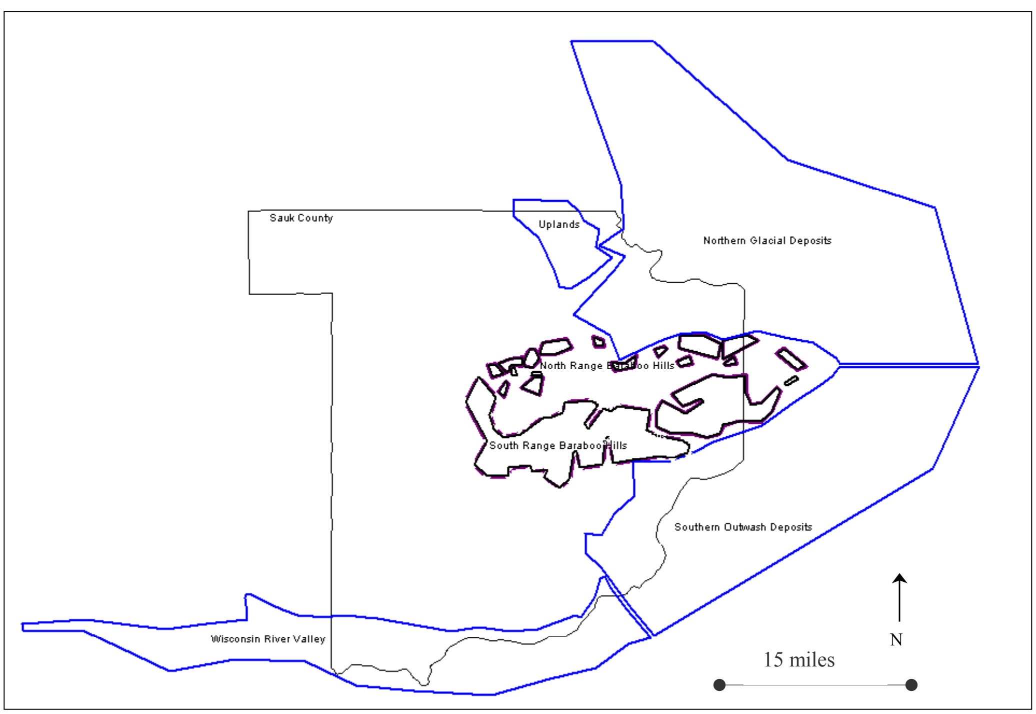

Figure 19. Inhomogeneities in the regional flow model.

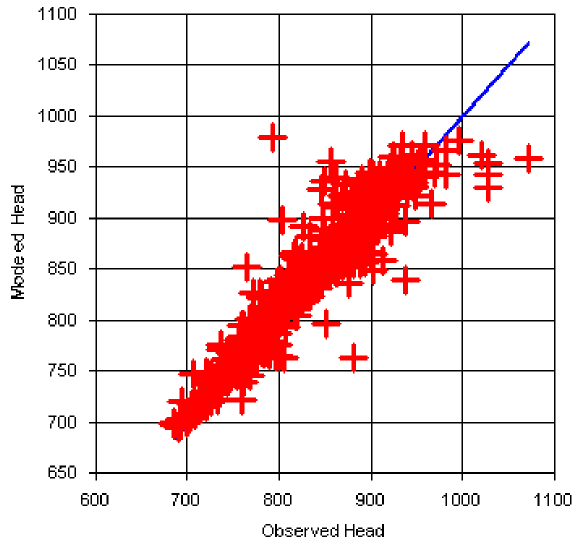

Figure 19. Simulated versus observed water levels for the regional GFLOWmodel

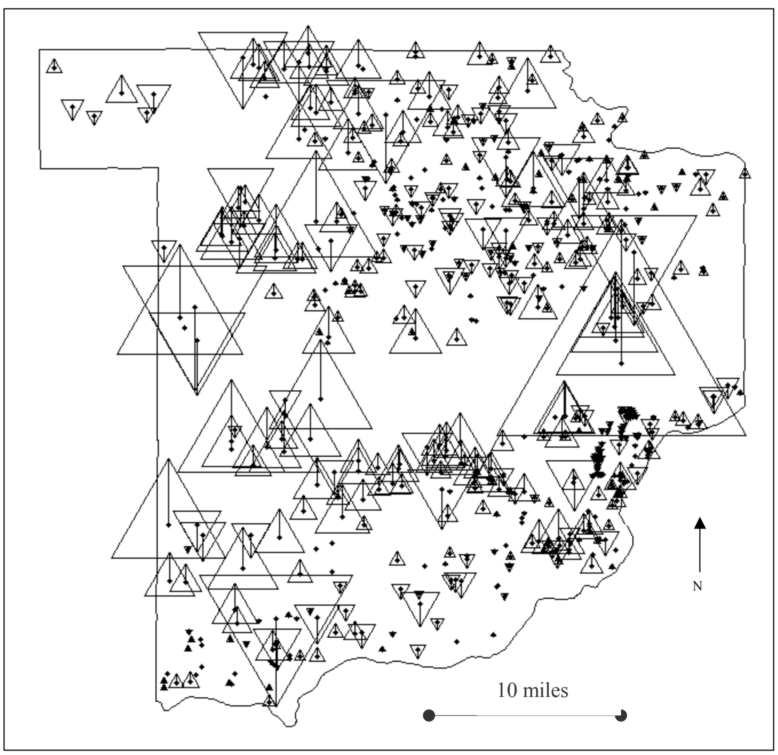

Figure 20. Distribution of error across the model domain.
Triangles are scaled; larger symbols represent a larger difference between measured and simulated values. Upward-pointing triangles indicate simulated head is greater than measured; downward-pointing triangle indicates simulated head is less than measured value.

Table 1. List of municipal wells and pumping rates.

Municipality	Local Well #	WI. Unique Well #	Aquifer Type	2000 Average Pumping Rate (gpm)	Pumping Capacity (gpm)	Modeled Pumping Rates for Calibration (gpm)	Modeled Pumping Rates for ZOC determinations (gpm)
Baraboo	7	AR322	Unlithified	523	1300	523	650
Baraboo	2	BG928	Sandstone	229	650	229	325
Baraboo	4	BG929	Sandstone	403	1100	403	550
Baraboo	6	BG931	Sandstone	413	1000	413	500
Baraboo	8	RX387	Sandstone	not in use	1000	0	799
Ironton	1	EP387	Sandstone	13	550	13	275
LaValle	1	BG932	Sandstone	26	182	26	91
Lake Delton	1	BG951	Sandstone	58	340	58	170
Lake Delton	2	EJ765	Sandstone	114	450	114	225
Lake Delton	3	EJ766	Sandstone	305	750	305	375
Lake Delton	4	EJ767	Sandstone	132	600	132	300
Lake Delton	5	OH433	Sandstone	not in use	950	0	475
Loganville	1	BG933	Sandstone	18	220	18	110
Merrimac	1	BG934	Unlithified	22	450	22	225
North Freedom	2	BG936	Sandstone	30	300	30	150
Plain	1	BG937	Sandstone	18	145	18	73
Plain	2	BG938	Sandstone	44	345	44	173
Prairie Du Sac	3	AY370	Sandstone	145	535	145	268
Prairie Du Sac	2	BG939	Unlithified	114	1375	114	688
Reedsburg	1	BG941	Sandstone	not in use	305	0	153
Reedsburg	2	BG942	Sandstone	not in use	285	0	143
Reedsburg	3	BG943	Sandstone	662	500	662	761*
Reedsburg	4	BG944	Sandstone	719	700	719	827*
Reedsburg	5	BG945	Sandstone	not in use	580	0	290
Reedsburg	6	CB345	Sandstone	485	1060	485	530
Rock Springs	1	BG946	Sandstone	0.03	150	0.03	75
Sauk City	4	BG954	Sandstone	141	1290	141	645
Sauk City	5	CN884	Sandstone	127	1200	127	600
Sk. Co. Health	2	BG901	Sandstone	0.14	not available	0.14	0.14*
Sk. Co. Health	3	BG902	Sandstone	15	not available	15	18*
Spring Green	1	BG949	Sandstone	46	430	46	215
Spring Green	2	BG950	Unlithified	179	900	179	450
Wis. Dells	1	BF378	Sandstone	69	580	69	290
Wis. Dells	3	BF380	Sandstone	125	600	125	300
Wis. Dells	4	BG952	Sandstone	102	600	102	300
Wis. Dells	5	BG953	Sandstone	93	1000	93	500
Wis. Dells	6	AC717	Sandstone	62	500	62	250
Wis. Dells	2	BF379	Sandstone	not in use	450	0	225

Notes: * indicates pumping rate used for ZOC determination is 15% greater than the 2000 actual average rate. All other pumping rates used for ZOC determinations are equal to ½ of the pump capacity.

Table 2. Non-municipal high-capacity wells and pumping rates in regional GFLOW model.

Well Name	**Permitted pumping rate (gpm)**
Oak Ridge Estates Mobile Home Park	60
Lower Dell Estates 1	60
Lower Dell Estates 2	60
Lower Dell Estates 3	60
Dellwood Mobile Home Park	60
Fairfield Center Elementary School	3
Living Hope Academy	60
Foremost Farms Baraboo	300
Cooperative Service Center	60
Spring Brook Falls	60
Christmas Mt. Oak Villas	60
Christmas Mt. Hotel/Chalet	7
Koenecke Ford Mercury	60
Hartje Lumber	60
Weston Elementary School	3
Weston High School	3
Foremost Farms Reedsburg	375
Foremost Farms Reedsburg	460
Loganville Elementary School	3
Foremost Farms Sauk City	300
Mueller Sports Medicine	3
Bluffview	1
Bluffview (I)	120
Badger Army Ammun. Office	60
Maple Park	60
USDA Dairy Forage Research Center	80
Summer Oaks Cove	40
Merrimac Mobile Home Park	60
Devils Head Resort Lodge	360
Blackhawk Elem. School	3
Tower Rock Elem. School	3
46 irrigation wells, various locations	60 each
9 school wells	3 each
6 Badger Army Ammun. Plant remediation wells	500 each
5 Badger Army Ammun. Plant remediation wells	220 each
19 commercial, industrial and park wells	60 each
Total non-municipal pumping in regional model:	10,910 gpm

Table 3. Summary of groundwater flow models by municipality

Municipalities in model domain	Model Code	Dimensions	Simulated hydrogeologic units		
			Sandstone aquifer	**Unlithified aquifer**	**Eau Claire shale**
Sauk County Region	GFLOW	2-D	X	X	
Merrimac	GFLOW	2-D		X	
Sauk City, Prairie du Sac	MODFLOW	3-D	X	X	X
Reedsburg	GFLOW	2-D	X		
Spring Green, Plain	MODFLOW	3-D	X	X	
Baraboo, N. Freedom, Rock Springs	MODFLOW	3-D	X	X	
LaValle	GFLOW	2-D	X		
Lake Delton, Wisconsin Dells	GFLOW	2-D	X		
Ironton	GFLOW	2-D	X		
Loganville	GFLOW	2-D	X		

Table 4. Optimized global and heterogeneity parameter values for regional GFLOW model

Model Area	Hydraulic Conductivity (ft/d)	Recharge (in/yr)
Global rate (near and far fields)	13.2	5.2
Wisconsin River valley	112.1	10.2
Northern glacial deposits	38.7	10.2
Southern outwash deposits	310.1	10.2
Uplands west of the Dells	2.0	Same as global

Table 5. Stream flow targets for regional GFLOW model

ADAPS Station name and number	Q_{50} (cfs)	Q_{80} (cfs)	Covariance (UCODE weight)	Simulated flux (cfs)
Baraboo River near Baraboo (05405000) *	290.0	197.1	0.01	222
S. Br. Baraboo River near Hillsboro (05404116)	15.4	9.9	0.20	5.7
Hulbert Creek near Wisconsin Dells (05403630)	4.3	3.4	0.20	1.5
Dell Creek near Lake Delton (05403700)	24.2	18.8	0.01	17.4
Narrows Creek near Loganville (05404200)	5.1	3.9	0.01	3.8
Miscellaneous records				
Honey Creek near Sauk City (05406300)**	73.6	53.7	0.20	57.5
Leech Creek north of Baraboo***	7.9	5.8	0.05	4.7

* using last 30 years of record only

** Honey Creek Q_{80} was estimated using miscellaneous measurements on 7/27/64 and 10/9/75, and the long term discharge record from 05405000, Baraboo River near Baraboo

*** Leech Creek Q_{80} is 0.73 of Q_{50} which is taken as the 7.9 cfs measured on 04/6/01and 06/29/01.

Table 6. Hydraulic conductivity values estimated from specific capacity and pumping tests

Aquifer	Geometric mean K (ft/day)	Range of K values minimum (ft/day)	maximum (ft/day)	Number of Wells
Ulithified	162	55	976	46
Sandstone	8	1	153	46

Appendix 1 Inset model of the Village of Merrimac

Village of Merrimac Hydrogeologic Setting and Conceptual Model

The Village of Merrimac, situated between the Baraboo Hills to the west and Lake Wisconsin to the east, has one municipal well (Merrimac #1) (Plate 2). The well is completed in the unlithified aquifer. In the vicinity of Merrimac, the unlithified aquifer consists of collapsed melt-water stream sediments composed of interbedded and non-contiguous clays, sands, and gravels. Stratigraphy at the well consists of coarse to very fine sand to 10 feet, silt and clay from 10 to 190 feet, and sand and gravel from 190 to 235 feet. The well is screened from 185 to 235 feet. WCRs from this area show that the clay layer is not regionally continuous. However, the potential for an extensive clay layer to restrict recharge to the well was tested with the model, as described below.

The general groundwater flow direction is southeast from the Baraboo Hills towards the Wisconsin River valley and the Wisconsin River. The dam at Lake Wisconsin is expected to cause reversal of groundwater flow in the vicinity of the Lake, where lake level is maintained at about 38 feet above the river stage at the base of the dam. This artificially maintained increase in stage probably causes lake water to discharge to groundwater near the dam. The relatively low average pumping rate (22 gpm) of Merrimac #1 is not expected to reverse the groundwater flow regime in the high permeability aquifer. This conceptual model is tested with a refined flow model.

Model development, calibration and sensitivity analyses

Based on the hydrogeologic setting and well construction, the two-dimensional regional GFLOW model was considered sufficient for simulating the ZOC for the Merrimac well. The model was refined in the vicinity of Merrimac by adjusting the K value applied to the unlithified aquifer heterogeneity in order to better match water levels in the vicinity of Merrimac. Refining the regional flow model calibration is appropriate here because Merrimac #1 is completed in the thick sequence of unlithified aquifer and is unlikely to be affected by the properties of the underlying sandstone.

A trial and error process was used to calibrate the inset model. K_h of the unlithified aquifer inhomogeneity was varied within the range of 50 to 600 ft/day. Lower K_h values provided a slightly better match to measured water levels close to Merrimac #1 but caused groundwater levels towards the southwest to be too low. A value of 300 ft/day was judged to provide the best overall fit to area targets. This value is very close to that used in the regional model, 310 ft/day.

In a steady-state model the effect of the porosity parameter is limited to the particle travel time calculation. Travel time is calculated using the average linear groundwater velocity. Given a particular amount of time, a particle travels a longer distance if porosity is lower, resulting in a longer ZOC. For the Merrimac ZOC simulation, a value of 0.2 was assigned to the entire model domain because it encompasses an area of sand and gravel deposits. .

The sensitivity of model results to the representation of Manley Creek and Prentice Creeks (located to the southwest and to the northeast, respectively, of Merrimac #1) was tested. The simulated water table in the vicinity of Well #1 was not sensitive to refinement of the linesinks representing these streams, which is attributed to their distance from the well.

Sensitivity of the model results to the representation of Lake Wisconsin was tested by increasing the hydraulic connection between the aquifer and the lakebed. There was no discernible difference between solutions with no lakebed resistance and with resistance set to 0.5 day. These model runs confirm that the well pumpage does not cause a reversal of groundwater flow direction in the unlithified aquifer, and the well does not receive water from Lake Wisconsin.

The sensitivity of model results to representation of the clay layer present in the vicinity of Well #1 was tested by simulating a decrease in recharge that would result from the presence of a laterally extensive clay layer overlying the unlithified aquifer. In the sensitivity run, recharge to the unlithified aquifer inhomogeneity was set to zero. The simulated ZOC capture zone was larger than the base model capture zone, but the flow direction of groundwater was similar, with the well receiving all of its flow from the northwest. The two capture zones are compared in figure A1-1.

Results and Conclusions

The 5- and 50- year ZOCs for Merrimac Well #1 are shown in Plate 2. The 100-year and 50-year ZOCs are identical because the capture zone intersects the water table at a travel time of approximately 14 years. The model indicates that the primary source of groundwater to this well is relatively recent recharge that falls to the northwest. It is very unlikely that Lake Wisconsin contributes water to the well. The capture zone is relatively insensitive to variations in the K and pumping rate and shows the source area to be between one-half and one mile to the northwest of the well. Discontinuous clay lenses at varying depths and locations in the unlithified aquifer are not expected to have a large effect on regional groundwater flow patterns.

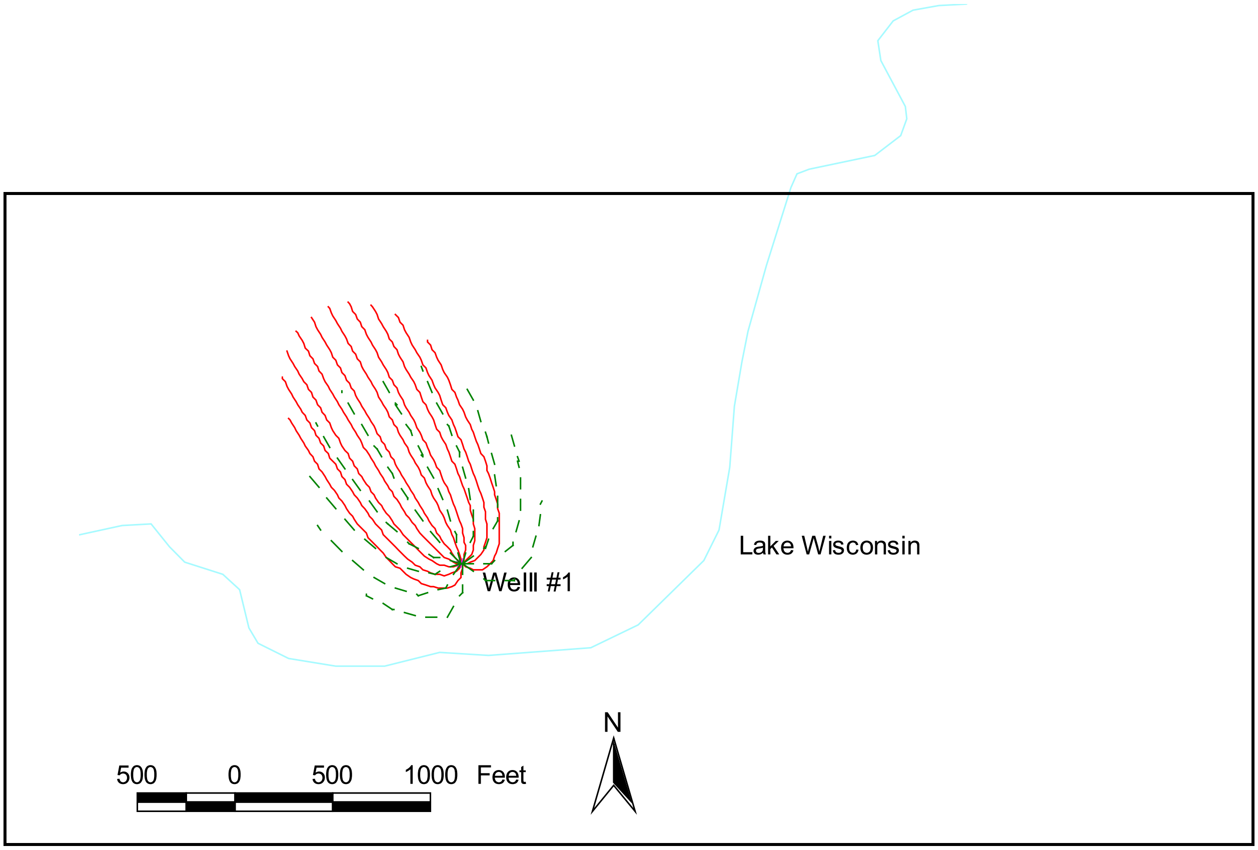

Figure A1-1. Merrimac well #1 sensitivity of particle traces to recharge.
Particle traces resulting from one-half calibrated recharge rate (dashed lines) are shorter and broader in extent than the particle traces using the calibrated recharge rate (solid lines).

Appendix 2 Inset model for Reedsburg, Ironton, LaValle, Loganville and Sauk County Health Center

Hydrogeologic setting and conceptual model

Reedsburg and the villages of Ironton, LaValle, and Loganville are situated in river valleys in northwestern Sauk County where the stratigraphy consists of a thin (5 to 35 feet) layer of unlithified deposits overlying Cambrian sandstones. The sandstone aquifer is generally homogenous in this portion of the County; geologic logs from Reedsburg and La Valle report fine- to coarse-grained sandstone at thickness up to 490 feet. Well logs from the Ironton and Loganville wells indicate that 10 to 15 feet of shale of the Tunnel City formation is present in the upper bedrock. The wells are cased through the upper bedrock and open to fine- to coarse-grained sandstones of the Elk Mound group. Here, the aquifer may be characterized as a thick sequence of relatively homogenous sandstone. The shale layer reported in the Ironton and Loganville wells does not appear to be laterally extensive.

Model development, calibration and sensitivity analyses

Based on the hydrogeologic setting and municipal well construction, the regional GFLOW model was used to simulate the ZOCs for these wells. Modifications to the regional model were limited to refinement of line sink strings (i.e., adding vertices) to improve resolution where municipal wells are located close to simulated streams. Because the shale reported in the Ironton and Loganville wells does not appear laterally extensive, the hydraulic effects of this layer are assumed to be very localized and not significant in terms of regional flow paths to these municipal wells. The shale is not simulated in this two-dimensional model.

The GFLOW parameter values for this model are identical with the regional model (table 4). Further calibration was not necessary to obtain a good match to targets in this area. Sensitivity analyses were performed to evaluate the potential for Reedsburg municipal wells to capture water from the Baraboo River and to assess the effect of near-by private high-capacity wells on municipal well ZOCs. Groundwater flow to the Reedsburg wells is of particular interest because utility managers have discontinued regular use of wells 1,2 and 5 due to water quality problems.

The sensitivity of model results to the resistance of the Baraboo River was evaluated because backwards particle tracking runs from Reedsburg wells 1,2 and 5 indicate that these wells receive some water from the river. The sensitivity runs were performed with the total volume of groundwater pumped in Reedsburg in 2000 distributed evenly among the Reedsburg municipal wells, so that each well pumped at a rate of about 375 gpm. Particle tracks using the calibrated model resistance value of 0.5 days (figure A2-1) compared to those using a resistance of 5.0 days (figure A2-2) shows that an order-of-magnitude increase in river resistance has an effect on the particle tracking results. As expected, a larger value of resistance reduces the hydraulic connection between the river and aquifer; fewer particles originate from the river and there is more draw down in the vicinity of the wells and river. There are no model flux targets in this area, so the effect of river resistance on the quality of calibration could not be evaluated.

Results and Conclusions

The 5-, 50-, and 100-year ZOCs for the wells are shown in plate 2. LaValle, Ironton, Loganville and the Sauk County Health Center wells have similarly shaped ZOCs. The size of the Ironton ZOC is significantly larger than the others because of the higher pumping rate assigned to the Ironton well in the simulations. The ZOCs for the Reedsburg municipal wells intersect in complex patterns because of their relative proximity to each other and to two high-capacity wells owned by Foremost Farms. The two Foremost Farms wells are pumped in the model runs for generating the ZOCs (plate 2) at their permitted rates of 375 and 460 gpm. Actual pumping rates at the Foremost Farms wells were not verified with the well owners.

Additional model runs were carried out to evaluate the effect of the Foremost Farms wells on the flow field near the Reedsburg municipal wells. Figures A2-3 illustrates that pumping from the Foremost Farms wells intercepts groundwater flow from the north and east. This shifts the ZOC of Reedsburg #5 to the west and causes a larger portion of flow to well #1 to come from the south and the river.

The model results show that the simulated ZOCs for Reedsburg wells 1, 2 and 5 are affected both by the river resistance term and the pumping rates assigned to the Foremost Farms wells. While these wells probably receive some flow from the river, additional information (such as stream flow measurements in this area, and head measurements from piezometer nests in or near the river) would be necessary to verify this result and to accurately simulate the hydraulic connection between the river and aquifer at this scale. Similarly, the actual pumping rates from the Foremost Farms well should be used to determine the actual effect of pumping from these wells on the municipal wells ZOC.

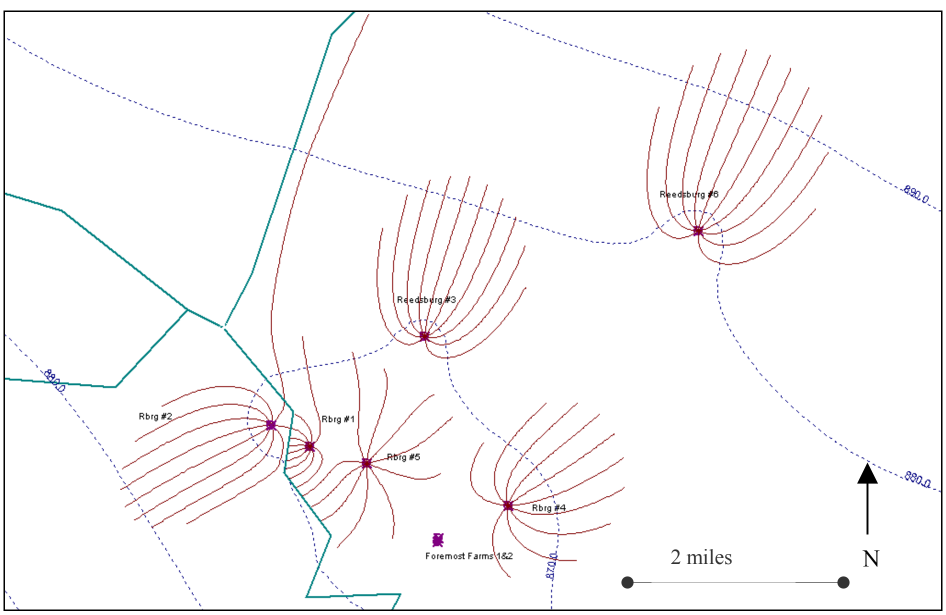

Figure A2-1. Particle traces with a 100-year travel time for Reedsburg municipal wells with Foremost Farms wells not pumping. Each municipal well has a Q of 375 gpm, river R =0.5 day.

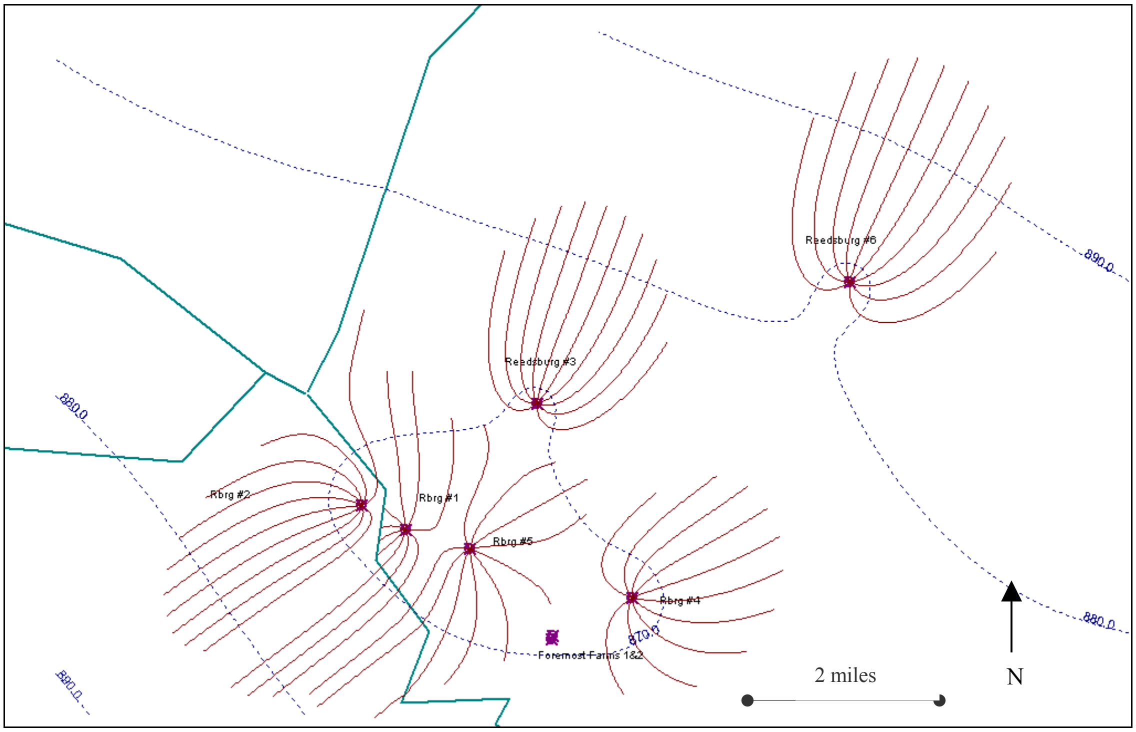

Figure A2-2. Particle traces with a 100-year travel time for Reedsburg municipal wells with Foremost Farms wells not pumping. Each municipal well has a Q of 375 gpm, river R = 5.0 day.

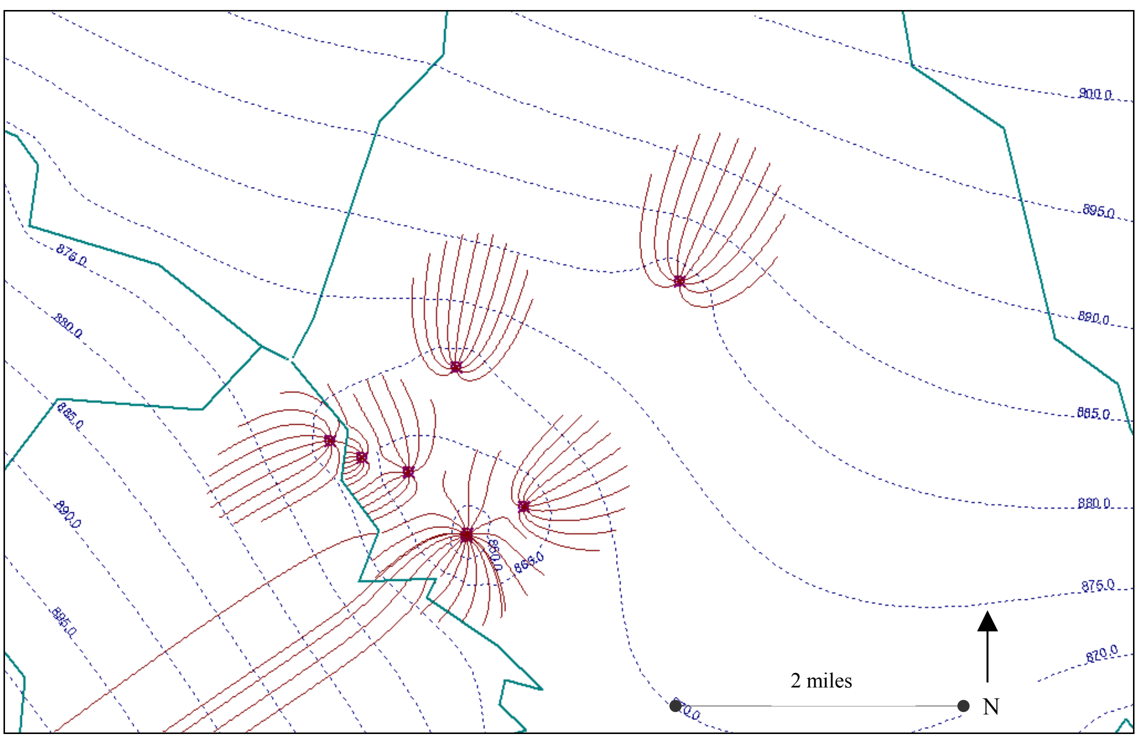

Figure A2-3. Particle traces with a 100-year travel time for Reedsburg municipal wells with the Foremost Farms wells pumping at permitted capacity. Each municipal well has a Q of 375 gpm, river R = 0.5 day.

Appendix 3 Inset model of Spring Green and Plain

Hydrogeologic setting and conceptual model

The City of Spring Green is located in southwestern Sauk County, along the broad outwash plain in the Wisconsin River Valley (figure 5). Here, the unlithified aquifer consists of sand and gravel deposits typically about 150 feet in thickness. The sandstone aquifer is at least 240 feet thick in Spring Green, and consists of the Eau Claire and Mount Simon formations. There are two municipal wells in Spring Green: Spring Green #1 is cased through the unlithified aquifer and is open to the sandstone aquifer and Spring Green # 2 is completed in the unlithified aquifer. Water levels in bedrock wells completed in the outwash plain show strong upward vertical gradients from the bedrock to the unlithified aquifer, indicating that the Wisconsin River valley is an area of regional groundwater discharge.

The Village of Plain is located approximately 7 miles north of Spring Green in the Honey Creek river valley. Here, the unlithified aquifer is about 110 feet thick and consists of fine- to medium grained sand and some gravel. The sandstone aquifer consists of fine- to coarse undifferentiated sandstones of the Elk Mound group, at least 290 feet in thickness. As in Spring Green, there is no aquitard between the unlithified and sandstone aquifers. Plain has two municipal wells, both of which are cased through the unlithified aquifer and open to the sandstone. Static water levels in the wells indicate upward vertical gradients from the sandstone aquifer to the overlying sediments, indicating that Honey Creek is a point of discharge for the unlithified and sandstone aquifers.

Model development, calibration and sensitivity analyses

In order to adequately model the vertical component of groundwater flow between the unlithified and sandstone aquifers, the regional GLFOW model was used to develop a three dimensional MODFLOW model for this area. This inset model was constructed by extracting specified flux cells, river cells and pumping wells from the regional GFLOW model. Top and bottom elevations for the two-layer MODLFOW model were generated from the regional hydrostratigraphy (figs 12 through 16). In the Wisconsin River valley, the upper layer (layer 1) of the model represents sand and gravel outwash deposits. In the areas of the model domain representing the uplands of the Driftless area, layer 1 represents the thin soil cover overlying bedrock. Here, the water table occurs in the sandstone and there is no unlithified aquifer. Layer 1 represents alluvial deposits in the Honey Creek Valley. Layer 2 of the model represents the bedrock aquifer across the entire model domain. Cell size is 2000 x 2000 feet, refined to 600 x 600 feet in the areas of interest (figure A3-1).

Two K zones were designated in layer 1 in order to differentiate between the Wisconsin River valley outwash and the Honey Creek alluvium (figure A3-1). The bedrock (layer 2) was assigned a uniform value of K. Recharge values were not changed from those used in the regional model; recharge is set to 5.5 in/yr in the uplands and 10.8 in/yr in the Wisconsin River valley. Porosity was assigned based on the range of values presented in the literature (Freeze and Cherry, 1979) for the various geologic materials (table A3-1).

K_h of layer 1 and K_h and K_v layer 2 were optimized with UCODE because the statistics of model sensitivity demonstrated that there were sufficient calibration targets to support estimation of these parameters. The head targets for this inset model were weighted in order to account for variability in accuracy of the target data. An error in the location of a well in the lowland will result in a relatively small error in the estimating the ground surface elevation of the well. However a small error in the location of a well in the uplands could result in a greater error in the estimated elevation because of the steep topography of the uplands. Following the guidance suggested by Hill (1998), uplands wells were assigned a weight of 0.04 and lowlands wells were assigned a weight of 0.17. The optimized K values (table A3-1) for this inset model are within the range of values determined from specific capacity and pumping test data on record for high-capacity wells (table 6).

Table A3-1. Parameter values for Spring Green / Plain inset model

Model Area	Horizontal hydraulic conductivity (ft/d)	Vertical hydraulic conductivity (ft/d)	Porosity	Recharge (in/yr)
Wisconsin River valley (layer 1)	297	29.7	0.25	10.8
Uplands and Honey Creek alluvium (layer 1)	50	5	0.15	5.5
Bedrock aquifer (layer 2)	19.1	0.1	0.15	--

Unweighted statistics comparing measured groundwater levels to calibrated model results include an average difference of 4.0 feet, with a RMS of 32.3 feet. The model provides a good match to targets in the areas of interest near municipal wells (figs. A3-2 and A3-3). The model has larger errors associated with targets in the uplands wells (these targets were assigned lower weights in the UCODE runs; therefore the optimized parameter values produce a better match to targets that were weighted more heavily, in this case, wells in the lowlands).

The sensitivity of model results to K_v of the bedrock aquifer was evaluated because it was noted during model calibration that this parameter affects the location of the "trough" in the potentiometric surface in layer two of the model. Because Spring Green Well #1 is located very close to the trough, small changes in its location have a large impact on the ZOC of this well. Figure A3-4 shows the simulated potentiometric surface in layer 2 and the associated ZOC for Well #1 pumping at half capacity, with K_v of 0.1 and 0.05 ft/d. The calibration statistics for the two simulations are similar (using a K_v of 0.05 ft/d, the average difference is 3.1 ft and the RMS is 31.3 ft). There is not sufficient resolution in the target heads to determine which simulation is more accurate. The ZOC simulated with K_v set at 0.1 ft/d encompasses a broader area (and is therefore more conservative), and so this K_v was used in the predictive simulations.

Results and Conclusions

Flow to the Plain wells is from the northwest (plate 2). At the simulated pumping rates, vertical gradients from the bedrock to the alluvial aquifer are upward along the entire 100-year flow path; neither of the Plain wells receives water from the overlying alluvium.

A majority of the flow to Spring Green #2, which is completed in the sand and gravel aquifer, comes from the north through the upper aquifer. However, because of the location of this well relative to the trough in the bedrock potentiometric surface, and because of strong upward gradients from the bedrock to the sand and gravel, flow paths of some particles tracked from this well originate to the south in the bedrock aquifer.

Particle tracks show radial flow from within the sandstone aquifer towards Spring Green #1. As discussed above, this result is affected by the location of this well relative to the trough in the potentiometric surface. The half capacity pumping rate used in this simulation (which is large compared to the actual rate) causes reversal of vertical gradients at the well, so that this well, which is cased into the sandstone, receives some flow from the upper aquifer. Because of the rapid flow rates in the upper aquifer, particles that originate in the upper aquifer have much longer flow paths than particles that originate in the bedrock.

The results for the Spring Green wells are sensitive to the simulated location of the trough in the potentiometric surface of the bedrock aquifer. The available data are not sufficient to reduce the uncertainty around key model parameters (K_v of the sandstone). Uncertainty in the model results could be resolved if additional field data became available. The model shows that the upper and lower aquifers are well connected, and that under the simulated pumping rates, both wells probably receive some groundwater flow from both the sand and gravel and bedrock units.

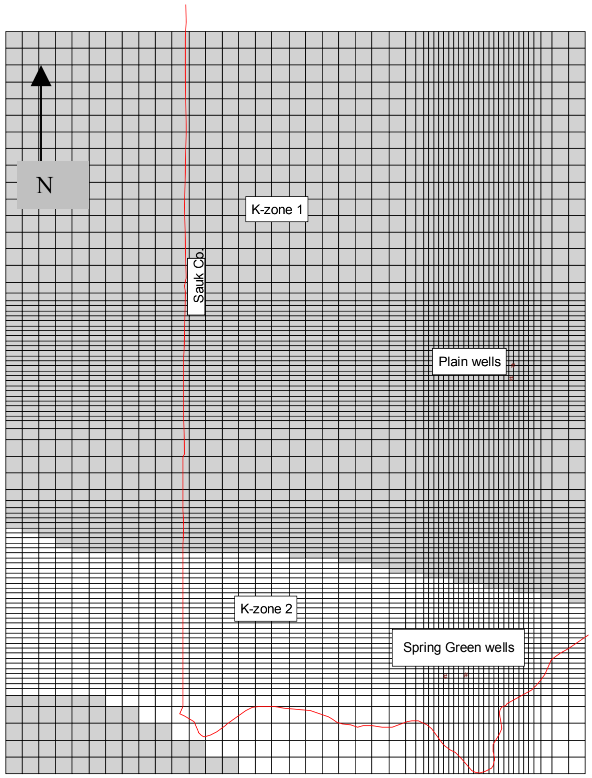

Figure A3-1. Spring Green / Plain inset model domain. K-zone 2 (white cells) shows area where layer 1 K represents river valley outwash deposits. Sauk County boundary is also shown. Cell size is 2000 x 2000 ft. refined to 600 x 600 ft. in the area of interest.

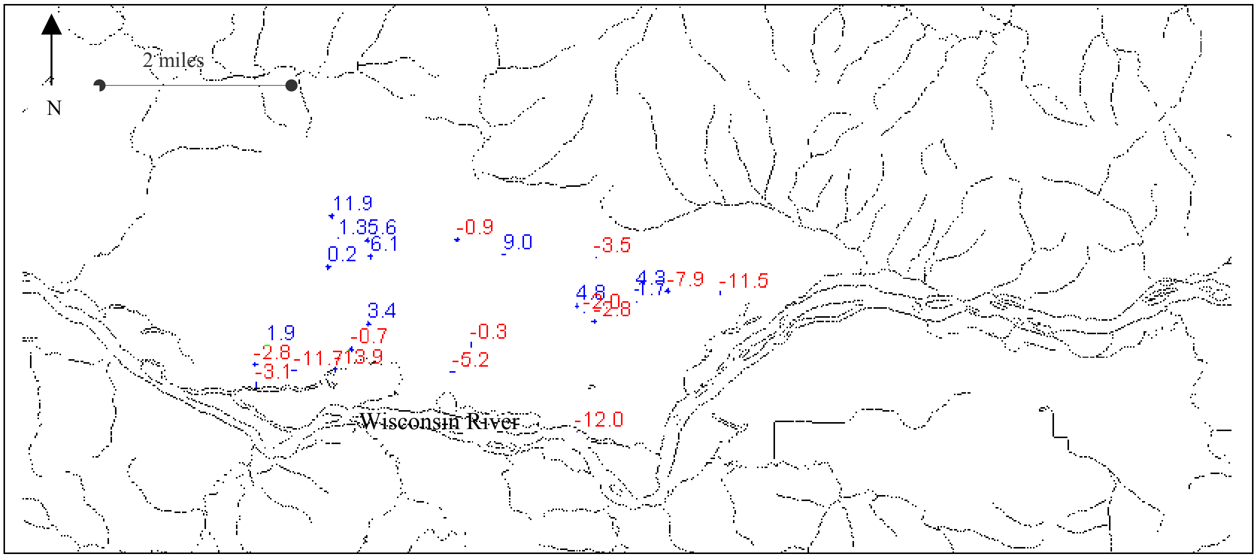

Figure A3-2. Residual error (in feet) for layer 1 targets in the Spring Green area.

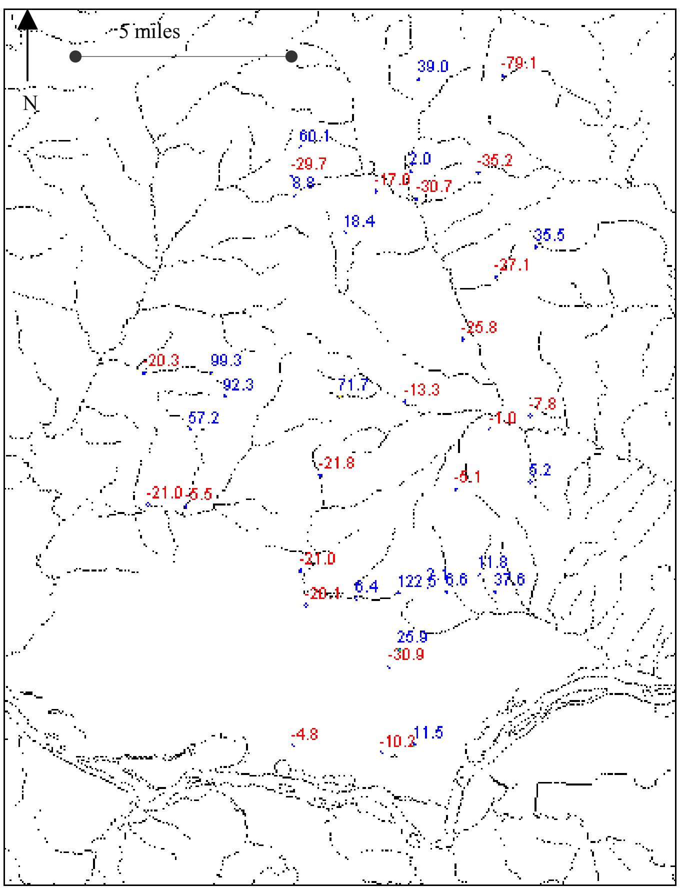

Figure A3-3. Residual error (in feet) for layer 2 targets in the Spring Green / Plain model.

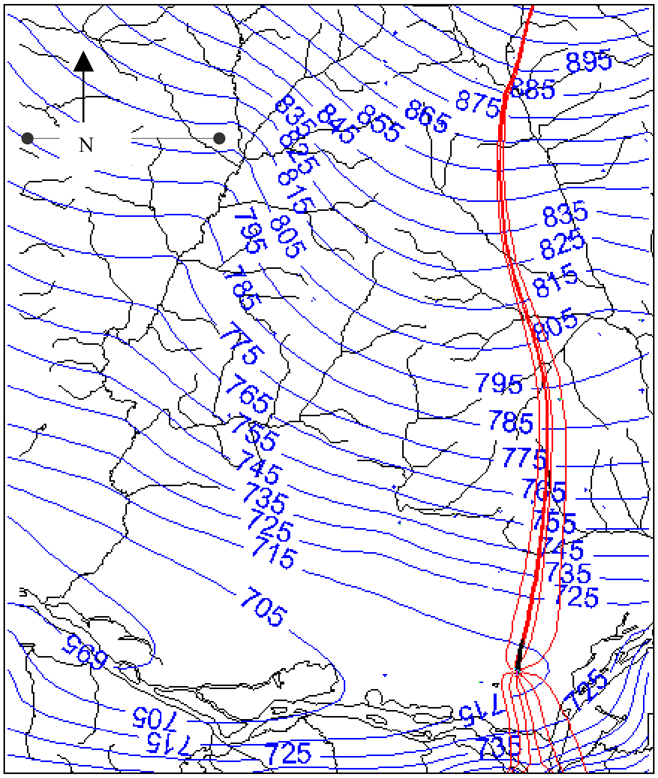

Figure A3-4a.

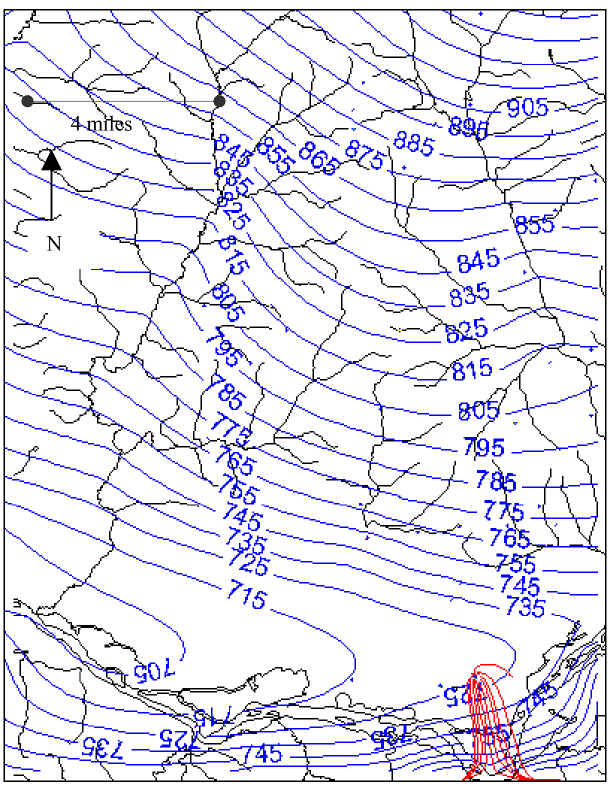

Figure A3-4b.

Figure A3-4. Area of Spring Green Model, showing Layer 2 potentiometric surface (in feet above mean sea level) and backwards particle tracking from Well #1. Well #1 is pumping at half its rated capacity. A3-4a shows result with K_v = 0.1 ft/d. A3-4b shows result with K_v = 0.05 ft/day.

Appendix 4 Inset model for Sauk City and Prairie du Sac

Hydrogeologic setting and conceptual model

Sauk City and Prairie du Sac are located in southeastern Sauk County, along the broad outwash plain in the Wisconsin River valley. About 150 feet of unlithified sand and gravel deposits overlie bedrock. Uppermost bedrock consists of a thin layer of sandstone of the Elk Mound Group overlying a shale facies of the Eau Claire Formation. In this area of the county, the Eau Claire Formation consists of shale, siltstone and dolomite at thicknesses up to 250 feet. The Mt. Simon Formation underlies the Eau Claire, and is a fine to medium-grained sandstone up to 500 feet thick.

The Village of Sauk City operates two wells (#4 and #5). Well #4 is cased into the Eau Claire and is open to the lower part of the Eau Claire and the Mt. Simon Formations. Well #5 is cased through the Eau Claire, open to the Mt. Simon. The Village of Prairie du Sac also operates two municipal wells. Well #2 is completed in the unlithified aquifer and well #3 is cased into the Eau Claire and is open to the lower part of the Eau Claire and the Mt. Simon Formations. Water levels in these wells indicate strong upward gradients across the shale facies of the Eau Claire Formation.

Our hydrogeologic conceptual model for the area is that of a four layer system. An upper, unconfined aquifer includes the sand and gravel deposits and the uppermost, relatively thin sandstone bedrock. The shale facies of the Eau Claire Formation separates the upper aquifer from the Mt. Simon sandstone aquifer. Shallow groundwater flows towards the Wisconsin River through the unlithified deposits and the upper sandstone. The Eau Claire shale confines the deep sandstone aquifer. The aquitard pinches out to the west (fig. 8, 9 and 15). Although there is a strong vertical gradient upward from the Mt. Simon to the Eau Claire, volumetric flux from the Mt. Simon to the upper aquifer and the Wisconsin River is expected to be relatively low because of the low K_v associated with the Eau Claire shale.

Model development, calibration and sensitivity analyses

The regional GFLOW model was used to develop a three-dimensional MODFLOW inset model of this area to accurately simulate effects of the aquitard on the ZOCs. Boundary conditions extracted from the regional model include specified fluxes around the MODFLOW domain, pumping wells within the domain, and river cells representing the Wisconsin River, Lake Wisconsin, Otter Creek, and Honey Creek (fig. A4-1). River conductances are determined for each river cell through the automated extraction procedure in GFLOW, which converts the GFLOW line sink resistance term to an equivalent MODFLOW river conductance term. Recharge in this model was zoned similarly to the regional model: it was set at 5.5 in/yr in the uplands and 10.8 in/yr in the Wisconsin River valley. The quartzite in the Baraboo Hills is modeled as an impermeable, no-flow boundary to the north. Discharge-specified linesinks used in the GFLOW model to represent focused recharge along the edge of the Baraboo Hills were translated to specified fluxes in the inset model.

The MODFLOW model grid (fig. A4-1) has variable cell spacing ranging from 250 x 250 feet in the area of interest to 2,000 x 2,000 feet at the outer edges of the domain. The model includes four layers: layer 1 represents the unlithified sand and gravel, layer 2 represents the upper sandstone unit, layer three represents the Eau Claire aquitard, and layer 4 represents the Mt. Simon aquifer. Top and bottom elevations for the layers were generated from the regional hydrostratigraphy. The model domain to the east of the Wisconsin River was assigned layer thicknesses consistent with the hydrogeologic interpretation developed for the regional groundwater model of Dane County (Bradbury et al., 1999).

Three K zones are assigned within layer 1 in order to differentiate between the outwash surrounding the Sauk City/Prairie du Sac (referred to in the regional model as the southern outwash deposits), the outwash to the south of Sauk City (referred to in the regional model as the Wisconsin River valley outwash), and the unlithified material present above bedrock in the uplands. K_h values for layers 1, 2 and 4 (table A4-1) were determined through trial-and-error calibration. K_v of these layers was set an order of magnitude lower than K_h. The Eau Claire aquitard (layer 3) was assigned a K_v of 7.2 x 10^{-4} ft/day, which is the value used in the Dane County model (Krohelski et al., 2000). Its K_h was set at 0.14 ft/day through trial and error. Porosity was assigned to the hydrogeologic units based on literature values (Freeze and Cherry, 1979).

Table A4-1. Parameter values for Sauk City / Prairie du Sac model

Model Area	Horizontal hydraulic conductivity (ft/d)	Vertical hydraulic conductivity (ft/d)	Porosity	Recharge (in/yr)
Uplands (layer 1)	80	8	0.25	5.5
Wisconsin River valley (layer 1)	120	12	0.25	10.8
Southern outwash deposits (layer 1)	320	32	0.25	10.8
Upper sandstone (layer 2)	14	1.4	0.05	--
Eau Claire aquitard (layer 3)	0.14	7.2 x 10-4	0.05	--
Mt. Simon aquifer (layer 4)	14	1.4	0.30	--

Calibration statistics for the 169 head targets within the model domain include an average error in head of 4.93 feet and a RMS of 16.3 feet. The model results match the head targets well in the areas of interest (near municipal wells) and in the valleys of Honey Creek and its tributaries. The model does not match head targets as well in the uplands. This may be partially attributed to increased difficulty in accurately locating and estimating water table elevations in the uplands.

The calibrated model indicates underflow of groundwater in the lower sandstone aquifer beneath the Wisconsin River due to the presence of the Eau Claire aquitard. Sensitivity analysis showed that increasing the K_v of the aquitard by two orders of magnitude (to 0.07 ft/day) prevented this underflow, allowing discharge from the Mt. Simon through the aquitard to the Wisconsin River. However, this increase in K_v of the aquitard results in a very poor match to head targets in the area of interest.

Results and Conclusions

ZOCs generated from this inset model (plate 2) show predominantly radial flow to Prairie du Sac well #3 and Sauk City wells #4 and #5. Sauk City #5, which is cased through the Eau Claire, receives all of its water within the 100-year travel time from the Mt. Simon aquifer, and, at this pumping rate, does not induce significant amounts of flow down through the Eau Claire aquitard (fig. A4-2). These particle traces also demonstrate that the aquitard restricts upward flux of water from the Mt. Simon to the Wisconsin River, and groundwater in the Mt. Simon underflows the Wisconsin River. Particle traces from Prairie du Sac #3 and Sauk City #4, which are open to part of the Eau Claire aquitard as well as the Mt. Simon aquifer, receive a small portion of their water from the Eau Claire aquitard but are predominantly fed by the sandstone aquifer.

Prairie du Sac #2, which is completed in the unlithified aquifer, has a long and narrow ZOC (plate 2) showing that most of the recharge area for the well is from the northwest. Both the 50- and 100-year particle traces extend to the upper portions of Otter Creek. However, the ZOC also extends east of the well because some particle traces originate in the Eau Claire aquitard or Mt. Simon aquifer, underflow the Wisconsin River through the aquitard, and discharge vertically to the unlithified aquifer.

The particle tracking results for wells open to the Mt. Simon aquifer are sensitive to the K_v of the Eau Claire aquitard. A lesser resistance to vertical flow shifts allows increased connection between the unlithified and Mt. Simon aquifers and shifts the ZOCs north. Although the calibrated model used to simulate the ZOCs provides the best match to measured heads, additional data regarding the aquitard would reduce uncertainty in the model results.

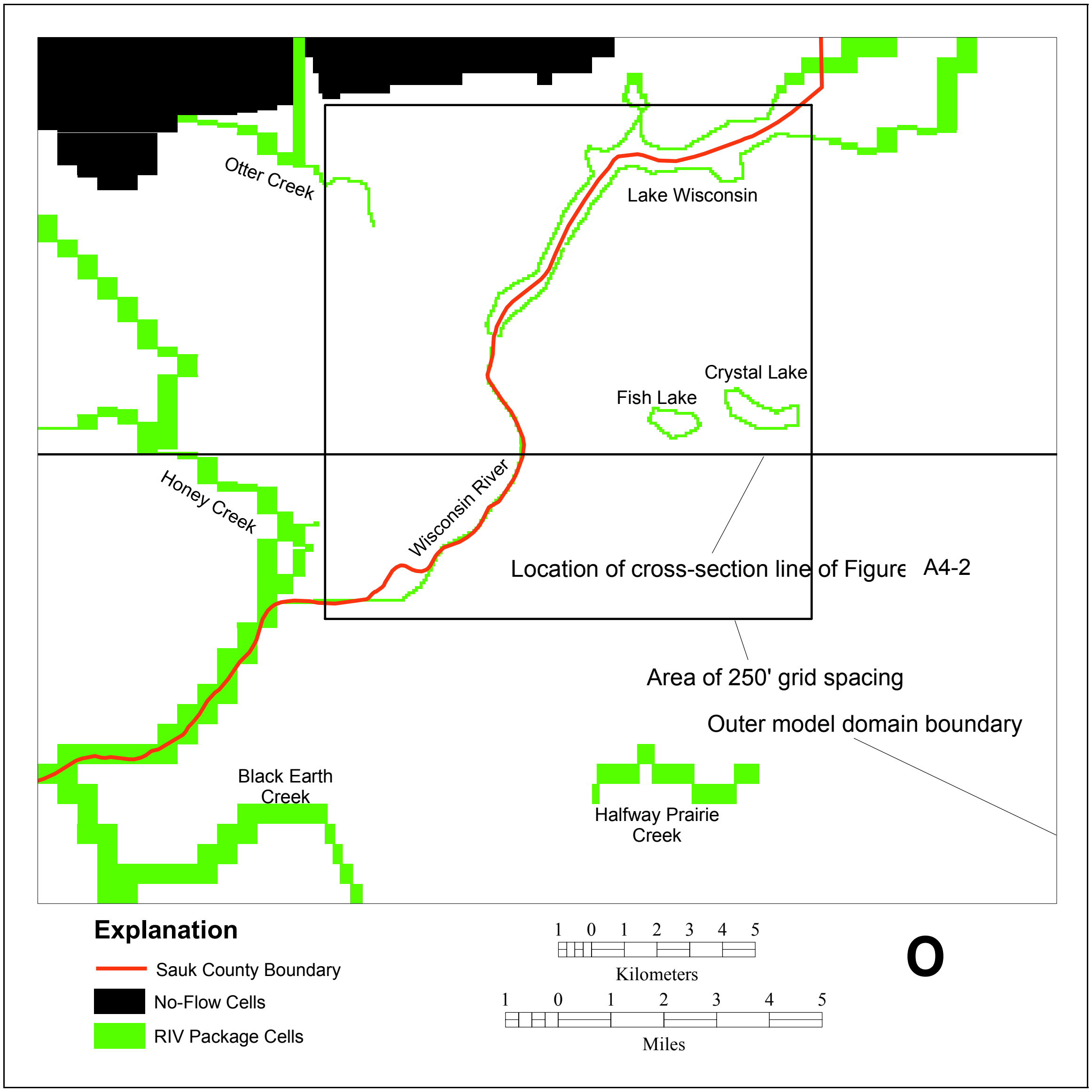

Figure A4-1. MODFLOW inset model domain for the Sauk City-Prairie du Sac area.

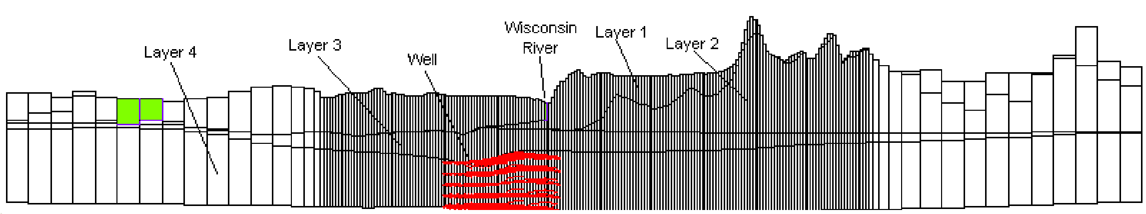

Figure A4-2. Particle paths for 100 year time-of-travel from Prairie du Sac well #3 indicating underflow beneath the Wisconsin River in the lower sandstone aquifer due to the presence of the Eau Claire aquitard. (Not to scale.)

Appendix 5 Inset model for Baraboo, North Freedom and Rock Springs

Hydrogeologic setting and conceptual model

Baraboo, North Freedom, and Rock Springs are located in central Sauk County, in the Baraboo Hills region (fig. 5). The complex geologic setting of this area results in a complex groundwater flow regime. The relatively impermeable Baraboo quartzite acts as a no-flow boundary to the sandstone aquifer. Where the quartzite is the uppermost bedrock, precipitation and snowmelt runoff the relatively impermeable surface, feeding local stream systems or recharging the sandstone aquifer where the sandstone laps onto the quartzite surface. Therefore, in this area the geometry of the quartzite surface exerts a strong control on recharge to, and flow directions within, the sandstone aquifer. Both the unlithified and sandstone aquifers within the basin are bounded by the quartzite (figs. 10 and 11) so that the groundwater in these two aquifers necessarily originates as recharge within the basin or on the Baraboo Hills. The municipal wells in this model are located very close to the hydrogeologic boundary formed by the quartzite. Therefore, the results of the numerical model and the simulated ZOCs for the wells will be constrained by the hydrostratigraphic representation in the model of the quartzite relative to the sandstone. The accuracy of the representation of this boundary is limited by the availability of data on the elevation and extent of the quartzite surface.

The city of Baraboo is located on the eastern side of the Baraboo Basin and the Baraboo River flows through the city. The unlithified aquifer consists largely of till, however there are thick alluvial sediments (sand and gravel deposits up to 230 feet thick) in the river valley. The sandstone aquifer is over 200 feet thick at some locations, but is not present in other areas of the city where the quartzite is the uppermost bedrock (figs. 10 and 11). Three of the four active municipal wells (Baraboo #2, #4 and #6) are completed in the sandstone aquifer. The fourth well, Baraboo #7, is completed in sand and gravel deposits next to the river. Baraboo drilled a new well in 2001, Baraboo #8, which is completed in the sandstone aquifer (this well had been drilled but was not yet in service at the time this model was developed).

The town of North Freedom lies to the west of Baraboo, within the Baraboo Basin and alongside the Baraboo River. Here, the sandstone is of variable thickness that diminishes over a short distances where knobs of Baraboo quartzite are in the subsurface (fig. 7). The municipal well, North Freedom #2, is completed in the sandstone aquifer where the sandstone is 205-feet thick and overlain by 30-feet of sand and silt deposits.

The town of Rock Springs is located on the northwest edge of the Baraboo basin, along-side the North Range. The sandstone aquifer is present in a narrow valley incised in the quartzite, near the confluence of the Baraboo River and Narrows Creek. A single municipal well, Rock Springs #1, is completed in the sandstone aquifer (fig. 7). The sandstone is 200-feet thick at well #1 and overlain by 30 feet of silt and sand.

Model development, calibration and sensitivity analyses

A three-dimensional MODFLOW model was developed for this area in order to adequately represent the complex flow field expected to occur where municipal wells are located adjacent to no-flow boundaries and rivers. The regional GFLOW model was used as a basis for this inset model; horizontal flow barriers, specified flux boundaries and pumping wells were extracted from GFLOW to MODFLOW. The specified discharge linesinks used in GFLOW to represent enhanced groundwater recharge from runoff at the base Baraboo Hills were converted to injection wells in the MODFLOW model. The injection rate on the wells was set to result in an equivalent rate of water inflow as in the GFLOW model. Top and bottom elevations for the two-layer MODFLOW model were generated from the regional hydrostratigraphy. The upper layer, layer 1, represents the unlithified aquifer. The lower layer, layer 2, represents the sandstone aquifer. The Baraboo Hills are represented as no-flow boundaries in the model. Recharge was set at the value used in the regional GFLOW model (5.2 in/year) and was applied to the highest active layer of the model area. The model grid is 200 rows by 400 columns with a uniform cell size of 200 ft by 200 ft.

Hydraulic conductivities were assigned to each layer through trial and error calibration considering both head and flux targets in the Baraboo inset model domain. Calibration statistics indicate an average difference of 1.18 feet and a RMS of 17.29 feet. Calibrated values for K_h are 200 ft/day for layer 1 and 10 ft/day for layer 2, similar to the geometric mean values determined from specific capacity and pumping test data (table 6). They are also consistent with the values that resulted from parameter optimization in the regional GFLOW model. K_v values were set to an order of magnitude lower than K_h. Porosity was set to 0.25 in layer 1 and 0.20 in layer 2.

Sensitivity runs were performed to investigate the effect of the representation of the Baraboo River on the model results for North Freedom well #2, which is located on the north side of the Baraboo River. The simulated ZOC using the half-pump capacity (150 gpm) is very different than that generated with the well pumping at its average annual rate (30 gpm). At the average annual rate, particle tracking indicates that the source of water for the well is the sandstone aquifer on the *north* side of the Baraboo River, with the groundwater flow direction from the northeast towards the well and the river. When pumping at ½ pump capacity (five times the average annual rate), particles reaching the well originate from the southwest, *south* of the Baraboo River, indicating underflow of the river through the sandstone aquifer. Groundwater flow directions to the well and the ZOC at the half-capacity pumping rate were not sensitive to changes in conductance of the river cells. Therefore, the change in flow direction resulting from the increased pumping rate at well #2 is attributed to the larger gradient induced by this pumping rate, and is not an artifact of the river representation in the model.

Results and Conclusions

Flow to the Baraboo wells completed in the sandstone aquifer is generally from the west and southwest. Baraboo well #7, completed in the unconsolidated aquifer, receives water from the west and the south. Vertical gradients remain upward from the sandstone aquifer to the alluvial aquifer under the half-pump capacity scenario; particle tracking shows that none of the sandstone wells receive water from the overlying alluvium. The 50- and 100-year ZOCs for some of these wells are strongly influenced by the Baraboo Hills (fig. A5-1). For example, the capture zone of Baraboo #7 extends to the southern no-flow boundary of the model, implying that recharge coming of the bluffs reaches the well within 50 years. Similarly, the ZOC of Baraboo #4 is largely determined by the location of the bluffs to the north. Because these results are wholly constrained by the location of the no-flow boundary and the enhanced recharge (injection wells) at this boundary, these ZOCs are designated on plate 2 as having an increased level of uncertainty associated with them. The 5-, 50-, and 100-year ZOCs for the Baraboo, North Freedom, and Rock Springs wells are shown in plate 2.

The simulated ZOCs for North Freedom #2 are also influenced by the representation of the Baraboo Hills in the model (plate 2 and fig. A5-1). The longer travel times for this well are noted on plate 2 as having an increased uncertainty because of this. The ZOC simulated for this well should also be used cautiously because groundwater flow direction with respect to the well is very sensitive to the pumping rate assigned to the well, as discussed above.

The 5-year ZOC for Rock Springs well #1 is generally radial and limited to the south side of Narrows Creek. The 50- and 100-year ZOCs are bifurcated; a portion of the flow to the well comes from the west, up the Narrows Creek valley, and a portion from the south of the creek. The longer travel time particle paths also show that the well receives groundwater originating in both layers 1 and 2 of the model. This finding is consistent with the available geologic data that show the sandstone aquifer thins and the unlithified aquifer (here, alluvial deposits) thickens to the west, up the Narrows Creek Valley. The extent of the ZOCs is strongly influenced by the location of the no-flow boundary with respect to the Narrows Creek Valley and the model representation of runoff from the bluffs (fig. A5-1).

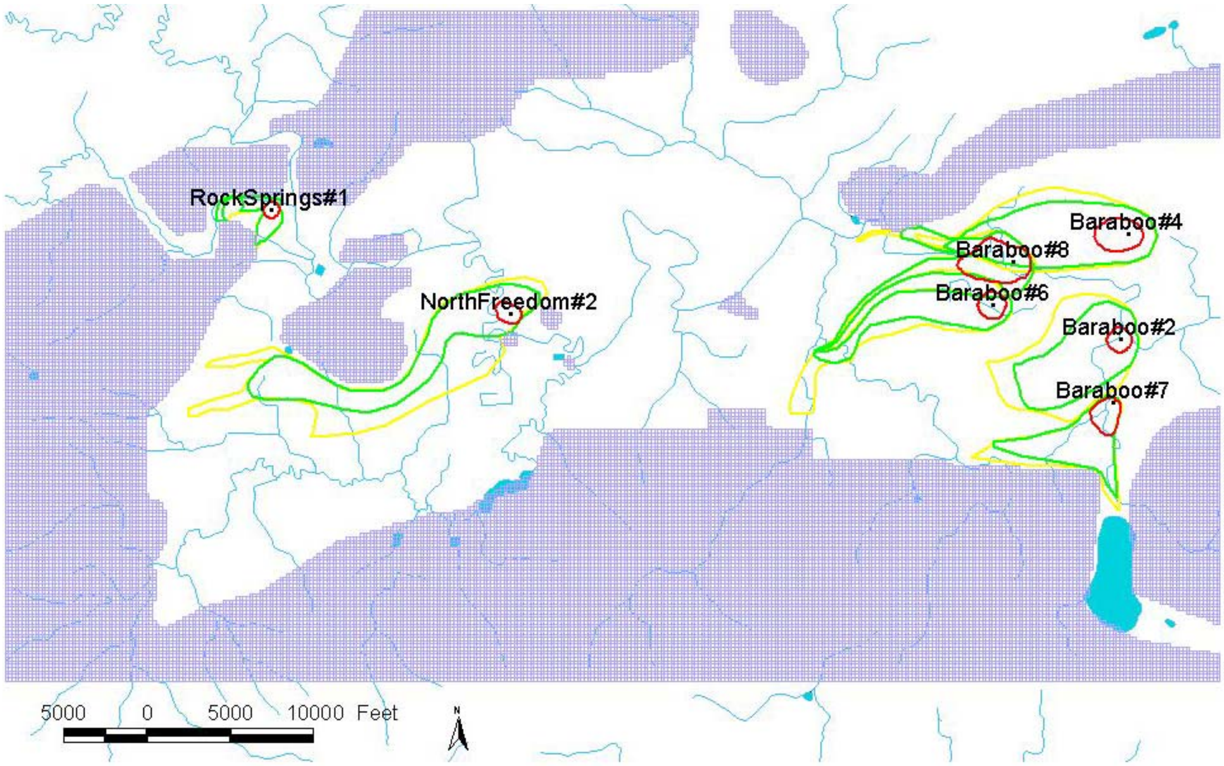

Figure A5-1. Representation of Baraboo Hills with respect to simulated ZOCs. Areas of model domain that are no-flow boundaries are shown in grey. Note the proximity of many of the ZOCs to the no-flow boundaries.

Appendix 6 Inset model for Wisconsin Dells and Lake Delton

Hydrogeologic setting and conceptual model

Wisconsin Dells and the Lake Delton area are located north of the Baraboo Hills, where the Wisconsin River valley is narrow and steeply down-cut through the Eau Claire and Mt. Simon formations. Sandstone bedrock crops out over much of this region, but unlithified glacial and alluvial material, varying from sand and gravel outwash to clayey tills and lake sediments, is present in the Lake Delton area. Lake sediments underlie Dell Creek and are present throughout the Dell Creek Basin (fig. 1) and consist primarily of sand with interbedded silt and clay. Dell Creek flows east through Mirror Lake into Lake Delton. Lake Delton has a control structure at its eastern-most edge; a short waterway connects lake discharge to the Wisconsin River. Although the general groundwater flow direction is eastward toward the Wisconsin River valley and the Wisconsin River, the artificially maintained lake stage probably causes lake water to discharge to groundwater along the shores of both Lake Delton and Mirror Lake.

The City of Wisconsin Dells, which spans the Wisconsin River, operates four wells east of the river in Columbia County (wells #1, #2, #3 and #6) and two wells in Sauk County (wells #4 and #5). Lake Delton has four active wells and a new well (well #5, that was not on-line in 2000), all of which lie within Sauk County. All municipal wells are completed in the sandstone aquifer, which is over 400 feet thick in this region. The unlithified aquifer is thin or absent at the well locations and is not regionally extensive in this area. The wells located in Columbia County are included in this model for completeness, however hydrogeologic conditions east of the Wisconsin River were not evaluated as part of this project.

Model development, calibration and sensitivity analyses

Based on the hydrogeologic setting and municipal well construction, the regional GFLOW model was used to simulate the ZOCs for these wells. Modifications made to the regional model included refining line sink strings in the area of interest, and refining and moving inhomogeneity boundaries, based on hydrogeologic detail of the municipal wells of interest. Five high-capacity wells (at the Ho Chunk Casino and village and the Ho Chunk Nation) were also added to the model.

Measurements of stream flow were made on Hulbert Creek in order to improve understanding of surface water and groundwater connections in the area. These additional flux targets (table A6-1) indicated that in this area, additional recharge was necessary in the GFLOW model to support stream base flow. Field investigations of Spring Brook (a tributary to Hulbert Creek) and Hulbert Creek were also used to evaluate which reaches of the streams were likely gaining groundwater from the aquifer and should remain in the GFLOW solution and which stream reaches (for example headwaters) were losing water to the aquifer and should therefore fall out of the model solution.

Table A6-1. Stream flow targets for Dells/Delton GFLOW inset model

ADAPS Station name and number	Q_{80} (cfs)	Simulated flux (cfs)
Hulbert Creek near Wisconsin Dells (05403630)	3.4	2.4
Dell Creek near Lake Delton (05403700)	18.8	17.4
Miscellaneous records		
Hulbert Creek 2 Trout Road at Hwy 23 *	4.0	6.3
Hulbert Creek 3 at Oak Hill Road **	1.0	0.9

* Hulbert Creek 2 Q_{80} was estimated using miscellaneous measurement on 9/26/02 (5.48 cfs) multiplied by the ratio (0.73) of 05403630 Q_{80} (3.4 cfs) and its 9/26/02 miscellaneous measurement (4.65 cfs)
** Hulbert Creek 3 Q_{80} was estimated using miscellaneous measurement on 9/26/02 (1.3 cfs) multiplied by the ratio (0.73) of 05403630 Q_{80} (3.4 cfs) and its 9/26/02 miscellaneous measurement (4.65 cfs)

Two conductivity inhomogeneities that were part of the regional GFLOW model are included in this inset model: the northern glacial inhomogeneity, representing glacial sediments to the east of the Dells, and the uplands west of the Dells, representing an area with low K_h (fig. A6-1). The uplands inhomogeneity was put in the regional model to improve calibration (by increasing the simulated heads) to water levels measured in shallow domestic wells to the west and northwest of the Dells/Lake Delton area. The domestic wells are open to sandstone units higher in the stratigraphic section, such as the Tunnel City and Wonewoc, which may have a lower K_h than the Eau Claire and Mt. Simon formations in this area of Sauk county. Alternatively, there may be a stratigraphic horizon in the upper portions of the section that restricts the downward flow of groundwater in the uplands, resulting in the higher water levels measured in the domestic wells. The recharge and K_h values for these inhomogeneities were not changed from those used in the regional model, though the boundaries were defined with more detail in the vicinity of the municipal wells. A large proportion of the area of interest in this inset model is encompassed by these two inhomogeneities.

Model calibration was achieved through trial and error by matching flux targets within the inset model area while maintaining the match to target heads. The regional GFLOW model parameter values were used as a starting point, and the recharge and Kh in the inset model were then increased proportionally in order to maintain the same ratio as in the regional model and thus maintain the match to head targets while increasing stream flux. The inset model calibration targets included fluxes and head targets falling within the inset model domain. The best calibration was obtained using a regional recharge of 10 in/yr and a proportional increase in K_h to 25.3 ft/d.

Sensitivity analysis was performed on the effect of the location of the boundary of the inhomogeneity representing a low-K area west of the Dells, because of its proximity to wells Lake Delton #3 and #5 and Wisconsin Dells #4 and #5. When the boundary of the inhomogeneity was moved closer to Wisconsin Dells #5, there was a small change in the resulting 5-year ZOC.

Results and Conclusions

ZOCs for Wisconsin Dells and Lake Delton wells are shown in Plate 2. Only the 5-year ZOCs are shown for Wisconsin Dells located in Columbia County (wells #1, 2, 3, and 6) because this shorter travel time results in flow paths relatively close to the Wisconsin River, where this model is expected to be a reasonable representation of hydrologic conditions. The 50- and 100-year ZOCs are not reported for these wells because the model was not calibrated to local conditions in Columbia County, and the quality of model simulations of these ZOCs could not be evaluated.

Flow paths to Wisconsin Dells #4 are long, originating from the northwest. The 100-year ZOC includes land in Juneau County. Flow to Wisconsin Dells #5, and Lake Delton #3 and #5 is from the west, and the 50- and 100-year ZOCs for these wells are affected by the locations of the low-K and glacial inhomogeneities in the model. Flow to Lake Delton wells #1 and #2 is from the south, and these ZOCs are not affected by inhomogeneities incorporated in the model. Because the sensitivity of these ZOCs to the location of the inhomogeneity boundary is relatively small, this model is useful for simulating the ZOCs. However, because of the large size of the inhomogeneities relative to the area of interest, the calibrated model aquifer parameters for this area reflect an average of the hydraulic properties of the rocks in the uplands, the glacial deposits, and the sandstone aquifer underlying them.

Backwards particle tracking for Lake Delton #4, which is located at the eastern end of Lake Delton, showed that all particle traces to the well originate from within the line sinks representing Lake Delton. This suggests that in addition to the sandstone aquifer underlying the lake, Lake Delton itself may be a source of water to this well. Additional field work evaluating the hydraulic connection between Lake Delton and the underlying aquifer would be necessary to determine the extent to which Lake Delton recharges the aquifer and ultimately provides water to the well. The 50- and 100-year ZOCs for this well also terminate within the aquifer underlying the lake.

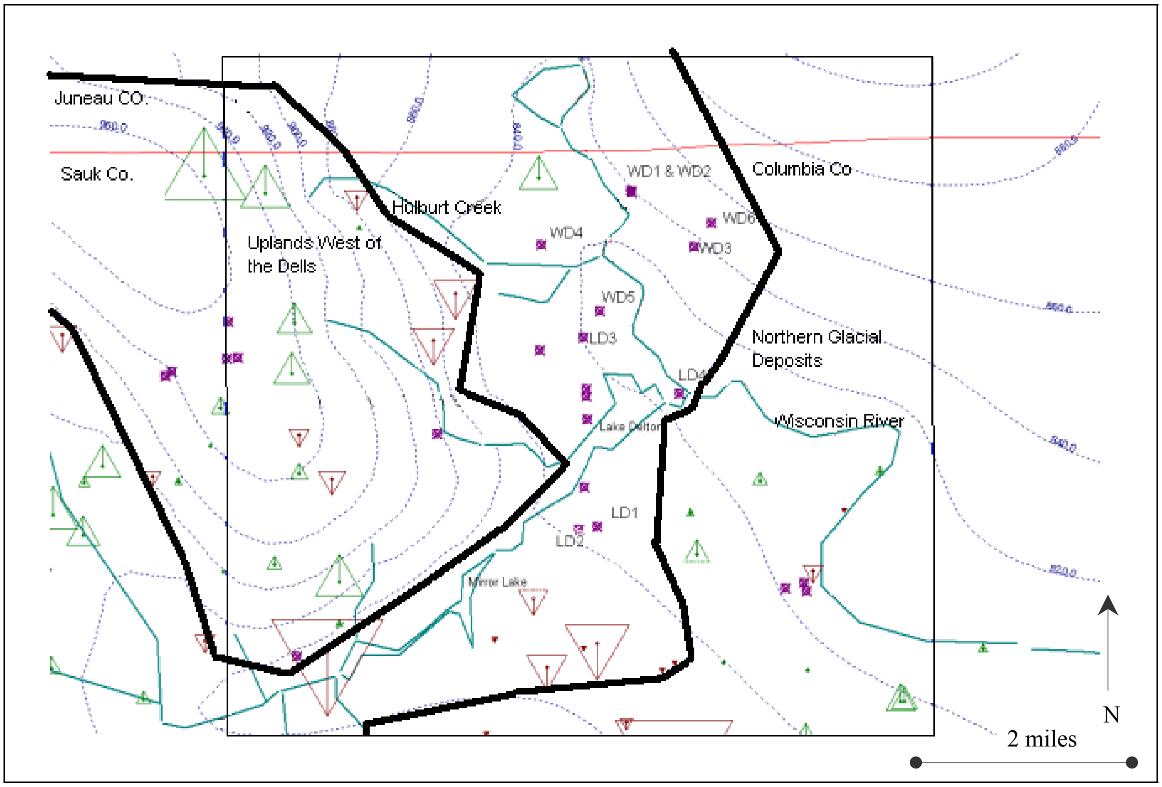

Figure A6-1. Figure A6-1. Area of regional model refined for Wisconsin Dells and Lake Delton. Well locations, water table contours, linesink strings, and the northern county boundary are shown. Areas of the two inhomogeneities (uplands west of the dells and the northern glacial deposits) are shown with heavy lines. Global recharge and K_h values are assigned to area between inhomogeneities. Triangles are scaled to represent error between simulated value and target.