MEMORANDUM REPORT NO. 167

SIMULATION OF SHALLOW GROUNDWATER FLOW IN THE VICINITY OF THE VILLAGE OF EAGLE

WAUKESHA COUNTY WISCONSIN

WISCONSIN GEOLOGICAL AND NATURAL HISTORY SURVEY
UNIVERSITY OF WISCONSIN-EXTENSION

SOUTHEASTERN WISCONSIN REGIONAL PLANNING COMMISSION

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WAUKESHA COUNTY, WISCONSIN

Prepared by the

Southeastern Wisconsin Regional Planning Commission
and
Wisconsin Geological and Natural History Survey (WGNHS), University of Wisconsin-Extension (UWEX)

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SOUTHEASTERN WISCONSIN REGIONAL PLANNING COMMISSION

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STATEMENT OF THE EXECUTIVE DIRECTOR

This report documents a study which simulated shallow groundwater flow in the vicinity of the Village of Eagle, specifically evaluating the potential effects of two Village of Eagle high capacity municipal water supply wells that are developed in the shallow aquifer and that went into operation in 2004. The study 1) investigates the effects of the municipal wells on groundwater flows to Eagle Springs and Lulu Lakes, associated springs and wetlands, and existing private domestic wells; 2) delineates areas influenced by the wells and areas contributing flow to the wells; 3) provides a tool to predict impacts to surface waters from present and future development; and 4) documents a methodology for using the previously developed Southeastern Wisconsin regional groundwater aquifer simulation model to create a refined smaller-scale submodel.

In 2003, the Village and Town of Eagle and the Eagle Spring Lake Management District requested that the Southeastern Wisconsin Regional Planning Commission (SEWRPC) conduct the study. The analysis was a cooperative effort involving SEWRPC and the Wisconsin Geological and Natural History Survey (WGNHS), University of Wisconsin-Extension. The study was funded by SEWRPC and the WGNHS. This report was prepared by the WGNHS and was conducted under the guidance of SEWRPC's Technical Advisory Committee on Groundwater Resources, whose membership includes both groundwater users and individuals with technical expertise in this field.

The development of the aquifer submodel documented herein represents an important step in understanding and maintaining the surface water and groundwater resources in the vicinity of the Village of Eagle and it establishes an approach to studying similar situations in Southeastern Wisconsin.

Respectfully Submitted,

Philip C. Evenson

Philip C. Evenson
Executive Director

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Introduction

Purpose

The purpose of this project is to demonstrate the development of a detailed groundwater flow model for the Village of Eagle, Wisconsin, located in southwestern Waukesha County. The local-scale model is derived in part from a large regional-scale model for southeastern Wisconsin (Feinstein and others, 2005a, 2005b) recently developed by the Wisconsin Geological and Natural History Survey (WGNHS) and U.S. Geological Survey (USGS) in cooperation with the Southeastern Wisconsin Regional Planning Commission (SEWRPC). The resolution of the regional flow model is necessarily coarse (~2500 foot minimum grid cell size), and not suited to the investigation of small-scale groundwater flow problems, which are of interest to many municipalities and other groups in the region.

The regional model provides a framework and starting point for development of refined, more-detailed groundwater flow models focused on specific areas of interest (for example, the township or village scale) and having specific objectives. Such local-scale models require more detailed representation of the hydrogeologic framework and surface water features than is possible in the regional model. Methods for developing refined models are needed to investigate problems such as the impacts of local groundwater pumping on local lakes, streams, and wetlands.

Project setting and scope

The model described in this report encompasses the Town of Eagle and portions of nearby watersheds of Lulu Lake and its tributaries, Eagle Spring Lake, Jericho Creek, and the upper Scuppernong River and Mukwonago River (figure 1). This local area was selected at the suggestion of SEWRPC, the Village and Town of Eagle, the Eagle Spring Lake Management District, and The Nature Conservancy. These parties identified concerns about the possible impact of two new shallow water supply wells for the Village of Eagle on nearby surface water and existing domestic wells. These new supply wells pump from a shallow sand and gravel aquifer. The shallow sand and gravel interacts with the deeper regional bedrock aquifer system, and this hydrogeologic complexity is similar to other areas of southeastern Wisconsin where refined groundwater flow models may be useful.

Portions of this report are based on an earlier unpublished report by Eaton (2004).

Objectives

This project has four major objectives:

1. Investigate the effect of the two new Village of Eagle municipal wells on flows to Lulu and Eagle Springs Lakes, associated springs and wetlands, and existing private domestic wells. Delineate areas of influence and contributing areas, and estimate groundwater travel time to the municipal wells.

2. Quantify predevelopment and modern fluxes to and capture zones for major surface water features in the area.
3. Provide a tool to predict impacts to surface waters from present and future development.
4. Document the methods of using the regional SEWRPC model to develop a refined submodel of a smaller area and performing the above analyses.

Acknowledgments

Dr. Timothy Eaton, currently at Queens College, City University of New York, prepared an earlier draft report on this project. Appreciation is expressed to the Village and Town of Eagle for requesting this study, and the Southeastern Wisconsin Regional Planning Commission for sponsoring and providing funding for the work involved. Professor Jean Bahr and her 2003 Hydrogeology field class collected stream flow data used in model calibration. Daniel Feinstein of the U S Geological Survey provided a critical review of this report.

Background

SEWRPC Regional Groundwater Flow Model

The SEWRPC regional groundwater flow model was developed by the USGS and WGNHS in cooperation with SEWRPC and with major funding from water utilities in the 7-county SEWRPC region. SEWRPC Technical Report 41 (*A Regional Aquifer Simulation Model for Southeastern Wisconsin*, SEWRPC, 2005) contains two reports (Feinstein and others, 2005b, 2005b) documenting model construction, calibration and use. Although the regional model includes all aquifer units in the region, its focus is on groundwater flow in the deep sandstone aquifer, which is the source of water for many deep high-capacity wells in the region. The regional model results demonstrate that these wells have caused significant drawdown in water levels in the deep sandstone aquifer. The regional model also demonstrates that these deep drawdowns induce downward flow from overlying shallow aquifers and surface-water features. The possible impacts of this increased downward flow included lowered water-table and surface-water levels and reduced base flow in streams, but it is difficult to document these impacts without extensive field study.

The regional SEWRPC model is based on a numerical finite-difference grid and uses the MODFLOW groundwater modeling code (McDonald and Harbaugh, 1988). Resolution of the regional model is limited by the grid spacing, which has a minimum size of 2500 feet. This resolution is generally too coarse to include more than very general shallow hydrologic features. Figure 2 shows the location of the Village and Town of Eagle along with part of the regional model grid.

Hydrogeology of the Eagle area

The Village and Town of Eagle are located in the southwestern corner of Waukesha County. Local geology consists of unlithified (sand, gravel, and clay) deposits of

Quaternary age over a series of bedrock units. Gonthier (1975) and SEWRPC (2002) describe the general hydrogeology of the area, and Clayton (2001) presents detailed descriptions and maps of the Pleistocene geology of Waukesha County. The area is adjacent to the famous Kettle Moraine, where glacial depositional features have resulted in a landscape with striking topographic features, including kettle holes, small lakes and ponds, and steeply rolling topography. The surficial geologic materials in and just south of the Village of Eagle consist of unlithified sands and gravels deposited by braided meltwater streams flowing from the northeast (figure 3). These unlithified materials cover the local bedrock, which consists of Silurian dolomite, Ordovician shale of the Maquoketa Formation, and dolomite of the Sinnipee Group (Clayton, 2001). Figure 4 shows a representative cross section through the Eagle area. The sand and gravel deposits are generally very permeable (Gonthier, 1975) and, even though locally less than 100 ft thick, they form a prolific and important shallow sand and gravel aquifer.

All residents of the Town and Village of Eagle use groundwater as a source of water supply. The Village operates a municipal water utility that supplies water to homes and businesses within the municipal service area. The village does not have a wastewater treatment plant, and village residents use onsite septic systems to dispose of wastewater. Outside the service area residents commonly operate private domestic wells for water supply. These domestic wells are generally completed in sand and gravel or in the Silurian dolomite aquifer.

Local surface water features

Numerous important and unique surface-water features occur in the vicinity of Eagle. The Village lies on near the topographic divide between the Mukwonago River watershed to the south and the Scuppernong River watershed to the north. The Mukwonago River watershed contains the Lulu State Natural Area, a region of important wetlands and springs. Lulu Lake and Eagle Spring Lake are major surface water features, and these lakes and the surrounding wetlands depend on groundwater discharge for base flow. Bahr and Trethewey (2005) and Gittings (2005) conducted detailed field and modeling studies of the springs in the Mukwonago River watershed. About three miles east of Eagle, Jericho Creek flows into Eagle Springs Lake. Northwest of the Village, the Scuppernong watershed, part of the Kettle Moraine State Forest, also contains vast wetlands and many springs. Paradise Springs, located about three miles west of Eagle has a discharge of approximately 500 gallons per minute (WDNR, 2005) and once supported a spring water bottling company. Figure 1 shows major hydrologic features in the area. Scuppernong Springs, located about four miles north of Eagle, and Stute Spring, located about three miles southwest of Eagle, are other nearby springs of historic significance located just outside of the area shown in figure 1.

New high-capacity wells for the Village of Eagle

Prior to 2003, the Village of Eagle Water Utility utilized two deep wells completed in the sandstone aquifer. Although these wells provided sufficient yield for the Village needs they produced water containing elevated levels of radioactivity, primarily radium. These radioactivity levels exceeded state and federal maximum levels for safe drinking water. Water treatment options for radium removal are complex and expensive, and the Village was forced to seek an alternative groundwater supply.

The shallow sand and gravel aquifer south of the Village was identified by the Village as a reasonable alternative to the deep aquifer for a groundwater source. After conducting a series of test borings, the Village's consultants selected a site south of the Village, in the northwest quarter of section 33, township 5N, range 17E for the installation of two new high capacity wells. These wells were installed in the sand and gravel aquifer, and a pipeline was constructed to the Village distribution system. The wells, referred to as wells 3 and 4, went online in 2004, and the Utility reduced use of the existing deep sandstone wells (wells 1 and 2). The new shallow wells produce water of excellent quality with no radioactivity.

Methodology

Conceptual model

Any groundwater model is based on a conceptual model of the real-world system, and is a simplification of the complex arrangement of geologic units, hydrologic features, and hydraulic stresses that occur in a real system. Numerical groundwater models translate physical features into a series of mathematical equations and then solve these equations using a computer. The conceptual model must include the relevant physical extent of the area of interest, physical and hydraulic boundaries to the area, hydraulic properties of the geologic units present, and the mass balance of the system (recharge, discharge, changes in storage). The conceptual model must be relevant to the specific questions to be addressed by the modeling exercise and should be as simple as possible to explain the system yet contain enough detail to be credible.

Figure 5 illustrates a conceptual model of the Eagle area. The model consists of a sand and gravel aquifer over bedrock. The bedrock consists of Silurian dolomite, Ordovician shale of the Maquoketa Formation, and Ordovician dolomite of the Sinnipee Group. The purpose of the Eagle model is to help evaluate groundwater flow in the sand and gravel aquifer. Groundwater also occurs in the bedrock units, but the hydraulic conductivity of these units is generally an order of magnitude less than the hydraulic conductivity of the sand and gravel. In the regional SEWRPC model, Feinstein and others (2005) assigned the sand and gravel in the Eagle area a hydraulic conductivity of 10 ft/day, while they assigned bedrock in the area values of 1-4 ft/day (Silurian dolomite), 0.0003-.3 ft/day (Maquoketa Formation), and 0.04-0.3 ft/day (Sinnipee Group). Furthermore, inspection of regional model output for the Eagle area showed that groundwater flow through the sand and gravel is almost entirely horizontal, while flow through the bedrock units is mostly vertical. Accordingly, the conceptual model need consider only horizontal groundwater flow through the aquifer and a two-dimensional model is appropriate for this problem. Although small vertical hydraulic gradients undoubtedly occur near wells and surface-water discharge points, ignoring these gradients should have no perceptible effect on overall model results (Haitjema, 1995).

The sand and gravel aquifer is unconfined, and the water table represents the top of the aquifer. The base of the aquifer coincides with the top of the bedrock surface, without regard for the specific bedrock formation. The bedrock surface in the Eagle area is an uneven erosional surface.

Water enters the aquifer as recharge from above and as flow out of particular surface water bodies. Water exits the aquifer as downward flow toward deeper bedrock units. The regional SEWRPC model allows quantification of the magnitude and location of this downward flow. Water also exits the model as flow to lakes, streams, and wetlands and as discharge to pumping wells. For these analyses, the system is assumed to be at steady state.

Model code selection

Description of GFLOW modeling code

The Eagle model uses the GFLOW 2.1.0 analytic element groundwater modeling code (Haitjema, 2005). This code is significantly different than the 3-dimensional MODFLOW finite-difference modeling code (McDonald and Harbaugh, 1988) utilized in both the regional SEWRPC model (Feinstein and others, 2005) and an earlier numerical model of the Eagle area (Eaton, 2004). Analytic element models have particular advantages for shallow groundwater problems involving significant groundwater-surface water interaction (Haitjema, 1995). Analytic element models utilize exact analytical solutions to a series of mathematical equations describing groundwater flow. The analytic element method represents each important hydrologic feature, such as a well, stream, or lake, by a series of analytic equations. The method superimposes the solutions to these equations to produce exact values of hydraulic head or hydraulic flux at any point in the model domain. The analytic element method is thus independent of scale, and does not require a mathematical grid. It yields exact solutions for problems at any scale, from a few square feet to many square miles. Accordingly, the method is very useful for groundwater problems such as the Eagle situation, where the model must represent regional effects as well as small-scale groundwater-surface water interactions.

The GFLOW code, like most analytic element codes, also has limitations. First, it is limited to flow problems that occur in two dimensions (called Dupuit-Forchheimer flow), and does not simulate vertical groundwater flow. However, it does mathematically approximate vertical particle movement using continuity considerations (Haitjema, 1995). Second, GFLOW has only limited ability to represent spatial heterogeneity. The code simulates spatial variations in parameters such as hydraulic conductivity, base elevation, and recharge by the addition of discrete zones called *heterogeneities* in GFLOW parlance. Although heterogeneities can have complicated shapes, and so can represent complex features, they contribute complexity to the analytical model solution and so must be used sparingly. In spite of these limitations, the GFLOW model is quite appropriate for the Eagle simulations.

The GFLOW model constructed for the vicinity of Eagle has the following characteristics:

- It represents groundwater as two-dimensional and steady state, and treats the sand-and-gravel aquifer as a single layer with variable thickness and hydraulic conductivity;
- It includes aerially-distributed recharge and downward flow to the deep sandstone aquifer;
- It simulates major surface-water bodies as a series of line sinks, and solves the conjunctive groundwater-surface water problem to evaluate base flow in major surface water features;
- It simulates the two Eagle municipal wells;
- It simulates groundwater flow paths and flow rates using forward and backward advective particle tracking;
- It links directly to base maps and GIS coverages, so that modeling is done directly on top of the base map;
- It is interactive, easily modified, and runs quickly; and
- It is linked to the parameter estimation program PEST (described below).

The GFLOW code is a steady-state code, meaning that it cannot simulate changes in groundwater storage or changes in groundwater levels through time. However, the GFLOW package contains a utility grid extraction module that allows construction of a simple finite-difference transient model that can be used to evaluate how long the system takes to reach steady state and to show how the system responds to short-term changes in pumping rates.

Model calibration

Model calibration is the process of adjusting model parameters (in the Eagle case, hydraulic conductivity, recharge rates, and streambed properties) within reasonable limits until the output of model simulations (hydraulic heads and fluxes of water) reasonably matches target values observed in the field. Calibration targets for the Eagle model consisted of water levels in local wells and water fluxes (flows) measured at local surface water features.

Head targets

Head targets included water levels in 109 local wells and surface water features (figure 6). Wells used for head targets were identified using well construction reports available in the WGNHS files. Only wells completed in the sand and gravel and having good construction records were used. Using modern and historic plat maps, WGNHS workers plotted the location of these wells on 1:24000 scale topographic maps, and estimated the surface elevation of each well from the map contours. Depth to static water in each well was taken from the well construction reports. Subtracting the depth to water from the surface elevation gives the hydraulic head in each well, in feet above sea level. The elevation of standing water in small permanent pothole lakes in the area provided several additional head calibration points; these elevations were estimated from topographic maps.

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

Flux targets

Flux (flow) targets included surface-water discharge measurements at five locations in the Upper Mukwonago River watershed (Jean Bahr, personal communication) plus an additional measurement at Paradise Springs, in the Scuppernong River watershed (WDNR, 2005). Figure 6 shows the flow measurement locations. As with the head targets, the flux targets contain considerable uncertainty. The Upper Mukwonago River is a low-flow stream with an often ill-defined channel, or multiple channels, through wetland complexes. Accurate measurement of surface-water flows in such situations is very difficult. Furthermore, the calibration targets assume base flow conditions and only relate to groundwater discharge, a situation difficult to verify in the field. Finally, as flows become lower, potential measurement errors become statistically proportionally higher. In spite of these uncertainties the available flux measurements are considered adequate to calibrate the Eagle groundwater flow model.

PEST parameter-estimation code

The PEST parameter estimation utility was used to aid model calibration. PEST (Dougherty, 2004) is a model-independent computer code that uses linear and nonlinear regression techniques to seek a best model fit to a given set of calibration targets. PEST links directly to the GFLOW 2.0.1 code and runs the flow model iteratively as it varies input parameters within a user-specified range and computes model sensitivity to each parameter. The model calibration process assigned equal weight to each of the two groups of head targets and flux targets.

Model predictions

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

Drawdown

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

Surface-water flows

GFLOW outputs simulated flux (flow) to or from every line sink representing a surface water feature. Differences in flux between the base (calibrated) run and subsequent runs represent the impacts of changes in the hydrologic regime on flow to surface water features. Note that GFLOW, as implemented in this study, does not simulate the *elevation* of surface water features, such as lakes or wetlands. Elevations of these features are part of the model input and are held constant. GFLOW does have the capability of simulating the elevation of surface-water features, such as lakes, but such simulation was beyond the scope of this study.

Contributing areas for wells and surface water features

GFLOW delineates groundwater flow paths and the contributing areas for wells and surface water features by advective particle tracking. Mathematical "particles" of water can be place at any point in the model domain; the code will then track these particles appropriately through the groundwater flow field. Tracking particles backward from a well is a common technique for delineating contributing areas for wells or surface water features.

Model Construction

Aquifer definition

This study simulates the upper, unconfined, sand and gravel aquifer in the Eagle region. This aquifer is continuous throughout the area of interest and is the most hydraulically conductive shallow aquifer present. Many local shallow wells are completed in the sand and gravel aquifer. Additional local wells obtain water from the Silurian dolomite aquifer, located immediately below the sand and gravel in part of the study area. This model does not simulate the dolomite aquifer or underlying bedrock.

Aquifer zonation

Aquifer zonation refers to division of the aquifer into zones of different hydraulic properties. Although the available Pleistocene materials maps (e.g. Clayton, 2001) provide some basis for aquifer zonation, such as making hydraulic distinctions between different types of braided stream sediment shown on maps, the model proved to be insensitive to such zonation during calibration. The final model consisted of only two zones of hydraulic conductivity, with an area of uncollapsed stream sediment to the northeast of Eagle having a higher hydraulic conductivity than the base value.

Hydraulic conductivities

The base value of hydraulic conductivity in the final calibrated model was 11 ft/day, with a value for uncollapsed braided stream sediment of 46 ft/day. These values are in the range suggested by Gonthier (1975) and also in the range required for calibration of the regional SEWRPC model (Feinstein, 2005). However, they are significantly less than values near 200 ft/day determined by consultants for the Village of Eagle using pumping tests on the new Village wells (AS&T, 2003). Based on these tests it is likely that a zone of higher hydraulic conductivity material occurs in the immediate vicinity of the new wells. However placing such a zone in the model did not improve model calibration, and there is no information about the lateral extent or shape of this high-hydraulic conductivity zone.

Boundary conditions

Far field boundaries

The GFLOW code uses the concept of far field and near field hydraulic boundaries. *Far field* boundaries are major surface water features located distant enough from the area of interest so that stresses at the area of interest do not reach the boundaries. The Eagle model represents far field boundaries as head-specified line sinks having no resistance to groundwater- surface water exchange. At these boundaries, the water table is assumed to be coincident with and directly connected to the surface water feature. The purpose of the far field boundaries is to anchor the model solution (hydraulic heads) at the perimeter of the model. Far field line sinks are not intended to simulate hydraulic features exactly and so are only coarse approximations of real-world features. No model analysis occurs in the far field region.

Near field features

The model *near field* encompasses the area of interest. Model features in the near field consist of point sinks (wells) and line sinks (rivers, lakes, drains, and wetlands). Near field line sinks can include resistance to groundwater-surface water exchange and also include surface-water routing. Near field features are entered very precisely as a series of nodes following the trace of surface water features, such as a stream or lake shoreline.

Figure 7 shows the far field and near field regions of the eagle GFLOW model. The near field region includes all features of interest near the Village and Town of Eagle (figure 1). The model represents surface-water features with 462 linesinks grouped into 62 segments each representing a stretch of river, wetland, or lake.

Along the Upper Mukwonago River and lakes (including Lulu Lake and Eagle Spring Lake) the model uses line sinks that have a specific hydraulic resistance to groundwater inflow. This hydraulic resistance represents the presence of silty or clayey sediments in the streambed or lake bottom, and has the dimensions of days (thickness divided by hydraulic conductivity). Haitjema (1995) give a comprehensive explanation of line sink resistance. Most line sinks in the model were assigned a resistance of 1 day; the resistances of some line sinks in the upper reaches of the Mukwonago were varied during the calibration process.

Upper and lower boundaries

The upper boundary of the model is the water table. The simulated aquifer is unconfined, and the water table moves in response to stresses on the model. The lower boundary of the model is the bedrock surface. The bedrock surface in the region is know to be irregular, particularly where it slopes to the Troy Valley to the south. The GFLOW model cannot include a continuous irregular bedrock surface but does allow zonation of the surface through a series of model heterogeneities. Actual bedrock elevations in the study area vary from about 550 to 950 feet above sea level (WGNHS unpublished data). The GFLOW model uses a base elevation of 700 feet, and includes an inhomogeneity representing the Troy Valley with an elevation of 550 feet. The model proved insensitive to a second inhomogeneity above 900 feet, and in fact this inhomogeneity degraded the model calibration and was removed.

Recharge

Recharge is the addition of water to the model from infiltrated precipitation - rainfall and snowmelt. Most investigators believe that recharge varies spatially in response to differences to topography, soil properties, vegetation, and other parameters. Recharge also varies seasonally. The Eagle model is a steady-state model, and uses steady-state average recharge applied to the model in a series of inhomogeneity zones.

Recharge zonation

The model uses a recharge zonation developed by Cherkauer (2001) for the regional SEWRPC model. Cherkauer based his zonation on base flow calculations from surface-water subbasins, and his estimates for the Eagle area range between 4 and 11 inches per year. Figure 8 shows the recharge zonation. The model recharge process varied these recharge rates as shown in Table 3.

Return flow

Return flow, or effluent discharged from onsite septic systems, is also an important source of recharge in the Eagle area. The Village of Eagle does not operate a municipal wastewater treatment system; instead, wastewater is disposed through individual septic systems distributed throughout the Village. This water leaches through septic drainfields and eventually reaches the water table. There are no reliable measurements of the actual volume of effluent discharged in this way, but a conservative estimate of the total discharge is about 80% of water pumped, meaning that there is a 20% loss through evaporation and offsite disposal. The model simulates return flow by adding recharge at a rate of 80% of water pumped distributed uniformly over the area of the Village. Return flow was included in all model runs.

Vertical flux due to regional pumping

Regional pumping from the deep sandstone aquifer in southeast Wisconsin has induced significant movement of groundwater from the shallow to the deep system (Feinstein and others, 2005). The regional SEWRPC model quantifies this increased vertical flux, and the Eagle model includes this vertical "leakage out the bottom" as one sink for the simulated groundwater flow system. Based on results of the transient SEWRPC model (Feinstein and others, 2005) the vertical flux from the upper sand and gravel aquifer to the deeper sandstone aquifer in the Eagle region is between 0.0001 and 0.0005 ft/day (0.4 - 2.2 in/yr). The Eagle model approximates these downward fluxes through additional inhomogeneities that include equivalent negative recharge approximating the water lost to the deeper aquifer.

High-capacity wells

The two new high-capacity wells for Village of Eagle are located in the NW1/4 of the NE1/4 of Section 33, T5N, R17E. The Village designates these wells as wells 3 and 4. The wells, respectively, are 102 and 108 feet deep, 12 inches in diameter, with wire-wrapped slotted screens over the bottom 20 feet. The wells were completed in 2003 and went online in 2004.

Pumping rates

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

Table 1 shows pumping rates for the Eagle wells. Reported rates are available from the Village consultant (Aquifer Science and Technology, personal communication), and from a 2004 summary maintained by the Wisconsin Public Service Commission. For purposes of simulating municipal pumping for wellhead protection, the Wisconsin source water protection program (SWAP) recommends using pumping rates calculated as the past year of record plus a 15 percent safety factor to account for future pumping increases as well as being conservative in case of model inaccuracy. In order to be consistent with other simulations done for Wisconsin's SWAP program the Eagle model uses these SWAP pumping rates, which are 57 gpm or 10915 ft^3/day for each well (table 1).

Table 1. Pumping rates for the Eagle wells

Well	pump capacity		1/2 pump capacity		consultant's reported rates		2004 PSC records		SWAP projection rates	
	gpm	cfd	gpm	cfd	gpm	cfd	gpm	cfd	gpm	cfd
3	450	86571	225	43286	55	10581	49	9491	57	10915
4	450	86571	225	43286	55	10581	49	9491	57	10915
	notes:									
	1:	*1 gallon = 0.1336 ft3; 1 gpm = 192.38 ft3/day*								
	2:	*model pumping rates represent average continuous pumping over one year*								
	3:	*SWAP rates represent average annual pumping plus 15%*								

Results of model calibration

Calibration process

The calibration process utilized the PEST parameter estimation code in conjunction with professional judgment about model stability and reasonability. Calibration runs included all model features except the new Village wells, which were turned off. The best calibration, referred to as the *calibrated base case*, produced a reasonable match between model simulated and field-measured target values for both the head and the flux data sets. As with any model, a perfect calibration was not possible. The early results of the calibration process suggested that the model was overly complex, and justified removal of several inhomogeneities representing variations in hydraulic conductivity and aquifer thickness.   Overall the calibration process required over 30 PEST runs, and each PEST run executed the model 75 to 150 times.

Figure 9 shows a plot of observed versus simulated heads at the targets. Although some significant outliers occur, the correspondence of measured to simulated heads is very good, with a median error of 3.6 feet and a mean absolute error of just over 10 feet. Recall that the estimated error in the calibration targets is plus or minus 5 feet.

The calibration to fluxes is also considered quite acceptable (figure 10). The model simulates the largest flux - the inlet of Lulu Lake - almost exactly. Other targets fall about equally on either side of the 1:1 line. The model underestimates springflow at flux sites 4 and 6, possibly because the springs receive some contribution from bedrock aquifers (Bahr and Trethewey, 2005) and the Eagle model does not include the bedrock. The model overestimates flow in the upper Mukwonago River at site 3. Additional field investigations would be necessary to improve model calibration in this area.

Calibrated water table

The simulated pre-pumping (base run) water table in the Eagle area slopes smoothly from the groundwater divide to local surface-water features (figure 11). The groundwater divide occurs at an elevation of about 885 ft in the vicinity of the new well location.

Summary of calibrated parameters

Table 2 summarizes the calibrated parameters. Note that the model calibration process suggested that both hydraulic conductivity and some recharge rates should be lower than initially assumed.   Calibrated results are considered to be very reasonable.

Table 2. Summary of model calibration parameters. See figure 8 for location of recharge zones.

Parameter	initial value				calibration value			
base hydraulic conductivity	10	ft/d			9.8	ft/d		
outwash hydraulic conductivity	100	ft/d			46.4	ft/d		
outwash in wellfield area	200	ft/d			absent	ft/d		
Muk 1 recharge	0.0019	ft/d	8.3	in/yr	0.0009	ft/d	3.9	in/yr
Muk 2 recharge	0.0017	ft/d	7.4	in/yr	0.0009	ft/d	3.9	in/yr
Muk 3 recharge	0.0014	ft/d	6.1	in/yr	0.0019	ft/d	8.3	in/yr
Muk 4 recharge	0.001	ft/d	4.4	in/yr	0.0022	ft/d	9.6	in/yr
Muk 5/8 recharge	0.00127	ft/d	5.6	in/yr	0.0009	ft/d	3.9	in/yr
Muk 6 recharge	0.00145	ft/d	6.4	in/yr	0.0009	ft/d	3.9	in/yr
Scu 1 recharge	0.0021	ft/d	9.2	in/yr	0.0039	ft/d	17.1	in/yr
Scu 3 recharge	0.00182	ft/d	8.0	in/yr	0.0040	ft/d	17.5	in/yr
Sug 5/9 recharge	0.0026	ft/d	11.4	in/yr	0.0009	ft/d	3.9	in/yr

Parameter sensitivity

Parameter sensitivity refers to the amount of change in the overall model fit for a change in value of the calibration parameters. PEST calculates sensitivity matrices for each parameter used in the calibration process. Table 3 reports the overall model sensitivity for all calibration parameters. Based on these results, the model is most sensitive to the regional hydraulic conductivity and to recharge in the Upper Mukwonago (Mukwonago 1) and Mukwonago 3 subwatersheds (see figure 8 for watershed locations). The model is less sensitive to the hydraulic conductivity of the outwash northeast of the Village and to recharge in other parts of the domain.

Table 3. Sensitivity of calibration parameters based on PEST calibration. Note that relative sensitivity is a dimensionless number indicating the relative sensitivity of the overall model solution to various parameters, with higher numbers indicating more sensitivity.

Model parameter	Group	calibrated value	relative sensitivity
regional K, ft/day	kh	9.8	6.0
outwash K, ft/day	khi	46.4	1.2
Muk 1 recharge, in/yr	rch	3.9	1.8
Mul 2 recharge, in/yr	rch	3.9	0.15
Muk 3 recharge, in/yr	rch	8.3	0.71
Muk 4 recharge, in/yr	rch	9.6	0.36
Muk 5&8 recharge, in/yr	rch	3.9	0.095
Muk 6 recharge, in/yr	rch	3.9	0.057
Muk 7 recharge, in/yr	rch	17.1	0.056
Scu 1 recharge, in/yr	rch	17.5	0.34
Scu 3 recharge, in/yr	rch	3.9	0.32
Sug 5&9 recharge, in/yr	rch	3.9	0.21

Model Predictions

Predictive model runs use the calibrated model with the two pumping wells added. Comparison of the hydraulic head fields and groundwater fluxes produced by the base case and stressed case shows the effects of the new Village wells.

Water table configuration

The presence of wells 3 and 4 pumping continuously alters the water table in the vicinity of the well field (figure 12). The 880 ft contour bows nearly ½ mile to the northwest, and other contours move more slightly to the northwest. However, the presence of the wells does not appreciably affect the overall hydraulic gradient toward the Mukwonago River.

Drawdown around municipal wells 3 and 4

Simulated steady-state drawdown in the vicinity of wells 3 and 4 is nearly 6 feet at the wells (figure 13). The wells create a shallow cone of depression nearly 1.5 miles wide. Simulated drawdowns of about one foot occur up to about 1.5 miles from the wells.

Magnitude of natural local water-level fluctuations

The drawdowns anticipated near the two new Village wells are of about the same magnitude as natural water-level fluctuations observed in two nearby long-term observation wells. Long-term observations from shallow wells near Mukwonago (well WK-1301) and Lulu Lake (well WW-0908) show that the water table in upland areas (as represented by WK-1301) fluctuates as much as three or four feet in an average year and as much as 6 feet in extreme years (figure 14). Near surface-water bodies, such as Lulu Lake, (represented by WW-0908) natural water-level fluctuations are less extreme - only about two feet in an average year.

Contributing areas for wells 3 and 4

Wells 3 and 4 capture groundwater flowing toward them from the north-northwest, and their joint steady-state contributing area extends about one mile in that direction (figure 15). This area includes part of the highway 67 corridor and much of the Old World Wisconsin site. The wells hydraulically interfere with each other, and the contributing area of well 4, the southeast (downgradient) well, wraps around the contributing area for well 3.

Figure 16 shows time-bounded contributing areas for travel times of 5, 10, and 50 years. The model generated these travel times using an effective porosity of 0.15; uncertainty in this porosity value would affect the travel distances but not the overall shape of the contributing areas.

Contributing areas for local surface-water features

Using backward particle tracking from the surface-water boundaries, the groundwater model simulates the contributing area for the north side of the Mukwonago River watershed, including Lulu and Eagle Spring Lakes (figures 17 and 18). The shaded area on these figures shows the land surface area beneath which groundwater flows to the watershed; path lines indicate specific flow directions throughout the area. The Village wells have negligible effect on the groundwater flow paths to these surface water features.

Simulated Impact of wells 3 and 4 on local surface-features

Flow reductions

Model simulations show how the village wells influence groundwater flow to local surface water features. GFLOW allows calculation of total groundwater flow into or out of any region or line sink in the model. Table 4 summarizes the well effects at the calibration points and at selected other features.

The model simulates significant flow reductions in the upper Mukwonago River at calibration targets 1 and 2 (table 4). However, the base flow in these reaches is very small, leading to large percentage errors in the model.

The model is probably more reliable in its predictions of impacts to flow at site 3, 4, and 5, where small reductions in base flows are predicted at sites 4 and 5. The most significant reduction in base flow is predicted at site 5, where the Mukwonago River enters Lulu Lake and the predicted base flow reduction is 3 percent of the base run, or about 10,000 cubic feet per day. It is important to note that the 3% reduction in flow in the river at the entrance to Lulu Lake does not mean that the lake itself receives 3% less flow; the lake also receives groundwater input from around its shoreline. Table 4 shows that the reduction in flow around the lake perimeter is very small - less than 0.01 percent. Flow reduction to the entire north side of the watershed (area delineated in figures 18 and 19) is about 1 percent of the total. Likewise, the flow reduction to Eagle Spring Lake is negligible.

Table 4. Simulated impacts Village wells on local hydrologic features. These simulations include return flow. Units are cubic feet per day (CFD) and cubic feet per second (CFS).

Flux point	site ID or description	base case, no wells		with pumping wells		difference		
		CFD	CFS	CFD	CFS	CFD	CFS	percent
Upper Mukwonago marsh	1	9620	0.11	2672	0.03	-6948	-0.08	-72%
Upper Mukwonago below reservoir	2	9273	0.11	2308	0.03	-6965	-0.08	-75%
Mukwonago R at Bluff Rd	3	118285	1.37	118060	1.37	-226	0.00	0%
Mukwonago R spring complex	4	44735	0.52	43844	0.51	-891	-0.01	-2%
Mukwonago R at Lulu Lk	5	298160	3.45	288428	3.34	-9733	-0.11	-3%
Paradise Spring	6	48083	0.56	47801	0.55	-282	0.00	-1%
Eagle Spring Lake	entire lake perimeter	209000	2.42	208495	2.41	-505	-0.01	0%
Lulu Lake	entire lake perimeter	11884	0.14	11878	0.14	-7	0.00	0%
north side Lulu Lake wetlands		120596	1.40	119339	1.38	-1257	-0.01	-1%
Mukwonago North Side Flux	entire north side contributing area	443800	5.14	440211	5.10	-3589	-0.04	-1%

Limitations of model predictions

The model predictions of impacts to water table levels and surface water flows are based on a series of assumptions that make them very conservative in the sense that they are more likely to over-predict than under-predict impacts. The assumptions are essential and reasonable for the scope and objectives of the Eagle model, but need to be clearly stated. These assumptions, and the effects of each assumption, are as follows:

- The model is at steady state.

  The steady-state model does not account for any water removed from or replaced to storage in the aquifer. Such a model tends to overestimate drawdown near the well but should still be relatively accurate for fluxes distant to the wells.

- The model does not include the high-conductive zone near the wells measured by pumping tests.

Pumping tests near the new Village wells detected a highly transmissive zone in the sand and gravel aquifer, and the subsequent success of these wells suggests that this zone is real. Model calibration was insensitive to such a zone, probably because pre-pumping hydraulic gradients near the well site were very low. Excluding this zone from the model probably results in overestimation of drawdown near the wells, but make little or no difference in distance flux predictions.

- The model may not accurately account for the ultimate fate of the water produced by the wells.

Much of the water produced by the Village wells is returned to the environment as wastewater discharge through local septic systems. This water eventually becomes part of groundwater recharge and replenishes the aquifer. The groundwater model simulates the return of 80% of the pumped water through onsite septic systems. This amount, and the actual locations of the septic systems are reasonable but untested assumptions.

- The model does not simulate the bedrock aquifer.

Bahr and Trethewey (2005) concluded that the bedrock aquifer might contribute significant flow to springs in the LuLu Lake area; the model described in this report does not simulate the bedrock. Ignoring these bedrock contributions might overestimate the impacts of the Village wells on the springs.

Evaluation of transient responses

Methodology

The steady-state results produced by GFLOW represent a conservative estimate of the impacts to the groundwater system because they assume that the wells pump steadily for an infinite amount of time with no removal of water from storage in the aquifer. Drawdowns and flow reductions simulated by the steady-state model represent the maximum impacts that might occur given enough time. A transient groundwater model helps predict how long the system will take to reach this steady state condition. The Appendix describes the construction of a simple transient groundwater flow model using the GFLOW grid extract utility. The transient model is uncalibrated and is only intended to be used to simulate transient effects near the pumping wells. This model uses the USGS MODFLOW code documented by McDonald and Harbaugh (1988).

Time required to reach steady state

Understanding the meaning of the steady-state condition requires an explanation of the source of groundwater that enters a well. In the sand-and-gravel aquifer near Eagle, water is stored in pores between the sand and gravel grains. A well that pumps from this aquifer obtains water from two different sources. The first source is the water stored in these pores; this is called aquifer storage. The second source is flow toward the well from recharge and water diverted from nearby surface-water features. As a well begins to pump, the water produced by the well initially comes from storage as the pores in the aquifer around the well begin to drain. For an unconfined aquifer, such as the aquifer at Eagle, there is significant water in storage. The specific yield, S_y, is a measure of this storage, and for the sand and gravel of the Kettle Moraine S_y is estimated to be about 0.15 (Feinstein and others, 2005). This pore drainage is the cause of water-table decline and the formation of a cone of depression around the wells. As the cone of depression expands, the hydraulic gradient it produces begins to capture more and more recharge. The cone stops expanding when the amount of recharge captured balances the water produced by the well. At this point in time pore drainage ceases as all the water produced by the wells is derived from recharge. This is the steady-state condition simulated by GFLOW.

Model simulations show that the new Village wells might take as long as ten years to reach a complete steady-state condition. Figure 19 shows simulated water-level declines versus time since the onset of pumping. The lines on the graph represent drawdown at four different distances from the wells: at the pumping center, 0.25 mile, 0.5 mile, and 1 mile. The near-vertical or curved parts of the lines (on the left-hand side of the plot) represent the transient response to the wells (drawdown increasing with time). The near-horizontal parts of the curves (on the right-hand side of the plot) represent the steady-state condition (drawdown is stable with time). The curves become nearly horizontal at about 10 years after pumping starts, meaning that the time to reach steady state is about 10 years. However, the slope of the curves during early time is very steep, and at least 50% of the drawdown occurs during the first year and about 90% within two years. Figure 19 also shows how drawdown propagates away from the pumping wells, with over five feet of drawdown near the wells and just under one foot of drawdown one mile away.

Effects of short-term increases in pumping rates

The steady-state GFLOW results show the impact of average groundwater use over a long time period. Some local citizens have expressed interest in knowing the impact of short-term increases in pumping that might occur during a drought, water main break, or firefighting situation. The transient model (Appendix) simulates this situation.

In order to determine a reasonable maximum pumping rate for the Village of Eagle we examined pumping records available from the Wisconsin Public Service Commission (PSC). The PSC reports list, among other statistics, the maximum single-day water use for the Village each year. During the past five years of available records (2000-2004) the maximum Village water use occurred on July 23, 2000, with a rate of 566,000 GPD. In order to simulate an extreme, but reasonable, case of high future water use, we used the transient model to simulate a 15% increase in this rate (to 650,900 GPD) and applied it for 30 days. In this scenario, each of the two Village wells pumps continually at 226 GPM for 30 days. Such a scenario is unlikely, but might be representative of the water-use response to a prolonged summer drought.

The 30-day period of increased pumping would increase short-term drawdowns near the two village wells but would have minimal impacts on water levels at distances greater than 0.25 miles from the wells. Figure 20 shows additional water-level declines through time caused by the increased pumping. After 30 days, the additional pumping would cause additional drawdown of about 7 feet near the pumping wells, but only about 0.5 ft of drawdown at a radius of 0.25 mile from the wells and imperceptible drawdown beyond 0.5 miles from the wells. In addition, figure 20 shows that water levels would recover to steady-state levels within a few months after the increased pumping ceased

Summary

Model Construction

A two-dimensional, steady-state model of groundwater flow in the vicinity of the Village of Eagle, Wisconsin provides a tool for evaluation of the effects of new high-capacity wells on the local groundwater system and adjacent surface-water features. The model uses the GFLOW analytic element code and successfully simulates the upper sand-and-gravel aquifer in the study area. Model construction used data and model results from a regional groundwater model previously developed for the entire SEWRPC region, but the Eagle model provides much more detail on local groundwater flow. The model is calibrated to targets consisting of hydraulic heads and surface water flows. The model successfully matches most targets, but possibly simulates groundwater interactions with a local wetland poorly. Additional fieldwork would be necessary to develop a better conceptual model of groundwater interactions with this wetland and the upper reaches of the Mukwonago River.

Impacts of Eagle municipal wells 3 and 4

The model simulates pumping from newly constructed wells 3 and 4 operated by the Village of Eagle. Model simulations show that these wells impact the local hydrologic system. Simulated drawdowns near the wells are about six feet, and one foot of drawdown occurs over one mile from the well site. Transient analyses suggest that the full development of the cone of depression might require several years from the onset of pumping.

The model also simulates reductions in groundwater flow to surface water features in the Upper Mukwonago River watershed. These reductions are generally quite small, with the largest reduction, 3%, occurring in the Mukwonago River at the entrance to Lulu Lake. The magnitude of these reductions is consistent with mass balance considerations. The model probably over-estimates these impacts because of assumptions made about pumping rates, hydraulic conductivity, steady state, and disposal of wastewater.

The model also allows determination of steady and time-delineated contributing areas for the Village wells. In addition, the model delineates the area contributing groundwater to the north side of the Upper Mukwonago River watershed.

Suggestions for future work

The GFLOW model constructed for this project is a tool that can be used to study other questions about groundwater flow and groundwater-surface water interactions in the study area. The model can be easily modified to include additional information or additional areas. The model could be improved by collection of more reliable data for calibration; such data would include accurate field measurements of hydraulic head in local wells and additional measurements of base flow in local streams and springs. More comprehensive fieldwork might be needed to understand groundwater-surface relationships in local wetlands so that the model could better predict water levels and stream flows in the upper reaches of the watershed.

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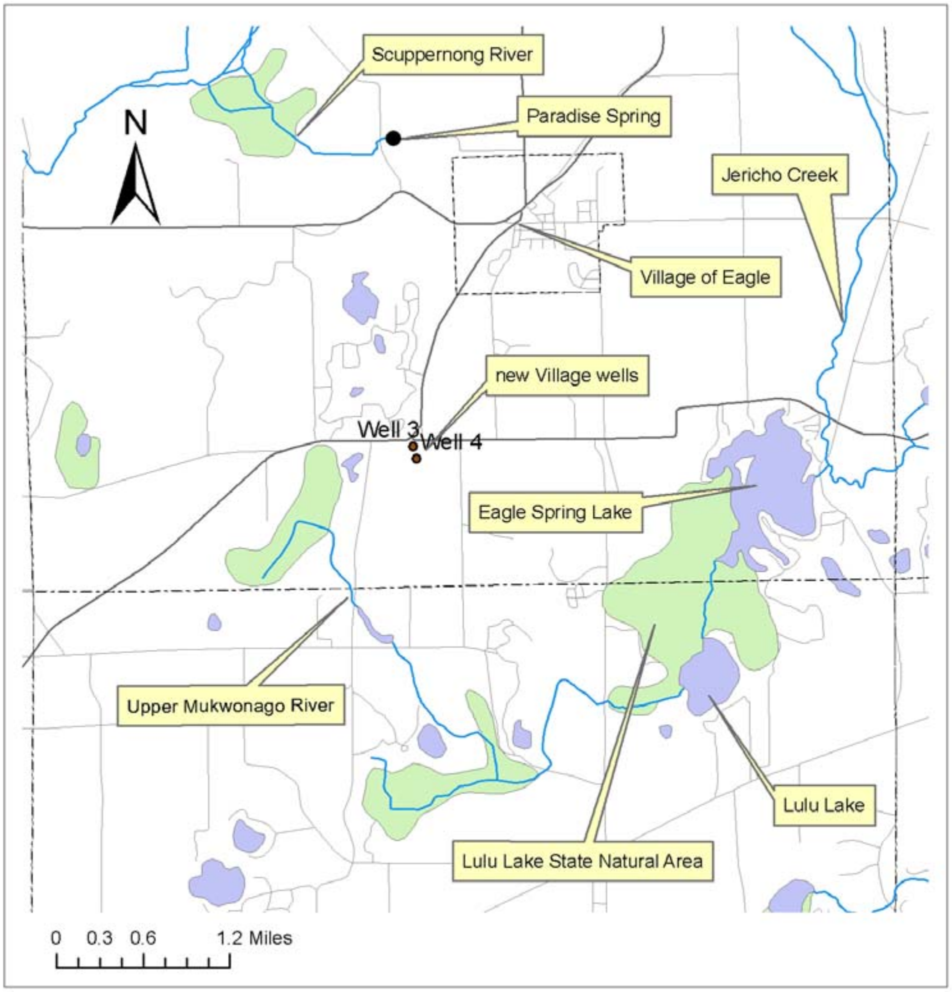


Figure 1. Location of the study area, showing important hydrologic features.

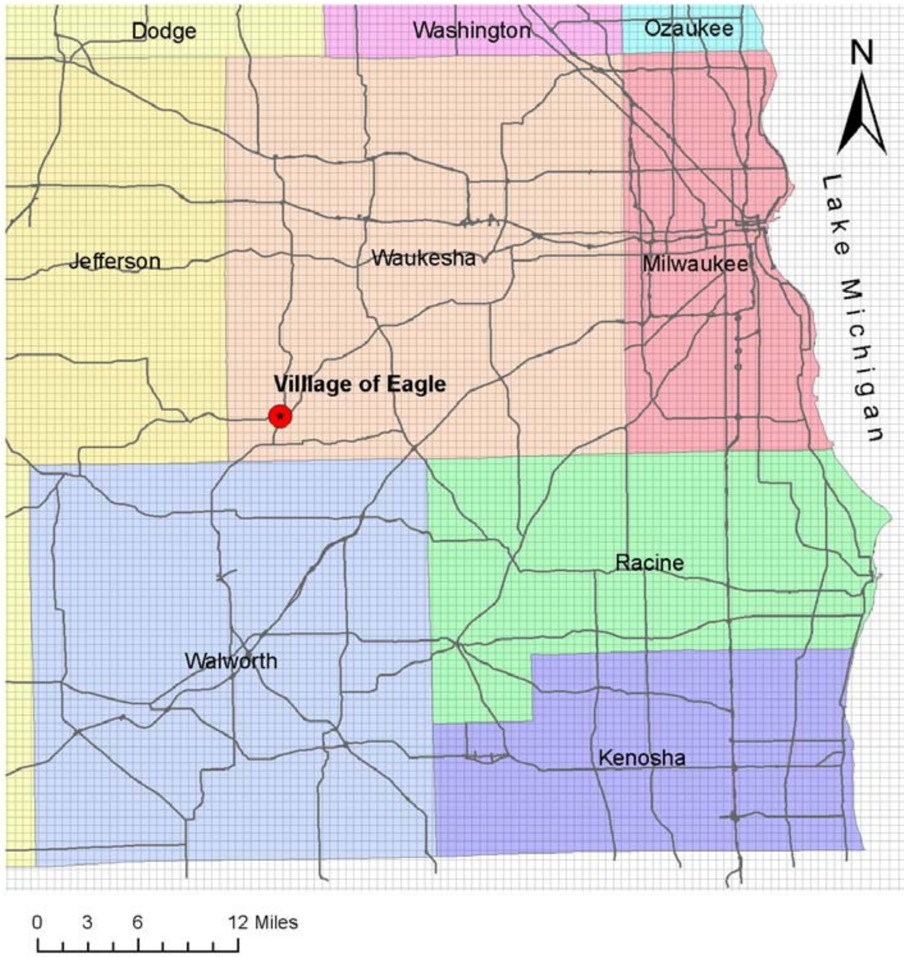


Figure 2. Southeastern Wisconsin, showing the location of the Village of Eagle and the grid spacing of the SEWRPC regional model.

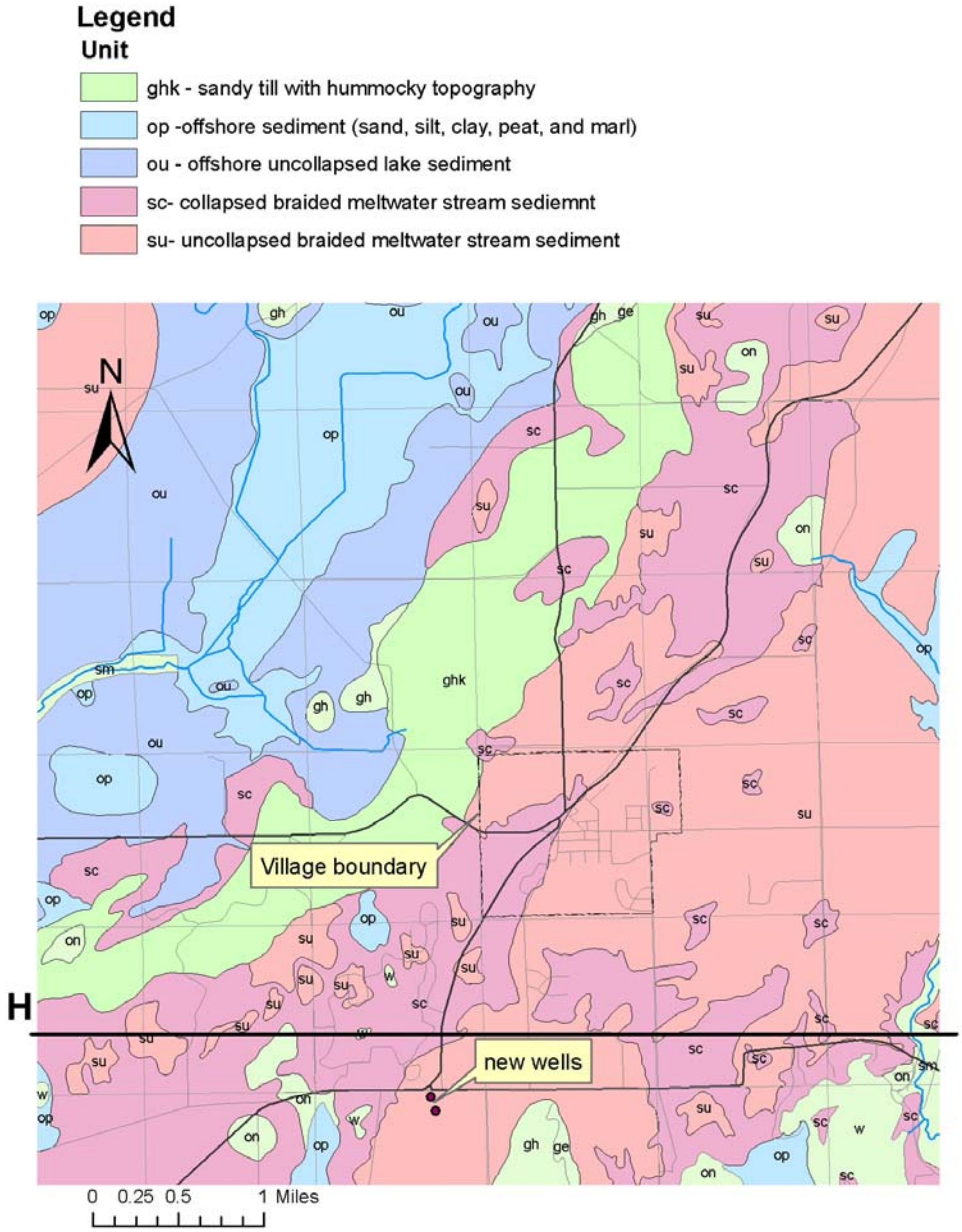


Figure 3. Pleistocene geology of the Eagle area (from Clayton, 2001).

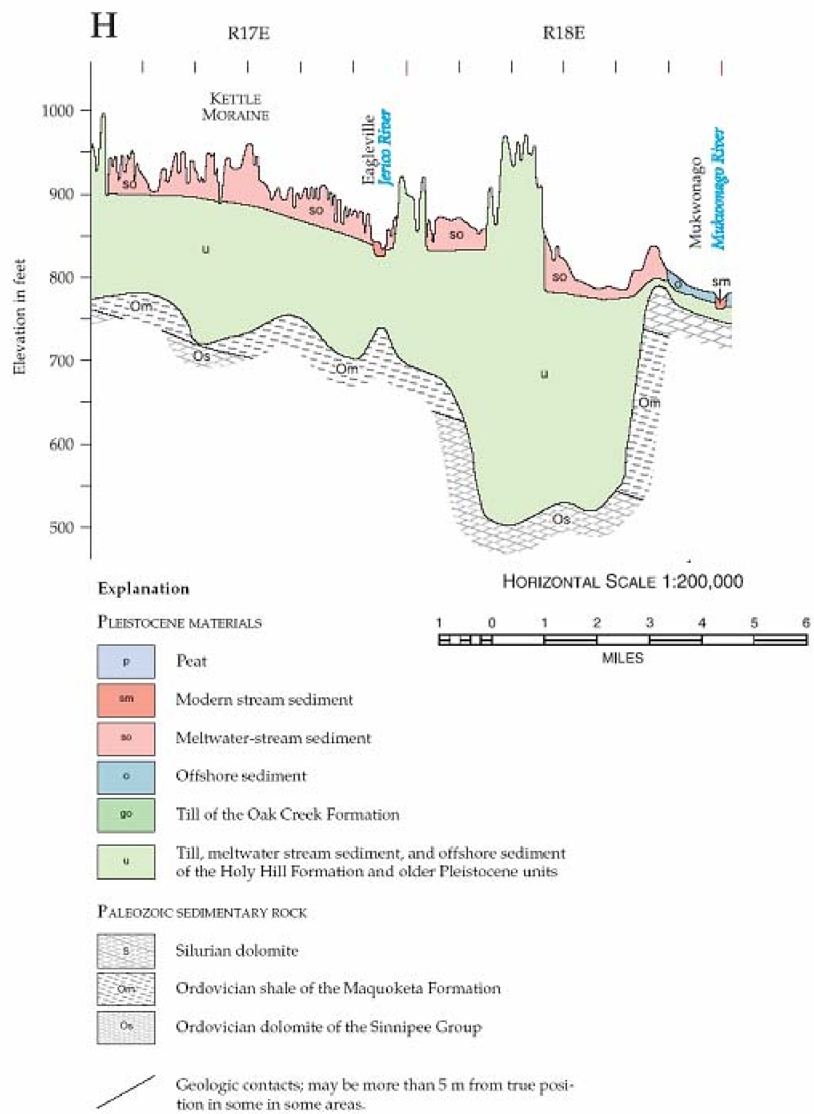


Figure 4. Geologic cross section through the eagle area (see line H on figure 3 for location). From Clayton, 2001.

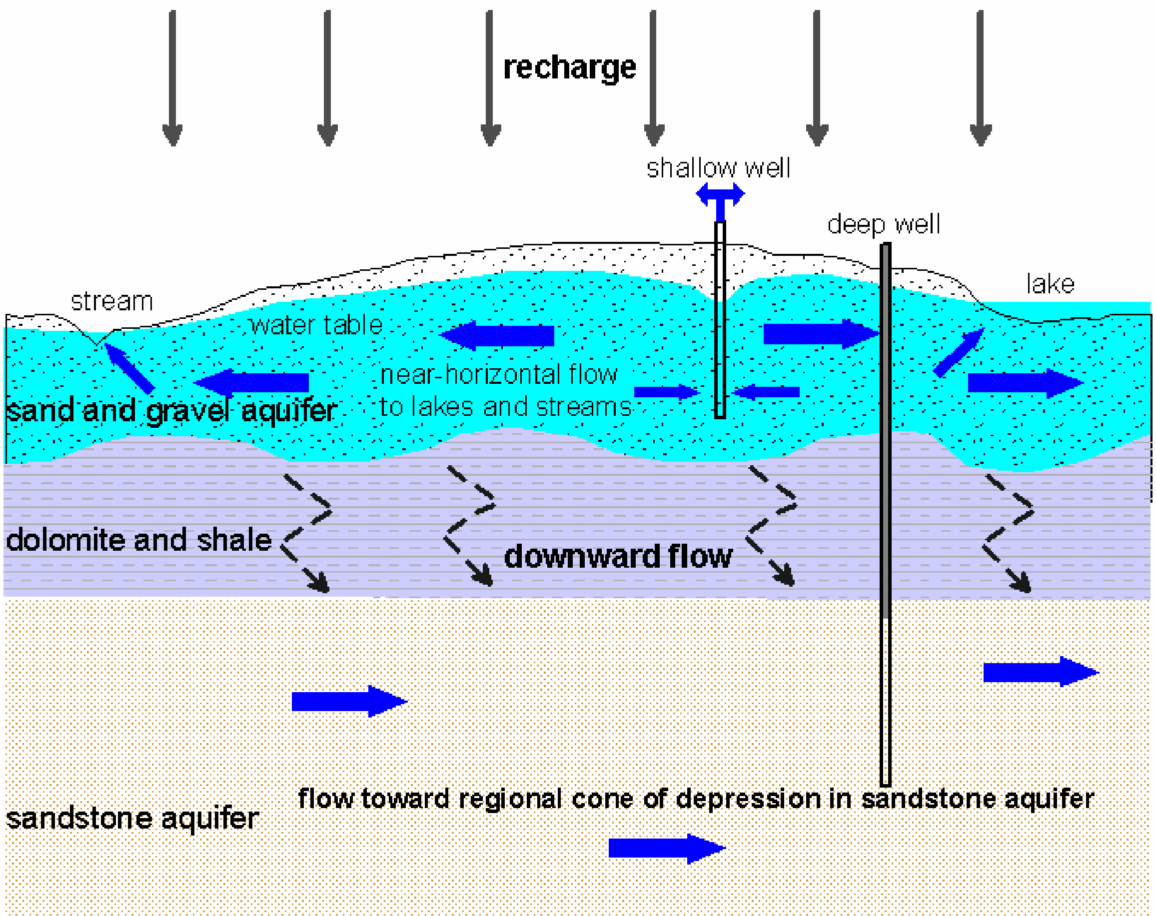


Figure 5. Conceptual model of groundwater flow in the Eagle area (not to scale).

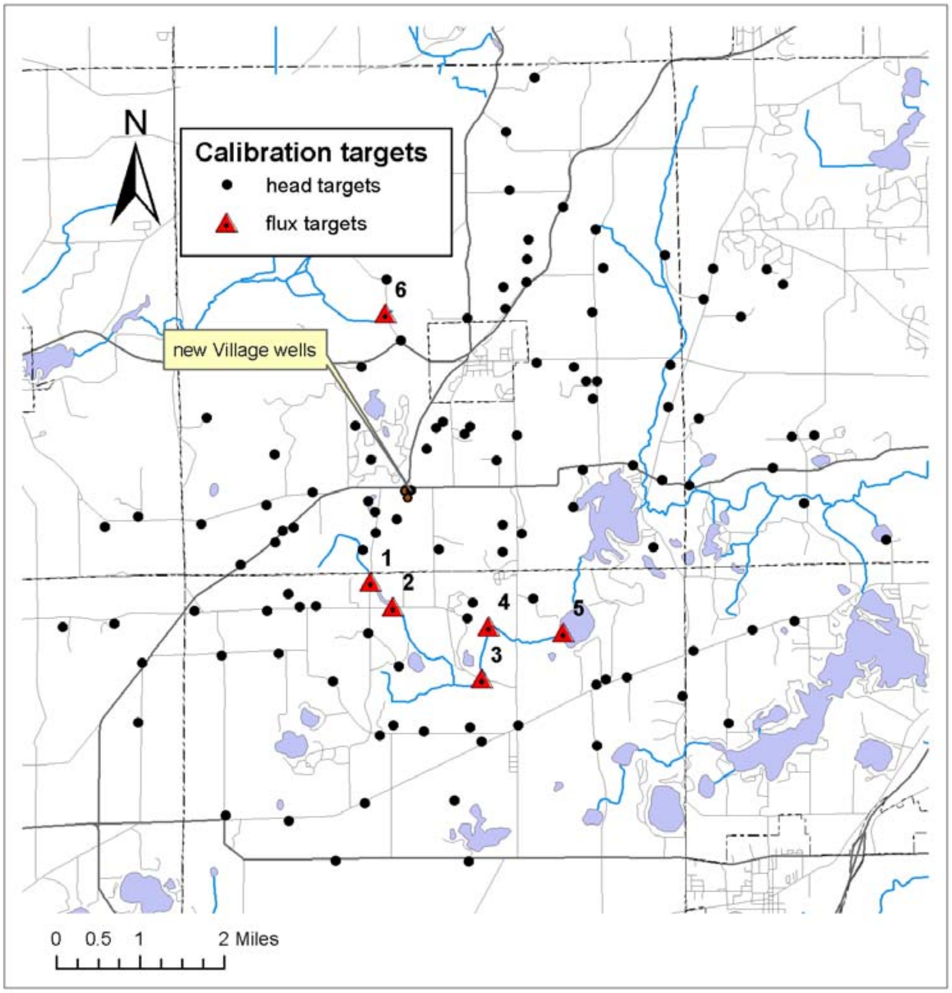


Figure 6. Model calibration targets.

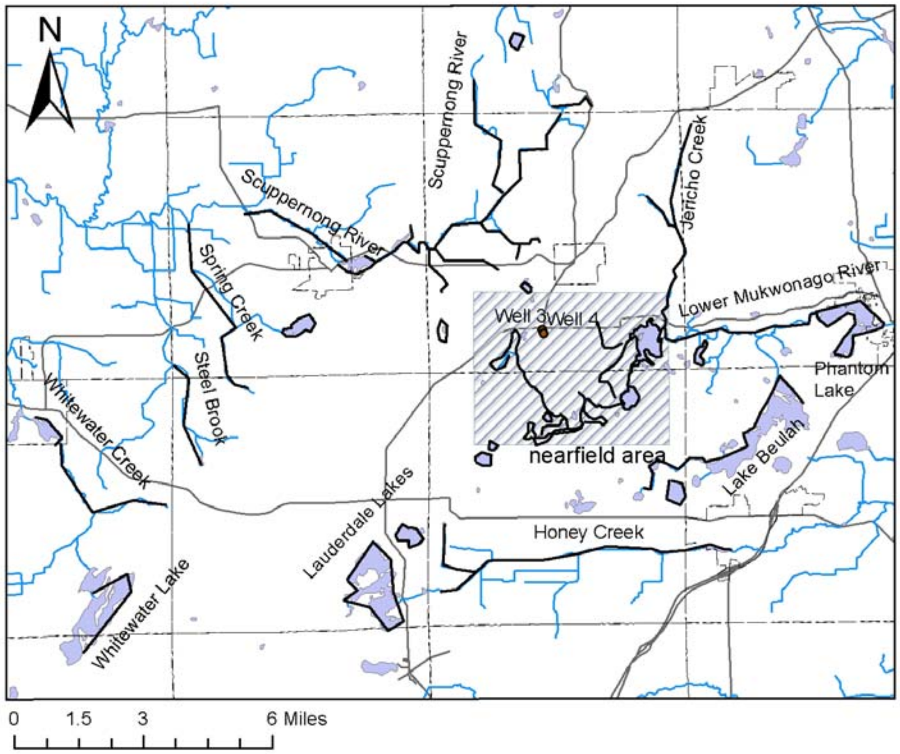


Figure 7. Far field hydrologic features in the Eagle model.

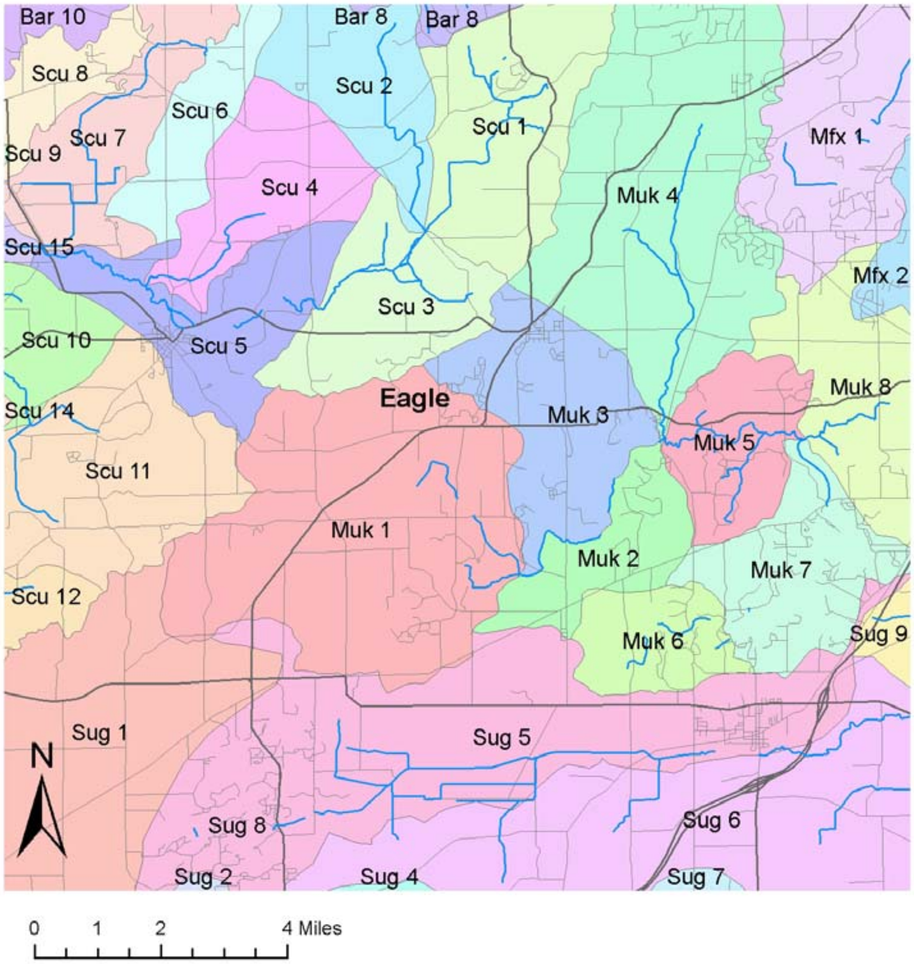


Figure 8. Recharge zones in the Eagle area (from Cherkauer, 2001). Abbreviations represent subwatershed names.

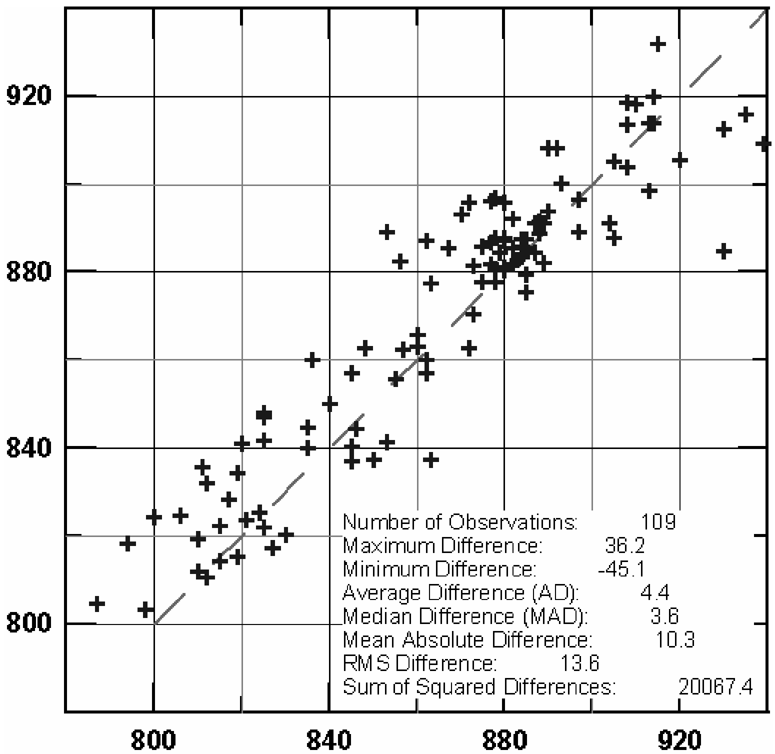
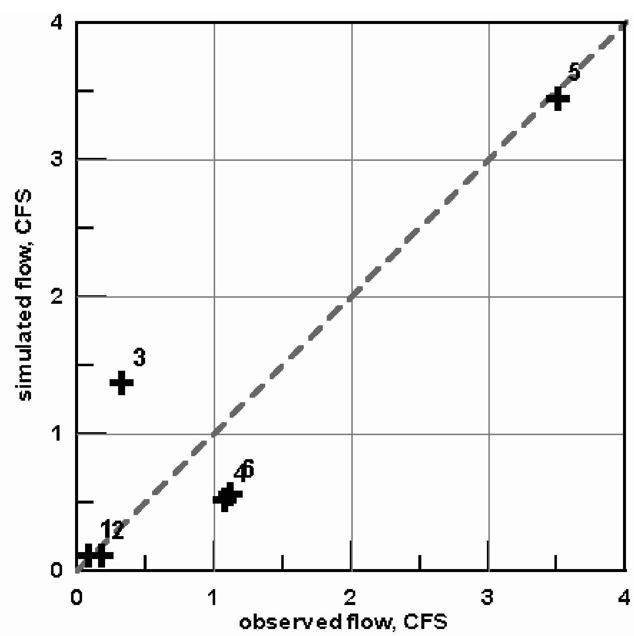


Figure 9. Observed versus simulated heads



Site ID	site	Observed	cfs	modeled	cfs
1	Upper Mukwonago	7000	0.08	9620	0.11
2	Upper Mukwonago below reservoir	15000	0.17	9274	0.11
3	Mukwonago R at Bluff Rd	28000	0.32	118285	1.37
4	Mukwonago R spring complex	92500	1.07	44735	0.52
5	Mukwonago R at Lulu Lk	302700	3.50	298161	3.45
6	Paradise Spring	96250	1.11	48083	0.56

Figure 10. Eagle flux calibration

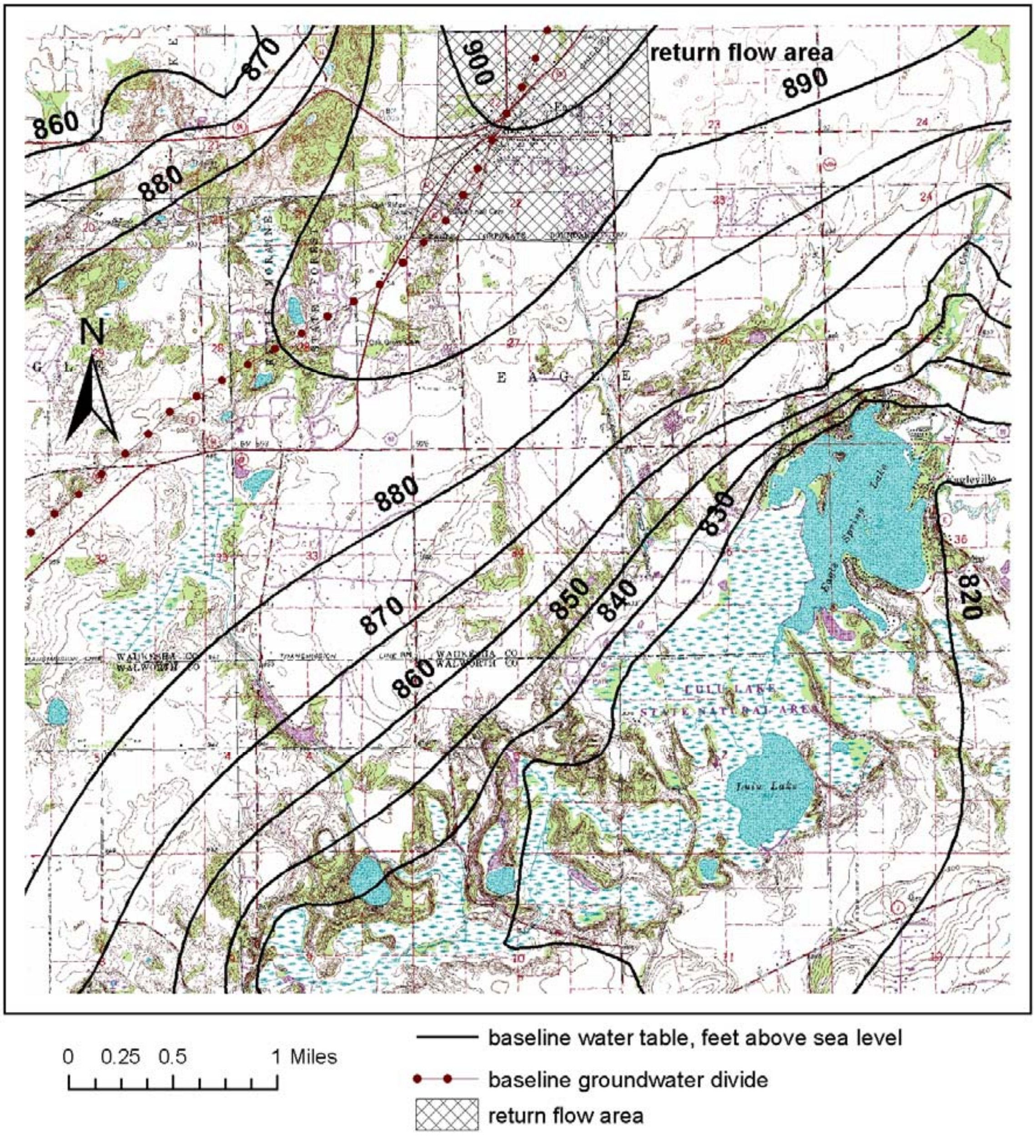


Figure 11. Water table simulated by the calibrated model.

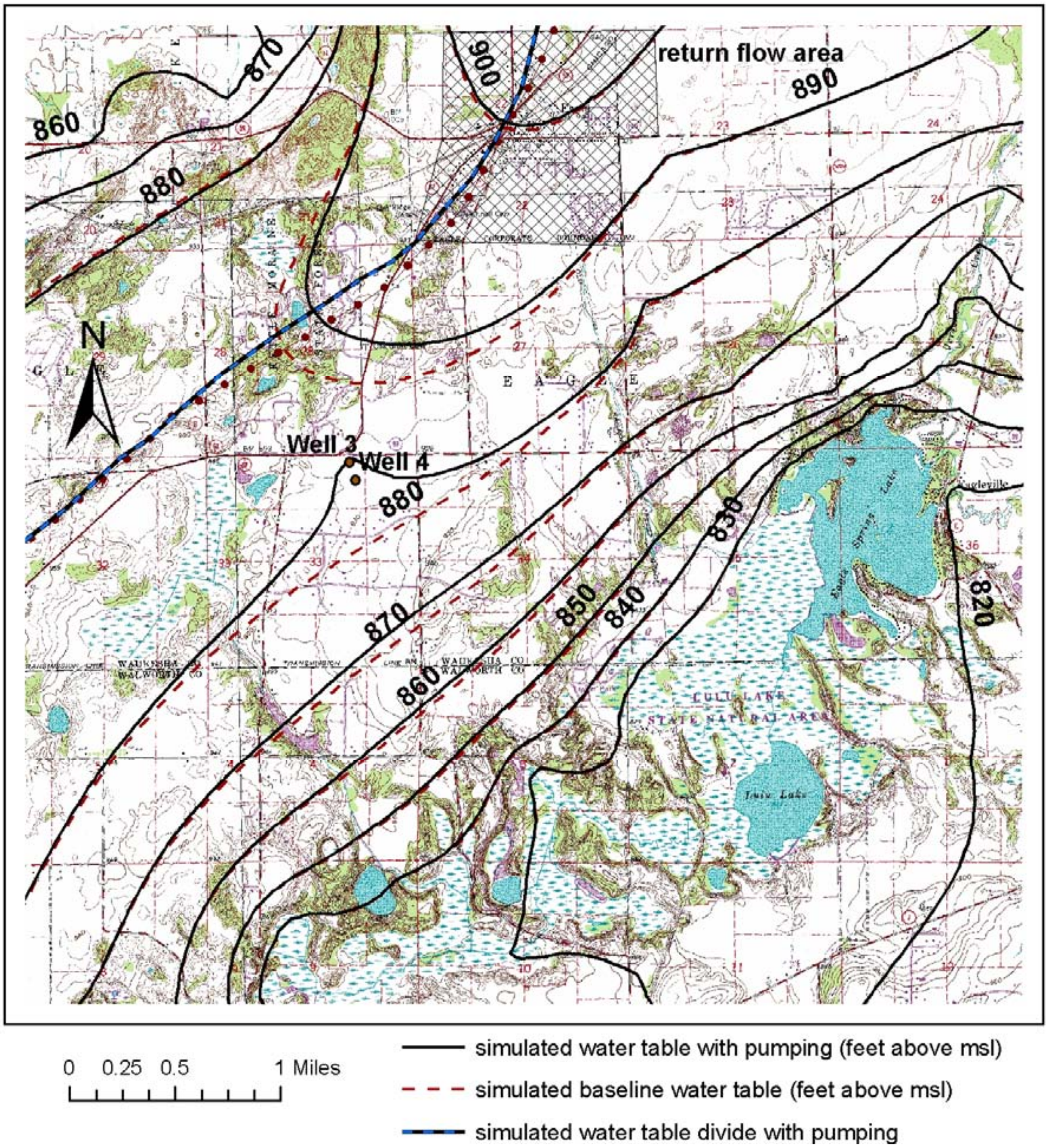


Figure 12. Simulated water table under pumping conditions.

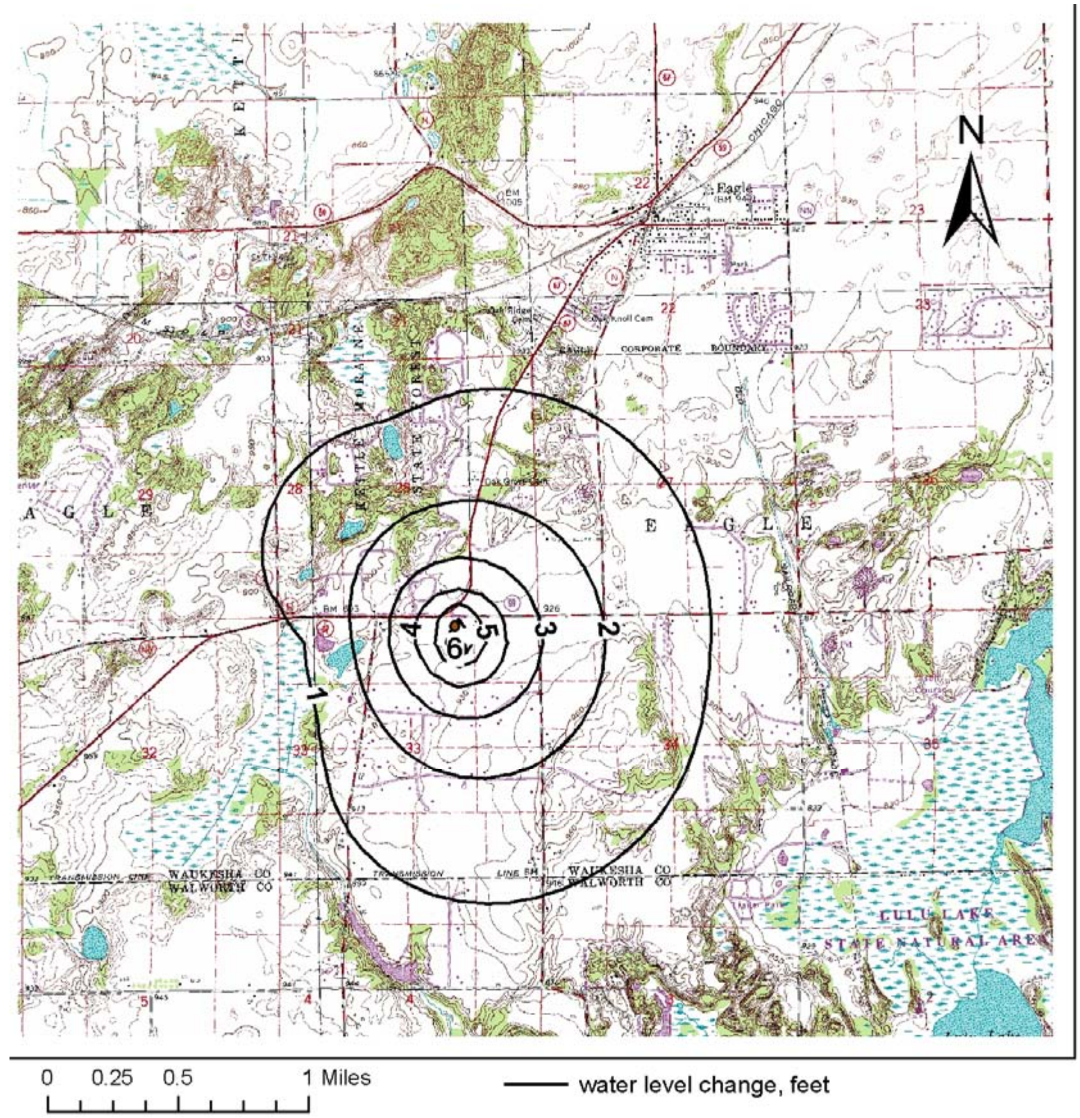


Figure 13. Simulated drawdown, in feet.

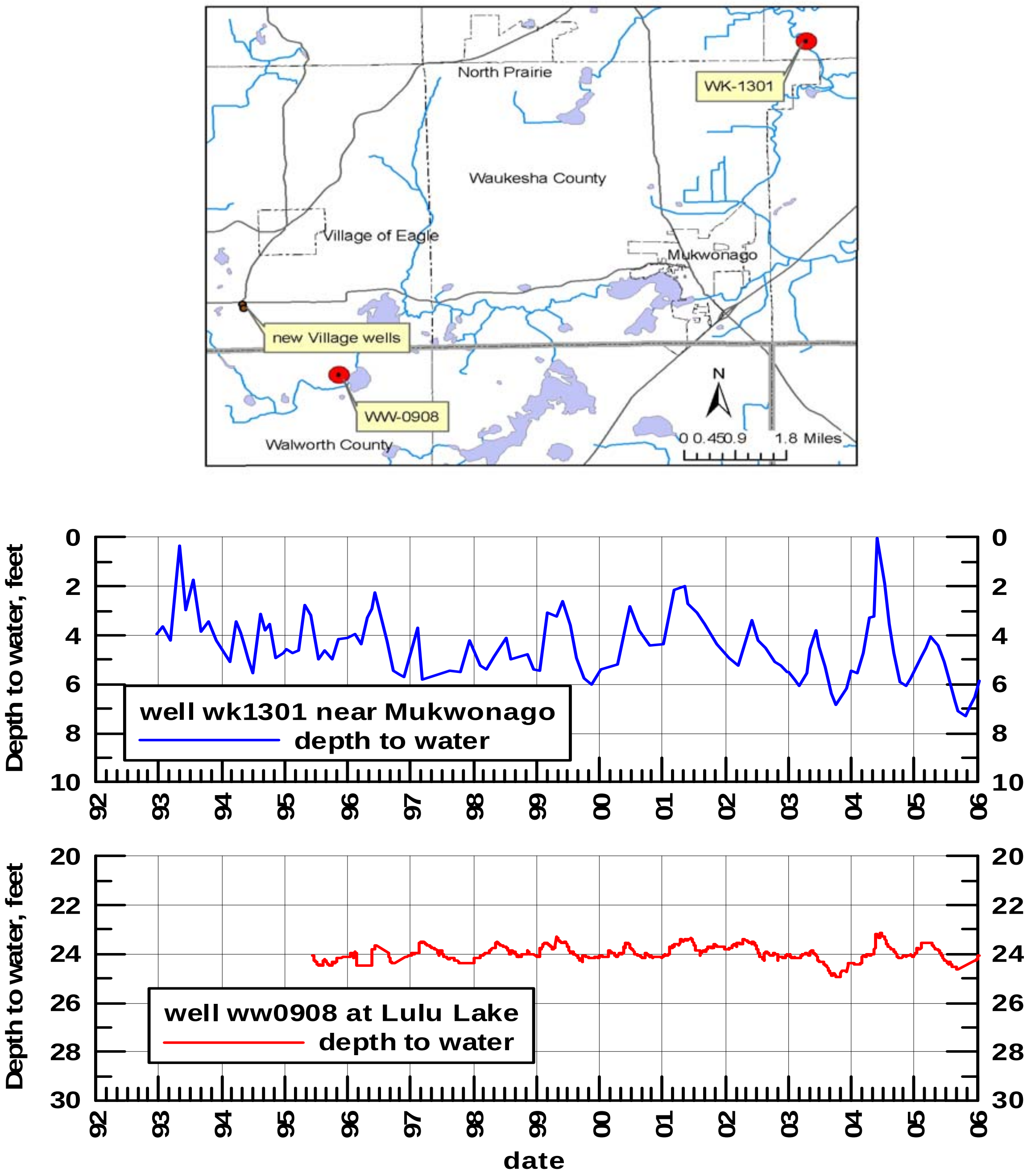


Figure 14. Hydrographs of shallow long-term observation wells in the vicinity of the Village and Town of Eagle.

Figure 15. Steady-state contributing area for wells 3 and 4.

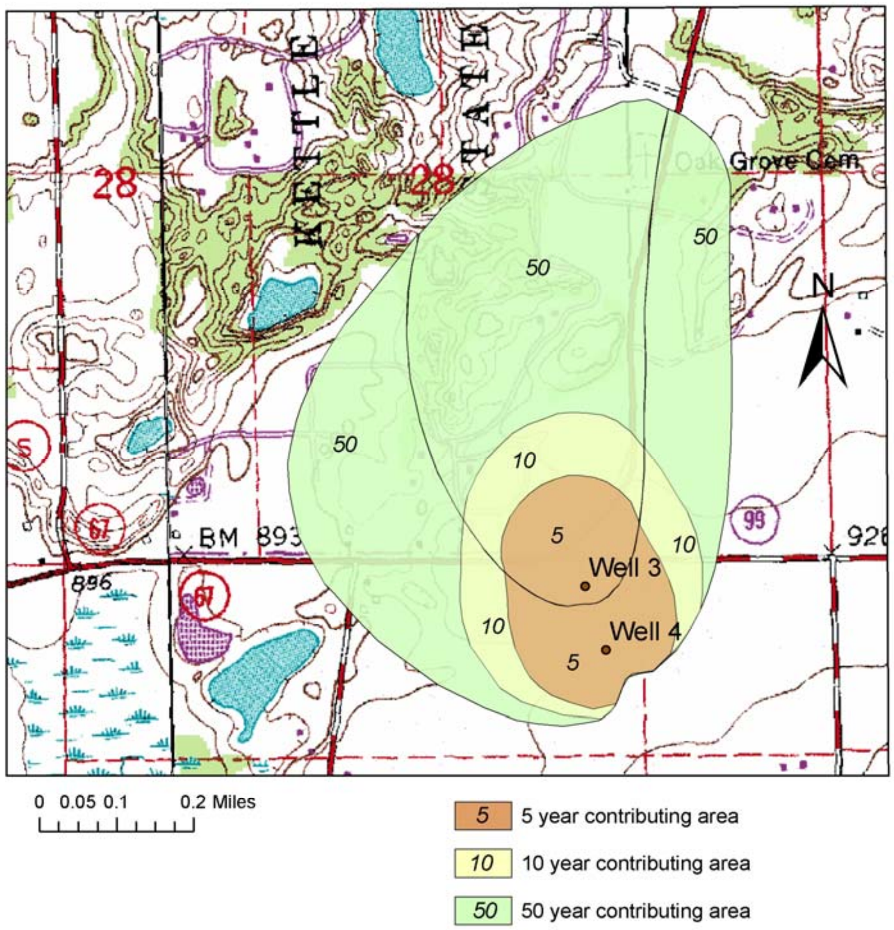


Figure 16. Time bounded contributing areas for wells 3 and 4. Travel times in years.

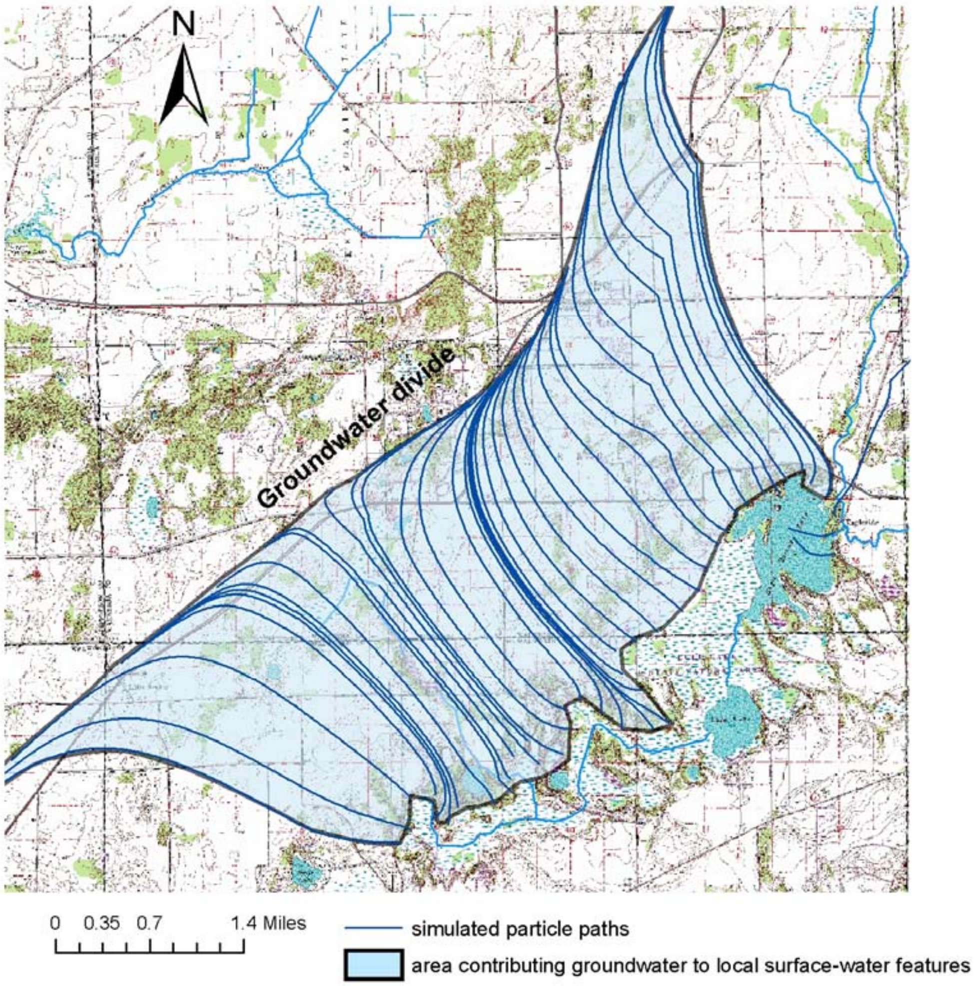


Figure 17. Contributing area for local surface-water features, showing simulated particle paths.

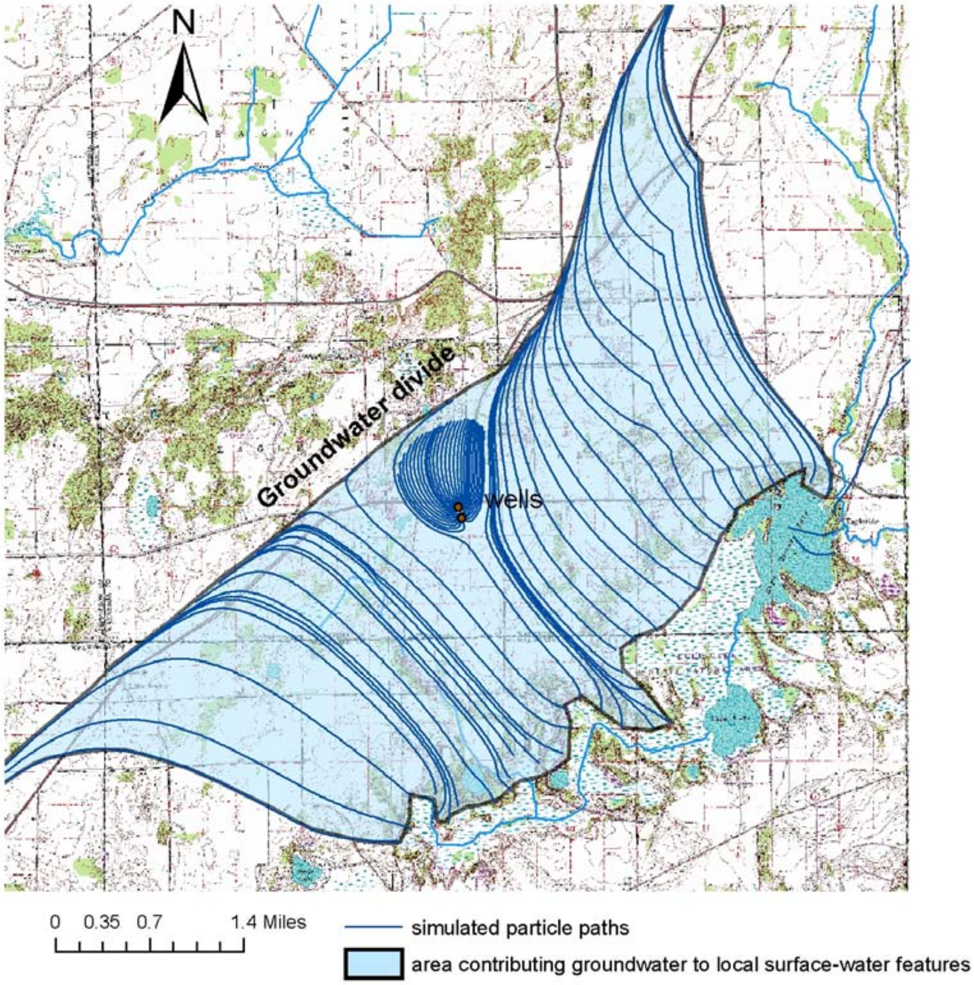


Figure 18. Contributing area for local surface-water features, showing simulated particle paths with pumping from shallow Village wells.

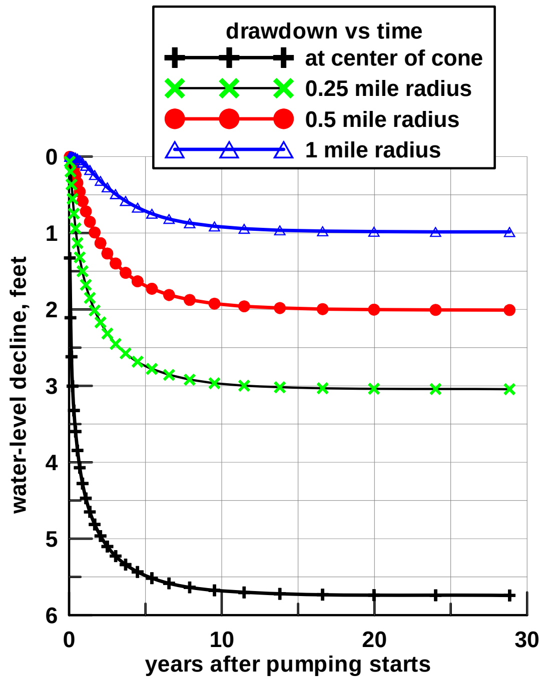


Figure 19. Simulated transient response to long-term pumping of the Eagle Village wells.

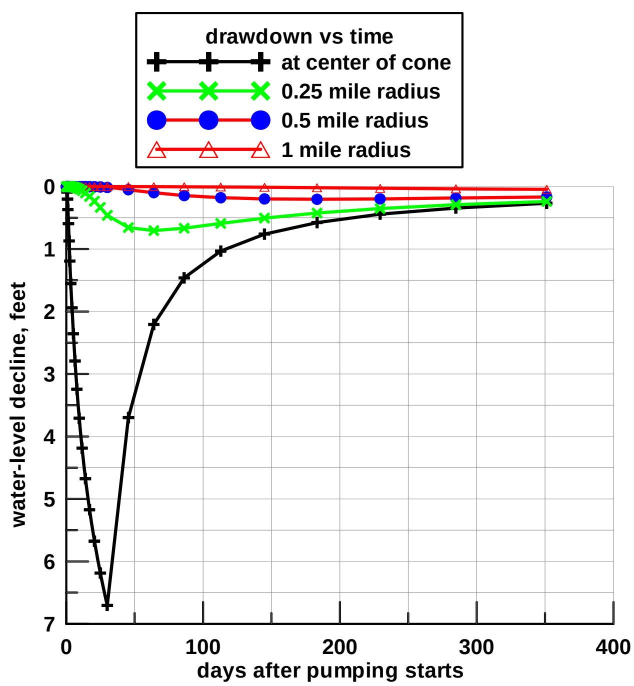


Figure 20. Simulated transient response to pumping the Village wells at a high rate for 30 days. Water-level declines are in addition to steady-state declines.

Appendix: Construction of a transient model based on the GFLOW model

Questions about time-related responses of the water table to pumping of the Eagle Village wells prompted construction of a transient finite-difference model of the region immediately around the new Village wells. The GFLOW code used for the overall steady-state model includes an option for extraction of a finite-difference grid and assembly of a finite-difference model using the MODFLOW (McDonald and Harbaugh, 1988) code. The objectives of this submodel were to examine the transient response of the system to changes in pumping rates. The transient model is designed to predict heads and drawdown near the pumping wells. It is not designed to predict flow rates to surface-water features.

Steps in creating transient model were as follows:

1. In GFLOW, solve the steady-state groundwater flow problem, producing a calibrated head field for the pre-pumping condition (wells 1 and 2 are turned off).
2. Using the GRID option in GFLOW, construct a finite-difference grid of appropriate dimensions. For the Eagle case, the extract grid consisted of 50 rows and 50 columns of uniform 400-foot spacing. The perimeter grid cells were set as constant head using the GFLOW solution.
3. In GFLOW, extract boundary conditions; this converts the GFLOW point sinks and line sinks to appropriate MODFLOW boundaries (river, drain, and constant-head cells).
4. In GFLOW, create MODFLOW files. This step creates the appropriate BAS, BCF, and other files used by the MODFLOW code. All aquifer parameters used in GFLOW (hydraulic conductivity, recharge) are automatically converted to MODFLOW format.
5. Using the Groundwater Vistas interface (Environmental Simulations, Inc, 2004), import the MODFLOW files. Groundwater Vistas (Vistas) is a user-friendly pre- and post-processor for MODFLOW.
6. In Vistas, orient the imported grid in space by using the Grid>offset command and entering the lower left coordinates of the grid extracted from GFLOW. Note that these coordinates must be converted from meters (used in GFLOW) to feet (used for grid construction in Vistas). In addition, the GIS option in Vistas must be set to "*GV is in feet and GIS is in meters*".
7. In Vistas, refine the grid around the wells using the grid>edit>refine grid command. The minimum grid spacing for Eagle model is 50 feet.
8. In Vistas, assign a specific yield of 0.15 to the entire model domain.
9. In Vistas run steady-state simulation; compare results to GFLOW simulation to be sure models are equivalent.
10. In Vistas, set up appropriate stress periods for transient run, and add appropriate pumping rates for wells.
11. Conduct transient runs and process results.

Figure A1 shows the finite-difference grid constructed for the transient simulation.

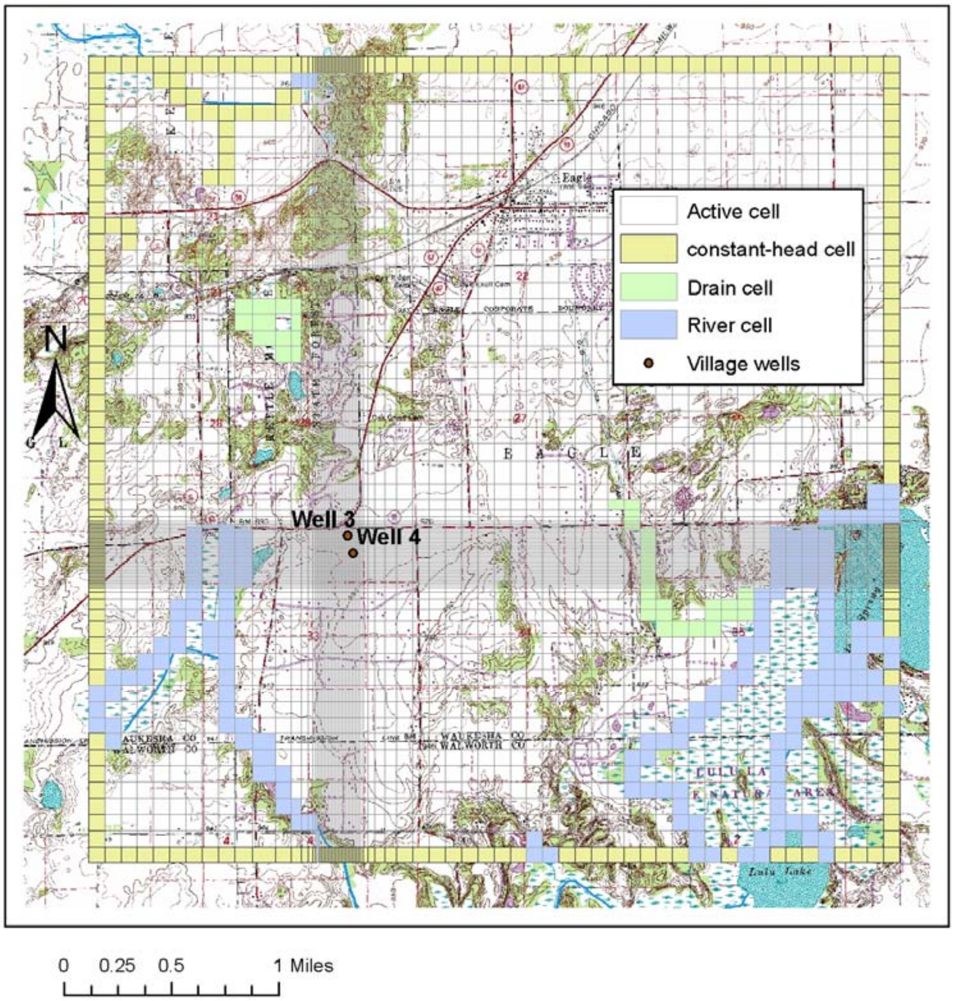


Figure A1. Finite-difference grid constructed for transient simulations.