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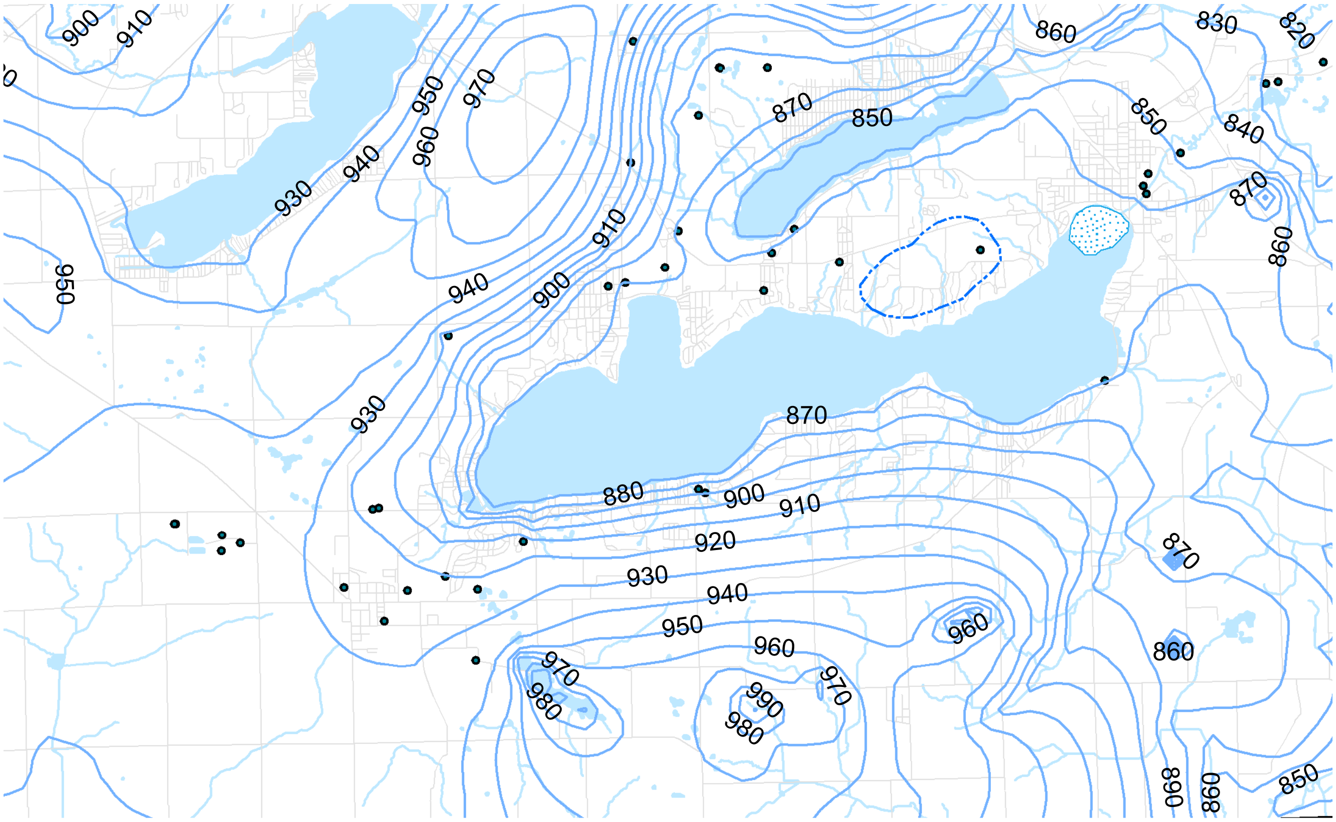
Groundwater flow model for the Geneva Lake area, Walworth County, Wisconsin

Report to the Geneva Lake Environmental Agency and project sponsors



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Abstract

At the request of the Geneva Lake Environmental Agency and with the support of surrounding communities and stakeholders, we developed a numerical groundwater flow model to assess groundwater–surface water interactions in the vicinity of Geneva Lake. The model simulates the full hydrogeologic system, including a shallow sand and gravel aquifer, a bedrock aquitard, and a deep sandstone aquifer.

The model demonstrates that the shallow groundwater system is closely connected to Geneva Lake and its tributaries. The groundwater shed of the lake extends to the west, beyond the surface watershed. Based on model results, Geneva Lake receives about 36% of its inflow from groundwater, 7% from stream baseflow, 19% from runoff and stormflow, with precipitation supplying 38% of inflow to the lake. The model simulates seepage to groundwater from the lake over a small region at the northeast edge of the basin, accounting for about 1% of outflow from the lake. Evaporation and surface discharge to the White River account for 35 and 64% of lake outflows, respectively.

Pumping changes the mass balance of the system by removing groundwater that would otherwise discharge to surface water. Model simulations demonstrate that pumping alters the shape of the water table, the locations of groundwater divides, and the groundwater shed of the lake. Compared to a predevelopment (no pumping) simulation, groundwater withdrawals in 2006 reduced total inflows to the lake by 4%, and reduced stream baseflow and groundwater discharge to lake by 9%.

Pumping from high-capacity wells near the west shore of the lake captures groundwater that would otherwise discharge to nearby streams. At 2006 pumping rates the model simulates baseflow reductions of 17%, 32%, and 35% in Gardens, Harris and Potawatomi Creeks, respectively, compared to predevelopment conditions. The model predicts much smaller impacts to Birches, Trinke and Buttons Bay Creeks because these streams are relatively far from high-capacity wells.

Several communities, including Williams Bay, Fontana, and Walworth, send wastewater to treatment plants outside of the Geneva Lake surface- and groundwater sheds. This water is diverted from the local ecologic and hydrologic systems. In contrast, pumped water that is returned to local streams or re-infiltrated to the water table does not divert water from the basin. For example, the Lake Geneva Utility Commission wells extract groundwater from the White River basin, and a large proportion of this water is returned to the basin at the Utility's infiltration ponds.

The model was also used to assess potential impacts of increased groundwater use. Based on regional population projections for 2035, we applied a 30% increase to 2006 municipal pumping rates. This change reduces the total simulated inflows to lake by about 0.5%, with stream baseflow and groundwater contributing about 1% less than under current conditions. Baseflow in tributary streams west of the lake are further reduced from current conditions, but streams located far from pumping centers are negligibly affected. Diversion of water from the basin would also increase under this scenario in the absence of alternative waster water treatment strategies. The 30% increase in pumping applied to the City of Lake Geneva wells does not significantly reduce the amount of water entering the lake, or tributary streams, because these wells lie east of the groundwater recharge area of the lake.

The model demonstrates that shifting pumping from shallow to deep wells operated by Williams Bay and Fontana would substantially decrease impacts to the *local* surface water–groundwater system by capturing groundwater that flows along deeper, regional flow paths. Shifting pumping to deep wells in these communities preserves groundwater discharge from the shallow aquifer to nearby streams and to Geneva Lake. This analysis considers water quantity issues only; water quality and water distribution to service areas are other important considerations related to increased reliance on deep wells.

This model is well-suited to evaluate impacts of pumping on lakes and streams. However, it does so without consideration of lake water quality. These model results should be viewed within the context of factors that affect lake water quality. For example, domestic wells and septic systems in unincorporated areas of the region were not considered significant with respect to water quantity, but these systems may impact lake water quality. Diversion of wastewater for treatment outside of the Geneva Lake basin has a negative impact on the water balance of the local hydrologic system, but diversion may be a good approach to reduce nutrient load within the lake basin.

This report includes a map of infiltration rates to groundwater in the Geneva Lake region. The soil-water balance model used to develop this map accounts for interception by the plant canopy, surface runoff, evapotranspiration, soil moisture storage capacity, and antecedent soil moisture conditions. This map identifies areas with high infiltration capacity, which is related to groundwater recharge. If these areas are developed, groundwater recharge can be preserved by drainage and storm water controls designed to maintain or enhance infiltration.

The Geneva Lake groundwater flow model and the soil-water balance model provide science-based information to inform decisions affecting groundwater flow, groundwater discharge to lakes and streams, and groundwater recharge. The models provide estimates of drawdown, delineate contributing areas of lakes and wells, and can be used to assess impacts of pumping and changes in land-use on the groundwater-surface water system. Stakeholders in the area can use model results to evaluate tradeoffs between groundwater use and preservation of flow to streams and lakes.

Introduction

Purpose

This report describes the development, construction, and application of a numerical groundwater flow model for Geneva Lake and surrounding area, in southern Walworth County, Wisconsin. Residents and businesses in and near the communities of Walworth, Fontana, Williams Bay and Lake Geneva depend on groundwater for water supply. Stakeholders in these communities also have a great interest in the health and quality of Geneva Lake, and streams and springs in the watershed. The purpose of this model is to advance understanding of the relationship between the groundwater system and these valued surface water features. Issues of interest include the effect of current and potential increases in groundwater pumping on surface water, groundwater flow into and out of Geneva Lake, potential impact of development on the surface water groundwater system, and identification of the groundwater recharge area of the lake.

The model described in this report encompasses 312 square miles including Geneva Lake and surrounding areas (figure 1). The model is derived in part from a regional-scale model of southeastern Wisconsin (Feinstein and others, 2005) developed by the Wisconsin Geological and Natural History Survey (WGNHS) and the U.S. Geological Survey (USGS) in cooperation with the Southeastern Wisconsin Regional Planning Commission (SEWRPC). The coarse resolution of the regional flow model (minimum grid cell size of 2500 ft x 2500 ft) is not suited to investigations of local-scale groundwater and surface water interactions that are of interest in this project.

Objectives

The major objective of this project is to investigate surface water–groundwater interactions in the vicinity of Geneva Lake. This is accomplished with development and calibration of a groundwater flow model of the area. Specific uses of the model include:

- Compare groundwater flow to and from the lake under predevelopment, current, and future groundwater pumping scenarios.
- Evaluate effect of climate variability on surface water–groundwater interactions.
- Determine areas of groundwater inflow and outflow to the lake.
- Identify the groundwater recharge area of the lake.
- Map areas of the watershed where groundwater recharge occurs.

Acknowledgments

The Geneva Lake Environmental Agency (GLEA) coordinated and managed this project, provided stream flow data, and conducted an inventory of springs. The following organizations provided financial support for this project: GLEA; Lake Geneva Utility Commission; the Towns of Linn, Walworth, and Geneva; the Villages of Fontana and Williams Bay; Geneva Lake Association; Geneva Lake Conservancy; the Geneva Lake Garden Club; and the Kikkoman Corporation. The authors are indebted to the Kikkoman Corporation, Pat Prahl of Geneva National, Craig Workman of Fontana, Jerry Mehring of Williams Bay, and the Snell Family, for providing data and access to groundwater wells. Pete Chase and Andrew Aslesen, WGNHS, installed temporary wells at the lake, and Randy Hunt and Mike Fienen of the USGS assisted in model calibration.

Background

Geneva Lake is an 8.2-square-mile lake in southern Walworth County, Wisconsin. It has a maximum depth of 140 ft, an average depth of about 61 ft and, as shown in figure 1, a relatively small surface watershed of about 28.6 square miles. Land use within the watershed is 28% urban (including 17% residential), 42% rural, and about 30% of the land surface is covered by water (SEWRPC, 2008).

The lake formed about 10,000 years ago during the late Wisconsinan glaciation. The Troy Valley, which is a buried pre-glacial valley, traverses north-south through the Geneva Lake area. The valley is filled with Pleistocene glacial deposits that range in thickness from tens of feet to several hundreds of feet. Geneva Lake lies within a topographic depression in these sediments.

Surface water features

A mix of perennial and ephemeral streams discharge to Geneva Lake. Buena Vista, Potawatomi, Van Slyke, and Gardens are tributary streams on the west shore of the lake. To the north, Harris and Southwick Creeks feed Williams Bay. Trinke and Birches discharge to the south shore; Buttons Bay Creek discharges to Buttons Bay on the southeast shore. Surface water flows from the lake at its northeastern end, where a dam (spillway elevation 864.38 ft mean sea level, msl) regulates discharge to the White River. Lake Como lies to the north at an elevation of about 849 ft msl, a full 15 ft lower than Geneva Lake.

Water flow into and out of the lake

A water budget for a lake is an accounting of the inflows to and the outflows from the lake. One purpose of this project was to quantify the water budget for Geneva Lake.

In a recent study of lake water quality, Robertson and others (2002) calculated the water balance of Geneva Lake using measurements of precipitation and surface water inflow from 1998 and 1999. Their study determined that precipitation and surface water contributed about 48% and 46% of lake inflow, respectively, during those years. Based on the lake stage and the groundwater elevation map compiled by Borman (1976), they noted that seepage from the lake to the underlying aquifer is likely limited to a small area at the northeast end of the lake. Therefore, they assumed that groundwater primarily flows from the aquifer into the lake and that there is generally little seepage from the lake into the aquifer. They estimated groundwater inflow to the lake, based on subtraction from the water balance, at 6% of the lake budget.

Outflow from Geneva Lake occurs through surface discharge to the White River, evaporation, and discharge to groundwater. Robertson and others (2002) estimated that water losses from the lake include approximately 60% flow to the White River and 40% evaporation. They assumed that there is no seepage from the lake to groundwater; and one purpose of this project was to evaluate that assumption.

Hydrogeologic setting

The hydrogeology of the Geneva Lake area is strongly influenced by the variability in the type and thickness of glacial sediment deposited during the last part of the Wisconsin Glaciation, approximately 25,000 to 10,000 years ago. Ham and Attig (2004) present a map of the glacial deposits showing the area surrounding Geneva Lake dominated by fine-grained till of the Holy Hill Formation. Highly permeable outwash deposits are located near Fontana, north of Williams Bay, the City of Lake Geneva, and Big Foot Beach State Park. Figure 2 illustrates the distribution of these materials based on the characteristic grain size of sediment, as described by Ham and Attig (2004).

The layering of the glacial sediments is variable and complex. The contrast in permeability between fine-grained sediment and coarse sand and gravel controls local-scale groundwater flow paths to springs, streams, and wells. Root and others (in review) collected a core of the 300-ft thick sequence of glacial sediments on the steep ridge between lakes Geneva and Como (figure 3). In this area, the uppermost New Berlin and Tiskilwa tills are unsaturated. On the ridge top, the water table is about 175 ft below ground surface, within a lens of sand and gravel and the underlying, clay-rich Foxhollow till. The Foxhollow is an aquitard, a low-permeability geologic material that restricts groundwater flow. The Foxhollow till overlies a lower sand and gravel deposit in some areas and bedrock elsewhere.

In the eastern portion of the project area, the Silurian dolomite is the uppermost bedrock, and it is underlain by the Maquoketa shale, a regional aquitard. As mapped by Evans and others (2004), both of these units subcrop within the Geneva Lake region (figure 4). The Sinnipee dolomite, the uppermost rock of the Cambrian-Ordovician aquifer, underlies the Maquoketa, and it is the uppermost bedrock in the western portion of the area, where the Maquoketa is absent. The sandstone and dolomite formations of the Cambrian-Ordovician sequence form a deep, regional aquifer that is up to 2000 ft thick (Feinstein and others, 2005). Figure 5 illustrates the stratigraphic sequence in the study area.

Most residential, agricultural, and public supply wells in the study area are completed above the Maquoketa shale. These wells draw groundwater from the upper aquifer, which consists of discontinuous and highly permeable sand and gravel deposits dispersed within lower conductivity tills. In the eastern portion of the study area, the upper aquifer also includes the Silurian dolomite, which is conductive where it is fractured.

Hydrogeologic conceptual model

Our conceptual model of the hydrogeology in the Geneva Lake region includes a shallow aquifer comprised of discontinuous, highly permeable sand and gravel glacial outwash deposits. These conductive lenses are distributed within laterally extensive fine-grained till aquitards that restrict groundwater flow. The upper aquifer includes the Silurian dolomite, where present. The Maquoketa shale, which pinches out near the west edge of Geneva Lake, is a regionally extensive aquitard that restricts the vertical flow of groundwater between the shallow and deep groundwater systems. West of the shale subcrop, vertical groundwater flow is not geologically restricted. This is an important recharge area for the deep aquifer. Regional groundwater flow paths are downward in this region, and shallow groundwater may be diverted to the deeper system.

Previous modeling efforts

The regional model developed by the USGS and WGNHS in cooperation with SEWRPC includes all aquifer units in the region, but it focuses on groundwater flow in the deep sandstone aquifer, which is the source of water for many high-capacity wells in southeast Wisconsin (Feinstein and others, 2005). The regional model demonstrates that there is significant drawdown in water levels in the deep sandstone aquifer due to pumping from these wells. The model results indicate that the drawdown in the deep system induces downward flow from overlying shallow groundwater and surface waters.

The SEWRPC regional model uses the MODFLOW groundwater model code (McDonald and Harbaugh, 1988). The coarse resolution (2500 ft x 2500 ft grid cell size) of the regional model is not suited to detailed simulation of groundwater flow in the Geneva Lake area. In 2002, the WGNHS refined part of the regional model to simulate municipal well capture zones in Walworth County for the Source Water Protection Program developed by the Wisconsin Department of Natural Resources. In 2006, at the request of the GLEA, the WGNHS evaluated the refined model as a tool to investigate affects of groundwater pumping on the lake and nearby streams and springs (Gotkowitz and Schoephoester, 2006). Results of this work indicated that the representation of lakes and streams in the existing model was too coarse to adequately simulate effects of pumping on surface water features.

Methodology

The primary focus of this project was development of a three-dimensional groundwater flow model to simulate groundwater–surface water exchange near Geneva Lake. In support of model development, new data collection efforts included measurement of vertical hydraulic gradients along the lake shore, monitoring seasonal changes in groundwater levels in the upper aquifer, and sampling groundwater for geochemical indicators of groundwater age and origin. Additional work addressed estimating groundwater recharge across the study area.

Vertical gradient measurements

The direction and magnitude of vertical hydraulic gradients between surface waters and underlying aquifers is an important indicator of flux between the two systems. Previous studies of the lake suggested that groundwater discharges to the lake around much, if not all of the shoreline. This project included installation of temporary piezometers at several locations along the lake shore during 2008 to measure vertical gradients between the lake and surficial aquifer. The piezometers, ¾-inch-diameter rigid plastic pipe with approximately 2 inches of screen at the base, were installed a few feet off shore. Installation consisted of pounding a steel pipe casing into lake bottom sediments, inserting the piezometer, and retracting the steel casing. The piezometers were installed to depths ranging from 1.0 to 3.3 feet below lake bottom. Piezometers were left in place for several hours to allow water levels to equilibrate before measuring the depth to groundwater.

Water samples analysis for environmental isotopes

This study included sampling water from springs, streams, wells, and Geneva Lake for analysis of environmental isotopes. Deuterium (^{2}H) and tritium (^{3}H), isotopes of hydrogen, and oxygen-18 (^{18}O), which is an isotope of oxygen, occur naturally and are often useful indicators of groundwater age and source area. Isotope samples were analyzed at the University of Waterloo (Ontario) Environmental Isotope Laboratory. Deuterium was determined by manganese reduction. Oxygen-18 was determined by mass spectrometry on CO_2 gas. Tritium was determined by liquid scintillation counting on enriched samples. Tritium results are reported in tritium units (TU, where one unit equals one tritium atom in 10^{18} atoms of hydrogen). Deuterium and oxygen-18 results are reported as ∂ ‰ (del per mil) differences from the concentrations in standard mean ocean water (SMOW).

Groundwater level monitoring

Seasonal changes in groundwater levels provide information about the response of an aquifer to precipitation, pumping, and other stresses on the groundwater system. The USGS and WGNHS cooperatively maintain a network of monitoring wells across Wisconsin, one of which is located at the Department of Public Works in Fontana. We installed Solinst pressure transducers and data loggers in the Fontana well and in a residential water well on the north shore of the lake. Water levels were monitored from February 2008 through August 2008.

Groundwater recharge mapping

Recharge is the addition of water to the groundwater system, and usually occurs when rainfall and snowmelt infiltrate through soil and reach the water table. Recharge varies both temporally and spatially, but generally occurs to some extent over most of the landscape. Various methods have been used to measure and estimate recharge. A watershed-based method, useful at a broad scale, was used in constructing the Geneva Lake groundwater flow model and is described beOne project objective concerns identification of groundwater recharge areas adjacent to Geneva Lake. For this purpose, a method that can be applied at a finer-scale is more appropriate. Here, we used a soil-water balance model (Dripps and Bradbury, 2007) recently applied to the SEWRPC region (Hart and others, 2008). This model is useful for land-use planning, as parcels as small as 80 acres may be delineated where model inputs are available at this spatial scale.

The soil-water balance (SWB) model estimates the amount of precipitation that infiltrates the ground. Several physical processes that affect infiltration and diversion of precipitation are accounted for, including interception by the plant canopy, surface runoff, evapotranspiration, soil moisture storage capacity, and antecedent soil moisture conditions. Model inputs used for the Geneva Lake area include daily climate records from the Genoa City and Lake Geneva weather stations, the 30-meter digital elevation model (DEM) from the USGS National Elevation Dataset (NED), digital soil data from the Natural Resources Conservation Service (NRCS) Soil Survey Geographic (SSURGO) Database, and land-use data for 2000, provided by SEWRPC. Limitations of the SWB model include those imposed by the resolution of these inputs. Hart and others (2008) provide a thoughtful discussion of application of these results to land-use planning.

Model construction

The Geneva Lake groundwater flow model was developed by refining and modifying the regional-scale SEWRPC model. This process included extracting boundary conditions from the area of interest within the SEWRPC model and improving model resolution in the Geneva Lake area. The simulated area (figure 6) is large to ensure that Geneva Lake and nearby communities are far from model boundaries.

Model grid

The model domain consists of a three-dimensional grid of rows, columns, and layers, which can be thought of as a cube of cells. The result or "output" of the model is an estimate of hydraulic head (the water table elevation) at the center of each cell and an estimate of groundwater flow through each cell. This type of model is referred to as a finite-difference model, and its strength is its ability to calculate groundwater flow in three dimensions.

We modified the grid of the regional model, adding rows and columns in the "near-field" area—the area surrounding the lake—to improve resolution in model results and to improve representation of hydrogeologic and surface water features in the model. Cell spacing is 417 ft in the model near-field, increasing to 2500 ft in "far-field" cells. Use of a large cell size in the far field increases the computational efficiency of the model. The model contains 114 rows, 173 columns and 17 layers, with a total of 329,179 active models cells.

The thickness and layering of geologic units in the Geneva Lake model, shown in figure 7, is generally consistent with the regional model with the exception of those representing the glacial deposits. In this model, layers 1, 2, and 3 represent the unlithified upper aquifer (figure 8). The lack of detailed information about glacial stratigraphy with depth prevented us from assigning these upper layers to a specific Quaternary formation. Since the total thickness of the top three layers varies across the domain, each cell was assigned a thickness of one-third the total thickness of glacial sediment at that location. The 30-meter digital elevation model (DEM) of Walworth County and the elevation of the bedrock surface mapped by Massie-Ferch (2004) provided good resolution of the thickness of glacial deposits.

Boundary conditions for the Geneva Lake model (figure 6) were selected from the regional groundwater flow model. The hydraulic heads simulated by the regional model for the time period 1990 to 2000 were applied to the edges of the Geneva Lake model as constant head boundaries. These were applied for the calibration and current condition simulations. We used regional model results for predevelopment, non-pumping conditions to generate the constant heads applied to the Geneva Lake model for predevelopment simulations.

Representation of surface waters

MODFLOW includes several options for simulating surface water. Geneva Lake is simulated with LAK7, a recent version of the MODFLOW lake package (Merritt and Konikow, 2000). The code computes lake stage from user-specified rates of precipitation, surface runoff, and evaporation while tracking surface water inflows and outflows between the lake and adjacent stream cells. The rate and direction of water exchange between the lake and aquifer are calculated with a user-defined conductance term (hydraulic conductivity divided by thickness of lake-bottom sediments), the calculated lake stage, and the calculated head in the aquifer. We adjusted lake conductance values during model calibration (described below) and applied the rates of evaporation, runoff, and precipitation reported by Robertson and others (2002) for Geneva Lake in 1998 (table 1). Simulated surface water outflow from the lake to the White River is based on a user-specified relation between lake

Table 1. Lake package parameters.

Parameter	Flux, ft/day	Volumetric flux, ft^3/day
Evaporation	6.87e-03 [a]	1.60E+06 [b]
Precipitation	7.55e-03 [b]	1.76E+06 [b]
Runoff	—	8.55E+05 [a]

[a] *From Robertson and others (2002).*

[b] *Calculated by LAK package from flux and simulated lake area.*

Table 2. Relation of Geneva Lake stage and discharge used in model.

Stage above dam, ft	Discharge, ft^3/day	Discharge, ft^3/second
0.05	139,000	1.6
0.10	489,000	5.7
0.15	939,000	10.9
0.20	1,489,000	17.2
0.25	2,139,000	24.8
0.30	2,889,000	33.4
0.35	3,739,000	43.3
0.40	4,689,000	54.3
0.45	5,739,000	66.4
0.50	6,889,000	79.7
0.55	8,139,000	94.2

stage and discharge (table 2). The stage-discharge relation is based on USGS data (appendix A).

Lakes that were not the primary focus of the model (Lakes Delavan, Como, and several smaller lakes) were assigned the head-dependent river boundary condition (figure 9). The river condition provides a relatively simple approach to simulating the transfer of water between surface and groundwater systems. Each river cell is assigned values of stage and vertical conductance (vertical hydraulic conductivity divided by thickness of bottom sediment). Flow is calculated from the conductance and the head difference between adjacent river and aquifer cells.

Flow in the White River and in streams discharging to Geneva Lake were simulated with the stream boundary condition (Prudic and others, 2004). This head-dependent boundary also requires user-defined values of stage and conductance, but it provides a more realistic and complex representation of surface water–groundwater exchange than the river option. The stream boundary condition implements routing of surface water flow: stream cells receive flow from up-gradient stream cells and through groundwater exchange, but flow from a stream cell to the groundwater system or down-gradient stream reaches cannot exceed flow into that stream cell.

Some areas of intermittent stream flow and wetlands, determined from 1:24,000 USGS topographic maps, that became flooded (simulated head exceeded land surface) during preliminary model runs were assigned the drain boundary condition. This type of head-dependent boundary simulates flow out of the model domain when the head in the cell exceeds a user-assigned threshold value. For example, a drain cell representing a wetland is assigned a head equal to the elevation of the wetland and a vertical conductance. When the model simulates ponding of water in the wetland (that is, the simulated head exceeds the assigned head) the water is routed out of the model. This water loss represents the physical processes of evaporation or evapotranspiration, neither of which is explicitly simulated in the Geneva Lake model.

Hydraulic conductivity

Prior to model calibration, hydraulic conductivity of sediments in the Geneva Lake region were estimated from specific capacity tests reported on well constructor's reports (table 3) with the method of Bradbury and Rothschild (1985). Estimates compiled from existing sources are presented in table 4.

Hydraulic conductivity values from the SEWRPC regional model were initially assigned to the various model layers based on the hydrogeologic strata. The extent of the Silurian and Maquoketa Formations were refined for the study area based on the bedrock map prepared by Massie-Ferch (2004). Hydraulic conductivity was assigned to the upper three model layers according to the Pleistocene geologic map (figure 2). Areas within the layers represent zones of coarse sand and gravel, fine sand and gravel, fine-grained till, very fine-grained till, and peat.

Aquifer porosity

Effective porosity is the volume of connected pore space in aquifer sediments. Porosity affects the velocity, or travel time, of groundwater in an aquifer. In the Geneva Lake model we assumed that effective porosity is equal to specific yield of glacial deposits and storativity of confined units. We applied the storage parameters used in the SEWRPC model (Feinstein and others, 2005), as reported in table 5.

Recharge

Recharge refers to the addition of water to the model from rainfall and snowmelt that infiltrates to the water table. In natural systems, recharge varies seasonally

Table 3. Hydraulic conductivity estimates from specific capacity tests.

		Hydraulic conductivity, ft/day		
Aquifer	Number of wells	Geometric mean	Standard deviation	Range
Sand and gravel	352	22	3.8	0.09 – 575
Silurian dolomite	82	4.2	0.9	0.04 – 503
Sinnipee dolomite	16	5.9	0.5	0.4 – 41

Table 4. Estimates of hydraulic conductivity.

Hydrogeologic unit	Method	Hydraulic conductivity, ft/day	Comment	Source
Sand and gravel	specific capacity tests	l80 to 400	n = 100 wells	Borman, 1976
Silurian	specific capacity tests	1 to 130	n = 50 wells	Borman, 1976
Sand and gravel	pumping test	49 to 81	Two 24-hour tests, Geneva National well VK054	Bender Consulting[a]
Sand and gravel	grain size analyses	10	n = 31 samples	Root, 2005
Foxhollow till	grain size analyses	0.2	n = 28 samples	Root, 2005
Silurian	pumping test	1.5	24-hour test, Woods School well FB242	Root, 2005

[a] *provided by Geneva National Co.*

and spatially, because it is affected by a variety of physical characteristics such as soil type, vegetation, land surface slope, temperature, and rainfall intensity. In the calibration and steady-state simulations, this model uses a constant, average value of recharge that varies over the model domain, as shown in figure 10. These recharge zones were developed by Cherkauer and Ansari (2005) based on stream baseflow estimates from surface water sub-basins in southeastern Wisconsin. Cherkauer's estimates for the Geneva Lake region range between 2.5 and 9.6 inches per year. During model calibration, the zone delineations were preserved, but the rates were increased by 25%.

Wells and pumping rates

Pumping from municipal and private high-capacity wells is simulated in the flow model. Wells were assigned to the model layers corresponding to the open interval reported for each well. For example, wells screened in the unlithified aquifer were assigned to one or more of the top three layers, depending on the depth and length of the well screen. Information on pumping rates, presented in appendix B, was compiled from sources including Public Service Commission records, typical water use rates (for example, irrigation rates at golf courses), and WDNR high-capacity well applications. User-reported pumping rates were applied in the model for wells where this information was available.

Pumping rates applied in the steady-state model reflect actual pumping rates at the wells, averaged over one year. These rates may be significantly less than the pump capacity of the wells because most wells do not run continuously. High-capacity wells, such as those operated by municipalities, factories, golf courses, and hotels, usually operate in response to demand, as opposed to continuous operation.

The model does not simulate pumping from private domestic water wells because of the small volume of water pumped from these wells. The Linn Sanitary District encompasses a majority of the unincorporated land within the watershed. Robertson and others (2002) estimated that about 1,200 of the 1,309 homes in this area have on-site septic systems. Assuming that a typical residence in southeast Wisconsin uses about 350 gallons per day (Gotkowitz and others, 2008), and that about 80% of this flow is returned to the groundwater system through on-site systems, the total withdrawal from private domestic wells in the water shed is likely on the order of 150 to 200 gallons per minute, or about 0.2 gallons per minute per well. The impact of this withdrawal is likely very low, because the wells are distributed across the entire watershed.

Table 5. Storage parameters.

Hydrogeologic unit	Value
Unlithified (sand & gravel or till, layers 1 & 2)	0.15
Unlithified (sand & gravel or till, layer 3)	0.20
Silurian, Maquoketa, Sinnipee	0.01
Sandstone	0.05

Particle tracking

Particle tracking is a modeling technique that mathematically traces the path of an imaginary particle through the groundwater flow system. We used this method to identify groundwater flow paths to the lake from the surrounding aquifer. The three-dimensional area delineated by these flow paths constitutes the groundwater recharge area of the lake. In other words, groundwater within this area discharges to the lake. Particle tracking was performed with the MODPATH code (Pollock, 1994).

Model calibration

Calibration process

Model calibration involves adjusting selected model parameters within reasonable ranges of values to obtain a model that simulates observed conditions reasonably well. The calibration process included use of the PEST parameter estimation software (Doherty, 2004). PEST operates successive MODFLOW runs, adjusting model parameters to obtain a best statistical fit to observations of groundwater levels and stream fluxes. Additional calibration efforts included some trial-and-error runs, with manual adjustment of parameters. Professional judgment plays a large part in model calibration with respect to model stability, features important to the project goals (such as the water balance of Geneva Lake), and experience gained from hydrogeologic field investigations near Geneva Lake (Root, 2005).

Calibration targets

Calibration targets include measurements of groundwater levels (head targets) and stream flows (flux targets) used to compare model results to observed conditions. The Geneva Lake model includes 796 head targets. The PEST runs assigned greater statistical weight to head targets in the near-field of the model and to head targets with greater accuracy in measurement and location.

Flux targets were compiled from several sources (table 6). Low-flow measurements of streams in southeast Wisconsin (Holmstrom, 1978) were converted to flux targets for streams in the model far-field. Flux targets for streams tributary to Geneva Lake were developed from a long-term record for 1998 at Birches Creek (Robertson and others, 2002) and from stream flow data provided by the GLEA. Calibration targets were not included for Geneva Lake. Rather, the lake package was considered calibrated when the mass balance of the lake was reasonable and the simulated stage closely matched typical lake stage.

Results of calibration

The model calibration in steady-state mode included all model features except wells that were not operating in the 1990s. The best calibration, referred to as the calibrated model, provides a good match to head and flux targets. The absolute residual mean, which is the average of the absolute difference between measured and simulated values, is 14.6 ft, which is reasonable considering that many of the targets have a likely error of +/- 10 ft from calculating groundwater elevation from

Table 6. Measured and simulated stream flows.

	Flux, ft^3/day		Flux, ft^3/s, cfs		
Stream	Target	Calibrated	Target	Calibrated	Source
Near-field streams					
Trinke Creek	5,180	5,206	0.06	0.06	GLEA (unpublished)
Gardens Creek	94,590	3,542	1.09	0.04	GLEA (unpublished)
Birches Creek	52,700	21,615	0.61	0.25	Robertson and others (2002)
Harris Creek	3,050	3,278	0.04	0.04	GLEA (unpublished)
Potawatomi Creek	146,500	36,530	1.70	0.42	GLEA (unpublished)
Buttons Bay Creek	6,100	5,343	0.07	0.06	GLEA (unpublished)
Far-field streams					
Como Creek	172,800	197,133	2.00	2.28	Holmstrom (1978)
White River at Lyons	1,728,000	3,607,359	20.0	41.8	Holmstrom (1978)
Tributary to Turtle Creek near Delavan	17,280	67,610	0.20	0.78	Holmstrom (1978)
Nippersink Creek at Zenda	283,000	323,747	3.28	3.75	Holmstrom (1978)
Piscasaw Creek at Sharon	142,000	106,858	1.64	1.24	Holmstrom (1978)
Turtle Creek near Darien and Delavan	172,800	181,319	2.00	2.10	Holmstrom (1978)
Ladd Creek, Allens Grove	172,800	224,461	2.00	2.60	Holmstrom (1978)

well construction records. The standard deviation between measured and simulated values is 21.5 ft, which is only 5% of the total range in water levels across the model domain. Figure 11 illustrates the relationship of observed to simulated heads. The cluster of points around the 1:1 line indicates that simulated groundwater elevations are generally well-distributed around measured values with the exception of several of the highest water-level measurements. Figure 12 shows the distribution of differences between measured and simulated groundwater levels across the model domain. The model has an area of bias in these "residuals" north of Lake Como, where the simulated water table is consistently lower than target values. We attribute this to an under-representation of very low-conductivity material, such as fine-grained glacial tills, in this area of the model domain.

Simulated stream flows are reported in table 6. These match measured stream flows reasonably well, particularly in the area of interest at the near-field streams near Geneva Lake.

Calibrated parameters

Initial and calibrated values of hydraulic conductivity are reported in figure 8. The upper values of hydraulic conductivity are well within the range of field estimates (tables 3 and 4). The lowest calibrated values of hydraulic conductivity for glacial sediments (simulated in layers 1, 2, and 3) are lower than field estimates but within the range reported in the literature for glacial till (Freeze and Cherry, 1979). It is reasonable to assign lower conductivity to these sediments than those reported from field estimates because most of the estimates are based on tests performed at water wells, which are preferentially completed in productive, high-conductivity deposits.

The glacial sediments are simulated with a broad range of hydraulic conductivity, consistent with the complex vertical distribution of unlithified materials documented in figure 3. In the region between Lakes Geneva, Como, and Delavan, lower values of conductivity dominate layers 1 and 2, and these are underlain by higher conductivity values in layer 3 (figure 13). This distribution allows the model to correctly simulate both the relatively high water table elevation in this region and the large pumping rates sustained by high capacity wells completed at depth in this aquifer.

Vertical hydraulic conductivity of the glacial sediments, the Silurian dolomite, and the Maquoketa shale varied within an order of magnitude of the calibrated SEWRPC model values; vertical hydraulic conductivity of bedrock layers representing below the Maquoketa shale were held to the SEWRPC model values during calibration.

Hydraulic conductivity and recharge are correlated parameters in flow models—lowering hydraulic conductivity or raising recharge increases simulated water levels. During calibration, recharge was varied between 0.75 and 1.25 of the initial values from the SEWRPC model. The best calibration was obtained with 1.25 times the initial values; raising recharge beyond this did not seem warranted. The under-prediction of heads in some parts of the domain is attributed to the complex distribution of high- and low-conductivity zones within glacial deposits. The calibrated model is a compromise of placing sufficient heterogeneity in the top three layers to achieve a good calibration in the area of interest without injecting more heterogeneity than can be justified from the Pleistocene map of the area (figure 2) and other data sources.

Calibration included adjusting the lakebed conductance term applied to Geneva Lake. This was initially set to 10 d^{-1}, which is the equivalent of 1 ft of sediment with hydraulic conductivity of 10 ft/day. Conductance was held to a single value in each model layer but was allowed to vary from 10 d^{-1} to 0.01 d^{-1} across the three lake layers. This range reflects our assumption that lakebed sediments are unlikely to be more permeable than aquifer material. The PEST model calibration resulted in increasing lakebed conductance in deeper layers (table 7).

Table 7. Lake bed conductance in calibrated model.

Model layer	Lake bed conductance, per day[a]
1	0.64
2	1.59
3	9.52

[a] Equivalent to hydraulic conductivity in ft/day assuming sediment thickness of 1 ft.

The simulated lake stage in the calibrated model is 864.68 ft., which is a reasonable match to the average lake stage of 864.48 ft in 1998 (USGS data, water.usgs.gov). The simulated hydrologic budget for Geneva Lake, presented in tables 8a and 8b, indicates that groundwater contributes 36% of inflow to the lake. Although higher than that estimated by Robertson and others (2002), this value is reasonable and is of a similar magnitude as results from groundwater–surface water models of other lakes in southeastern Wisconsin, such as Silver Lake (Dunning and others, 2003) and Fish Lake (Krohelski and others, 2002).

Sensitivity of model to parameters

A sensitivity analysis provides insight into the uncertainty associated with a groundwater flow model. This analysis compares changes in the simulation match to model targets when assigning different values to selected parameters. The analysis sheds light on which parameters have the largest affect on the model results. PEST includes calculation of model sensitivities. In the Geneva lake model, near-field and far-field stream flux targets are most sensitive to recharge. The hydraulic conductivity of several model zones also affects the calibration to fluxes. The composite sensitivities (that is, all head and flux targets) calculated by PEST show that the model is most sensitive to the hydraulic conductivity assigned to an area of sandy surficial aquifer in layer one. This area can be seen in figure 13, layer one, as the zone assigned a hydraulic conductivity of 10 ft per day. The model is not sensitive to values of lake bed conductance.

Analysis of the groundwater system and Geneva Lake

This analysis involved simulation of various pumping scenarios and changes in precipitation. Results, in terms of configuration of the water table, discharge to streams, and components of the lake budget, indicate the degree to which streams and the lake respond to changes affecting the groundwater flow system.

Current conditions

A simulation of current conditions is based on application of pumping rates from 2006 (appendix B) to the calibrated model. This model run includes discharge of treated wastewater to the City of Lake Geneva's infiltration ponds, which are located east of the city. The ponds are represented as an area of increased recharge to the water table. Based on records provided by the Lake Geneva Utility for 2007 (personal communication, Winkler, October 1, 2008), we simulated a recharge rate of 900 gpm (172,918 ft^3/day) from the ponds. This is the equivalent of discharging about 90% of the groundwater pumped from the city wells.

The water table under these conditions, figure 14, reflects the primary flow direction in the shallow system from west to east, with groundwater discharging to the lake from the west, south, and north shores. The model identifies a small area at the northeast end of the lake over which lake water seeps to the groundwater system. Infiltration at the Lake Geneva wastewater treatment ponds results in a water table mound of about 20 ft.

Delineation of the recharge area for groundwater flowing to Geneva Lake was simulated with backward particle tracking and examination of cell-by-cell flows in the model (figure 15). The recharge area extends well beyond the surface water shed of the lake, encompassing a large region to the west and south. As evident from the location of wells with respect to the shape of the recharge area, several high-capacity wells intercept groundwater that would otherwise discharge to the lake. Pumping from high-capacity wells west of the lake results in drawdown of the water table and shifts the groundwater divide and the lake recharge area farther west.

The simulated hydrologic budget for Geneva Lake under current conditions (table 8a) is essentially the same as that of the calibrated model. This is a reasonable result, given that much of the increase in pumping between the calibrated and current simulations occurs at wells located further from Geneva Lake.

Predevelopment conditions

The effects of the dam and of pumping on the groundwater-surface water system are illustrated with two non-pumping simulations. Boundary conditions from the predevelopment version of the SEWRPC regional model were applied to this model. In the first run, the dam is simulated along with no pumping. Simulated lake stage is 864.7 ft., and stream baseflow and groundwater inflow contribute 45% of the lake budget (table 8a). Seepage from the lake to the underlying aquifer accounts for about 0.5% of outflow from the lake.

The second non-pumping scenario alters the representation of Geneva Lake and the White River to simulate the lake without a dam in place. This illustrates the dam's effect on the system. In this case, the model-simulated lake stage is 857.3 ft, in good agreement with a historic stage of about 858 ft prior to dam construction (SEWRPC, 2008). The configuration of the water table is similar in shape to current conditions but is approximately 10 to 20 ft lower in places (figure 16). The predevelopment recharge area of the lake (figure 15) is smaller than under current conditions and does not extend as far to the west. In the absence of the dam, the lower lake stage reduces the hydraulic gradient between the lake and the underlying aquifer, and a very small volume of lake water seeps from the lake to groundwater. However, the total volume of water passing through the lake is about 2% higher without the dam, and discharge from the lake to the White River increases.

Impacts of current pumping

Groundwater pumping in the Geneva Lake region reduces groundwater discharge to the lake and reduces baseflow in local streams; this is a largely inevitable consequence of pumping and subsequent diversion of pumped water out of the local hydrologic basin. The hydrologic system maintains mass balance—that is, the amount of water removed from the system through pumping is balanced by reductions in groundwater flow to other features in the system such as lakes, streams, and groundwater flow out of the region. In comparison to predevelopment conditions, current pumping reduces the total flow through the lake by 4% and reduces contributions to the lake from stream baseflow and groundwater by 9% (table 8a).

Table 8a. Simulated hydrologic budgets for Geneva Lake.
Comparison of predevelopment and very high and very low recharge rates against current conditions.

					PREDEVELOPMENT—NO PUMPING				GROUNDWATER RECHARGE			
Component	Calibration, 1990s rates (ft^3/day)	%	Current conditions, 2006 rates (ft^3/day)	%	No dam (ft^3/day)	%	Dam in place (ft^3/day)	%	High recharge (ft^3/day)	%	Low recharge (ft^3/day)	%
INFLOW												
Precipitation[a]	1,735,774	38	1,735,774	38	1,735,774	36	1,735,774	37	2,658,414	31	111,625	7
Stormflow[a]	854,800	19	854,800	19	854,800	17	854,800	18	2,137,000	25	128,200	8
Baseflow[b]	311,440	7	338,260	7	237,930	5	402,140	8	965,010	11	192,610	12
Groundwater[b]	1,649,700	36	1,642,900	36	2,044,500	42	1,769,800	37	2,897,700	33	1,169,600	73
Total input	4,551,714	100	4,571,734	100	4,873,004	100	4,762,514	100	8,658,124	100	1,602,035	100
OUTFLOW												
Evaporation[a]	1,600,640	35	1,600,640	35	1,600,640	33	1,600,640	34	2,124,868	25	1,414,248	85
Surface water[b]	2,900,200	64	2,922,400	64	3,263,200	67	3,138,400	66	6,536,500	75	0	0
Groundwater[b]	55,840	1	52,269	1	9,111	0	24,830	<1	5,042	<1	251,220	15
Total output	4,556,680	100	4,575,309	100	4,872,951	100	4,763,870	100	8,666,410	100	1,665,468	100

[a] *Value input to model.*

[b] *Calculated by model.*

Table 8b. Simulated hydrologic budgets for Geneva Lake.
Comparison of increased pumping scenarios against current conditions.

			INCREASED PUMPING							
Component	Current conditions, 2006 rates (ft^3/day)	%	30% increase, ALL municipal wells (ft^3/day)	%	100% increase, Lake Geneva Utility Comm. wells (ft^3/day)	%	100% increase, Fontana & Williams Bay munic. wells (ft^3/day)	%	Current rates at Fontana & Williams Bay shifted to deep wells (ft^3/day)	%
INFLOW										
Precipitation[a]	1,735,774	38	1,735,774	38	1,735,774	38	1,735,774	38	1,735,774	38
Stormflow[a]	854,800	19	854,800	19	854,800	19	854,800	19	854,800	19
Baseflow[b]	338,260	7	329,470	7	338,230	7	325,670	7	358,620	8
Groundwater[b]	1,642,900	36	1,633,100	36	1,641,000	36	1,619,100	36	1,660,900	36
Total input	4,571,734	100	4,553,144	100	4,569,804	100	4,535,344	100	4,610,094	100
OUTFLOW										
Evaporation[a]	1,600,640	35	1,600,640	35	1,600,640	35	1,600,640	35	1,600,640	35
Surface water[b]	2,922,400	64	2,894,700	64	2,894,800	63	2,885,600	64	2,961,000	64
Groundwater[b]	52,269	1	60,553	1	78,091	2	52,340	1	52,237	1
Total output	4,575,309	100	4,555,893	100	4,573,531	100	4,538,580	100	4,613,877	100

[a] *Value input to model.*

[b] *Calculated by model.*

Table 9. Impacts of pumping on tributaries to Geneva Lake.

		Current conditions			Increased pumping		
Stream	No pumping flow, ft³/day	Flow, ft³/day	Change from no pumping, ft³/day	Change, %	Flow, ft³/day	Change from no pumping, ft³/day	Change, %
Harris	6,276	4,258	-2,018	-32	3,941	-2,336	-37
Gardens	4,197	3,467	-730	-17	3,436	-761	-18
Potawotami	70,337	45,928	-24,410	-35	42,523	-27,814	-40
Birches	24,359	23,128	-1,230	-5	23,105	-1,253	-5
Trinke	6,175	5,795	-380	-6	5,793	-382	-6
Buttons Bay	5,898	5,718	-181	-3	5,695	-203	-3

Model simulations indicate that streams nearest high-capacity wells (Potawotami, Harris, and Gardens Creeks) face the largest reductions in baseflow, on a percentage basis, due to pumping. These streams are impacted to a greater degree than are Birches, Trinke, and Buttons Bay (table 9), which are farther from high-capacity wells.

Increased pumping

We used the model to compare potential impacts of increased pumping on the surface water and groundwater resources of the area. The first simulation is based on a projected population increase in Walworth County of 30% from 2005 to 2035 (SEWRPC Technical Report 11). Simulated pumping rates were therefore increased by 30% at municipal wells. Pumping rates at wells operated for industry, irrigation, and existing hotels and resorts was not increased, based on the assumption that most development in the region will occur within municipal service areas.

A 30% increase in pumping from municipal wells translates to a total increase of 6% from current conditions. The lake budget predicted under this scenario (table 8b) is nearly identical with respect to the proportion of inflows and outflows of lake water. However, total flow through the lake is reduced by about 0.5% (18,590 ft³/day). The contribution to the lake from stream baseflow and groundwater is about 1% less than under current conditions.

The simulated increase in pumping further reduces groundwater discharge to Harris, Gardens, and Potawotami Creeks (table 9). These results show that other tributaries located farther from pumping centers would be negligibly affected by increased pumping.

The location and depth of wells relative to the lake and tributary streams are strong controls on the impact of pumping on the hydrologic system, as is the location of discharge following use and treatment of pumped water. High-capacity wells operated by Fontana and Williams Bay are within the lake recharge area, and these wells divert groundwater out of the basin. The model simulations that are described below illustrate the impact of this pumping on the lake budget and streams. However, it is important to note that the model-simulated lake level is insensitive to pumping from these wells; the simulated lake stage is largely controlled by the dam. The model simulates average conditions (for example, average rates of pumping, evaporation, and stream flows), and the change in lake stage attributable to these pumping rates is less than the resolution of the model.

In contrast, wells operated by the Lake Geneva Water Utility are located east of the lake recharge area and a majority of the water pumped from these wells is returned to the local groundwater system at the infiltration ponds. Pumping from these wells affects the groundwater system in two ways. Drawdown from pumping lowers the water table near the wells, which increases the vertical gradient between the lake and the underlying aquifer. The second change to the groundwater system is the development of a water table mound beneath the Utility's infiltration ponds.

Two model simulations illustrate the differences between pumping from within and outside of the lake's recharge area. One simulation involves pumping from the four Lake Geneva Water Utility wells and return of water to the infiltration basins at double the current rates, with no concurrent increase at other wells. While this increase in pumping is much greater than might occur in light of current population projections, the large increase is necessary to illustrate the relationship between flow from Geneva Lake and conditions that are hydraulically down-gradient, east of the lake. Doubling pumping rates at these wells increases total simulated pumping by 12% from current conditions but causes no change in the total volume of the lake budget. Drawdown of the water table results in a 1% exchange between lake outflow to seepage and the White River. Seepage from the lake to groundwater increases by about 26,000 ft^3/day and surface water discharge over the dam to the White River decreases by a similar volume (table 8). Return flow to the local shallow aquifer occurs through groundwater recharge at the infiltration basin, which is within the White River basin.

The second simulation illustrates the impact of a large increase in pumping from wells at the west end of the lake. Doubling current pumping at Fontana and Williams Bay wells increases total simulated pumping by 6% from current conditions. The model predicts a 4% decrease in the contribution of stream baseflow to the lake, and a 1% reduction in the total lake budget compared to current conditions (table 8). Assuming wastewater from these systems continues to be transferred out of the basin, the 1% decrease in the lake budget reflects diversion out of the local hydrologic system.

The villages of Williams Bay and Fontana operate shallow wells, completed in the sand and gravel aquifer, and deep wells that are completed in the sandstone bedrock. An additional model simulation was completed in which all of the current pumping from the shallow wells is transferred to the deep wells. As shown in table 8, this increases flow to tributary streams and the resulting baseflow to the lake, as less water is diverted from the shallow aquifer system. Overall, this change would increase the total lake budget by about 1% compared to current conditions. The water pumped from the deeper system is diverted from other locations in the flow system that do not directly impact Geneva Lake, including shallow flow from further west. Although shifting pumping to the deep aquifer may have a positive effect on local lakes, springs and streams, the quality of groundwater from the deep wells should also be considered. Deep wells in some regions of southeastern Wisconsin produced groundwater with elevated concentrations of radium. Local water utilities may also face issues regarding distribution across service areas when considering shifting pumping from shallow to deep wells.

Climate variability

The model is a useful tool to simulate changes in the hydrologic system resulting from variation in annual precipitation. The soil-water balance model (Hart and others, 2008), described above, was used to simulate rates of groundwater recharge to the water table in 1972, when the region received about 50 inches of precipitation. The increased precipitation was applied to the lake. Surface runoff to the lake and evaporation from the lake were increased by 250% and 30%, respectively, based on the ratio of each component to precipitation presented by Robertson and others (2002). Current conditions pumping rates were applied to the model.

The model-simulated lake budget for a year of high precipitation demonstrates that surface water–groundwater exchange is sensitive to climate variation. The model simulates an 89% increase in total flux through the lake compared to an average year (table 8). The lake budget also changes, with a higher percentage of baseflow from streams. The increase in recharge causes higher water table elevations, which in turn increase stream flows throughout the system.

Groundwater recharge during a dry year, 1956, was simulated with the soil water balance model. The 1956 precipitation rate, 21.2 inches, was applied to the lake surface. Runoff and evaporation were decreased by 88% and 12%, respectively, from average years. The simulated lake budget for a very dry year shows a large decrease in surface water–groundwater exchange, with a total flux through the lake less than half that of an average year (table 8a). The total volume of stream baseflow and groundwater seepage to the lake is about 37% of that in an average year. Seepage from the lake to groundwater increases under this scenario, driven by a high gradient between the lake and the lower water table.

Independent methods to assess model results

Hydraulic gradients

Based on the regional water table map and model results, groundwater discharge to the lake occurs along much of the shoreline and a small area of lake seepage to groundwater exists in the northeast area of the lake near the City of Lake Geneva. We assessed the distribution of vertical gradients at the lake edge by installing temporary piezometers at several locations around the shoreline. The findings of the gradient survey were largely consistent with the model results. Upward gradients, meaning that the head, or water level, in the aquifer exceeded the lake stage, were measured along the west, north and south shores (table 10). Downward gradients, meaning that lake stage exceeded underlying groundwater levels, were measured at several locations in Lake Geneva, although not for the entire project period. Upward gradients measured at these locations in August 2008 are attributed to high precipitation rates in June and July 2008.

Table 10. Vertical gradients measured at Lake Geneva shoreline.

Location	Date	Gradient	Direction
Williams Bay, west end of beach	11-Mar-08	0.03	up
	8-Aug-08	0.01	up
Williams Bay, east end of beach	11-Mar-08	0.04	up
Lake Geneva, city beach	11-Mar-08	0.02	up
Lake Geneva, city beach	11-Mar-08	0.01	up
Lake Geneva at Riviera Beach	17-May-08	0.02	down
	8-Aug-08	no gradient	—
Lake Geneva, south of dam	17-May-08	0.13	down
	8-Aug-08	0.01	up
Lake Geneva, public boat launch	17-May-08	0.06	down
	8-Aug-08	0.01	up
Fontana, boat dock	29-Jul-08	0.01	up
Big Foot Beach State Park	29-Jul-08	0.01	up
	8-Aug-08	0.01	up
Chapin Road at boat launch	29-Jul-08	0.02	up

Table 11. Isotopic results for wells and surface waters.

Location	^{18}O, del per mil SMOW[a]	^{2}H, del per mil SMOW[a]	^{3}H, tritium units	Aquifer
WELLS				
Fontana 1	-8.83	-58.15	7.1 +/- 1.0	shallow
Fontana 2	-7.84	-50.62	7.9 +/- 1.0	shallow
Fontana 3	-8.89	-59.12	7.6 +/- 0.9	shallow
Fontana 4	-8.02	-52.56	<0.8 +/- 0.7	deep
Williams Bay 1	-8.39	-55.62	<0.8 +/- 0.7	shallow
Williams Bay 2	-8.47	-54.97	<0.8 +/- 0.7	shallow
Williams Bay 3	-8.39	-55.91	1.7 +/- 0.7	deep
SURFACE WATER				
Geneva Lake	-3.93	-32.01	<6 +/- 8	NA
W4065	-8.69	-55.35	8.0 +/- 1.0	NA
Gardens	-8.48	-55.76	7.5 +/- 1.0	NA
Birches	-8.16	-54.29	8.3 +/- 0.9	NA
Bigfoot	-8.75	-55.48	7.4 +/- 0.9	NA
Kishwauketoe	-10.66	-56.85	7.0 +/- 1.0	NA

[a] *SMOW = standard mean ocean water*

NA—well depth is not applicable to surface water samples

Comparison of flowpaths to isotopic results

The isotopic results (tritium, oxygen-18, and deuterium) suggest that water in streams and wells recharged the aquifer over a wide range of time and that these wells and streams do not capture water from Geneva Lake. Tritium, reported in table 11, can be used as a relative indicator of travel time from recharge to the well. Tritium values range from less than 0.8 to 8.3 TUs (tritium units). The current tritium content of precipitation in Wisconsin ranges from about 5 to 15 TUs. Precipitation that fell during the 1960s had elevated tritium due to atmospheric nuclear testing. Pre-1960s precipitation had essentially no tritium. Three of the four Fontana supply wells produce water with essentially present-day tritium content; this water probably fell as precipitation within the past 10 years. Fontana well 4 and all three Williams Bay wells pump older water. The surface water sampling locations indicate that flow to these systems is dominated by recently recharged groundwater.

The relationship between deuterium and oxygen-18 indicates whether a component of surface water is present in groundwater. These are both stable isotopes of hydrogen and oxygen, respectively, and both isotopes are present in molecules of water. In lakes and wetlands, evaporation of surface water affects lighter isotopes preferentially over heavier isotopes, so that the surface water takes on a signature enriched in heavier isotopes. Isotopically heavy surface water that recharges a groundwater system results in different isotopic signature than recharge that originated from precipitation. Although the signature in precipitation may vary seasonally with temperature, the ratio between deuterium and oxygen-18 remains constant within a geographic region. This relationship, referred to as the meteoric water line (mwl), is determined from the deuterium and oxygen-18 ratio from several samples of local precipitation. Plotting groundwater samples on the same graph indicates which samples have some component of surface water; points falling far to the right of the meteoric water line indicate that surface water is a primary source of water to the well, whereas points falling to the left of the line suggest terrestrial recharge.

Samples from wells and head waters of streams plot to the left of the meteoric water line, showing no surface water component (figure 17). The samples collected from Geneva Lake shows a typical departure from meteoric water, falling to the right of the line. This meteoric water line is derived from precipitation data collected near Sturgeon Bay, Wisconsin (Rayne and others, 2001). A line derived from precipitation in the study region would be preferable for this interpretation but was prohibitively expensive to collect. The interpretation that these wells and streams are recharged by precipitation rather than surface water is consistent with their locations, which are hydrogeologically upstream up the lake.

Model limitations and uncertainty

The Geneva Lake model is well-calibrated to available data and is a useful tool for simulating the groundwater system in the region and the relation between groundwater and the lake. The model has several limitations, one of which is a necessary simplification of glacial sediment due to lack of site specific information. These materials have highly variable hydrogeologic properties, and this complexity is not fully represented in the model. This can result in model errors, particularly with respect to local-scale flow paths from ridge-tops to nearby streams and springs.

The model does not simulate some infrastructure in developed areas that can affect the shallow aquifer. For example, it is beyond the scope of this project to calculate return to the shallow aquifer from leaks and main breaks in water distribution lines. Although it is also widely acknowledged that sanitary and storm sewers can leak outward, the same leaks or breaks in these lines can drain shallow groundwater when the water table is high. Although the significance of water leaks to, and drainage from, the groundwater system could be assessed, it is beyond the scope of this project.

The model represents steady-state conditions, simulating average conditions over a long period. These simulations do not examine the response to conditions that fluctuate over time scales of weeks or months. Transient simulations could be carried out with the model; however, there is not sufficient data to calibrate to local storage parameters.

While the groundwater flow model addresses the rate and quantity of groundwater flow, it does not address issues relating to water *quality*. For example, the impact of pumping from private domestic wells on the lake budget is expected to be very small, in part because much of this water may be introduced back to the groundwater system through on-site septic systems. However, the impact on water quality from these septic systems is not considered in this analysis. Similarly, the model demonstrates that additional pumping from Lake Geneva Utility Commission wells would have no effect on the volume of the lake budget, but this analysis does not examine potential impacts related to changes in land use. These may include differences in the quality and quantity of runoff and infiltration in commercial, residential, and agricultural lands.

Similarly, the language of this report focuses on groundwater quantity. Hence, the diversion of pumped water from the local hydrologic system is accounted for as a loss in the volume of water in the local hydrologic system. However, we recognize that diversion of this water for treatment and discharge may represent an improvement to the quality of water in local streams.

Map of groundwater recharge

Recharge varies both temporally and spatially, but occurs to some extent over all of the Geneva Lake region. The estimated amount of precipitation that infiltrates the ground over the study area is shown in plate 1. The soil-water balance model (Dripps and Bradbury, 2007) used to derive this map accounts for interception by the plant canopy, surface runoff, evapotranspiration, soil moisture storage capacity, and antecedent soil moisture conditions.

The soil-water balance model is not accurate in some land use types, such as sand and gravel pits or quarries, and wetlands (Hart and others, 2008). These areas, along with open water, are mapped as "uncertain" on plate 1. In wetlands and some open water bodies, evapotranspiration happens continually because plant roots are presumably always in contact with the shallow water table. This process is not accounted for in the model, which simulates evapotranspiration after precipitation or snow melt events. Infiltration within a quarry is related to when and where dewatering occurs, and the model does not incorporate information on dewatering.

The map identifies areas of high infiltration, which is related to high groundwater recharge. Groundwater recharge in these areas, if developed, could be preserved by incorporating surface water runoff and drainage designs that maintain or enhance infiltration. With respect to preservation of recharge, these design practices may not be as critical on parcels with naturally low infiltration rates.

Suggestions for future use and maintenance of the model

The Geneva Lake groundwater flow model is a tool that can be used for analyses of groundwater flow in the region. The model is designed to be portable and flexible through use of the Groundwater Vistas (ESI, 2004) graphical user interface. Similarly, the soil-water balance model recharge may be applied to evaluate changes to recharge. The model should be used by stakeholders in the area to evaluate tradeoffs between groundwater use and preservation of flow to streams and lakes. Suggested uses of the model include the following:

- Better understand, through maps and graphics, groundwater flow and its relationship to streams and Geneva Lake.
- Determine the potential drawdown and areas of influence for existing or proposed high-capacity wells.
- Delineate contributing areas for wells for well head protection efforts.
- Investigate local groundwater-surface water interactions.
- Assess the impacts of wells and pumping rates on surface waters.
- Assess impacts of potential long-term changes in precipitation patterns and the related potential for an elevated water table.
- Investigate potential effects of land-use change on the groundwater-surface water system.

Summary

At the request of the Geneva Lake Environmental Agency and with the support of surrounding communities and stakeholders, we developed a numerical groundwater flow model that simulates fluxes between the groundwater system and Geneva Lake. The model simulates the full hydrogeologic system, including a shallow aquifer consisting primarily of glacial deposits, an underlying regional aquitard, and the deep sandstone aquifer. The model uses the MODLFOW code (McDonald and Harbaugh, 1988), the LAK package (Merritt and Konikow, 2000) and stream flow routing (Prudic and others, 2004), all developed by the US Geological Survey, to improve the utility of the model in assessing groundwater–surface water interactions.

Shallow groundwater in the region is closely connected to Geneva Lake and its tributaries. The model shows that the groundwater shed of the lake extends to the west, beyond the surface watershed, under both predevelopment and current pumping conditions. Under pumping and non-pumping scenarios, Geneva Lake receives a large component of its budget, about 36%, from groundwater. Discharge to groundwater from the lake occurs over a small region at the northeast edge of the basin and accounts for about 1% of lake outflows.

Pumping from wells alters the overall mass balance of groundwater systems because pumping removes water that would otherwise discharge to surface water. Simulations with this model demonstrate that pumping alters the shape of the water table, the locations of groundwater divides, and the groundwater shed of the lake. In comparison to predevelopment conditions, pumping in 2006 reduced total flow through the lake by 4%, including a 9% reduction in the inflow contributed from stream baseflow and groundwater. Pumped groundwater that is diverted out of the basin for wastewater treatment is ultimately lost from this local hydrologic system.

The Geneva Lake model demonstrates that the location and depth of wells relative to streams and lakes has a large impact on the effects of pumping. Pumping from wells that are east of the lake groundwater recharge area has no impact on the total volume of flow through the lake because these wells are located hydraulically down-gradient of the lake. In contrast, increasing pumping at high-capacity wells at the west shore of the lake further decreases baseflow in nearby streams and reduces the volume of the lake budget. The model demonstrates that shifting pumping from shallow to deep wells in these communities on the west shore of the lake would substantially decrease impact to the *local* surface water–groundwater system by capturing groundwater from deeper, regional flow paths. Other issues, such as groundwater quality in the deep wells, would require evaluation prior to shifting pumping from the shallow system.

Model simulations of groundwater and surface water features during years of high and low precipitation suggest that climate variability can have a large affect on the hydrology of the region. During very wet years, a large increase in groundwater recharge and direct precipitation to the lake will result in a high total flux through the lake and a higher percentage of flow to the lake from streams as compared to an average year. This results from high water table conditions, which increase groundwater discharge to streams throughout the vicinity of the lake. Under very dry conditions, the model simulates a lake budget one-third that of current conditions. In this case, the model forecasts a large drop in lake stage with no outflow from the lake to the White River.

The model is useful to understand groundwater quantity and flow to lakes, streams, and wells. However, the project reported on here did not incorporate information on lake water quality.
The model results, which illustrate the relationship between the groundwater and surface water systems, should not be applied to management of these resources without consideration of water quality. For example, we used the model to estimate changes to the lake budget resulting from increased pumping. If the increase in pumping is concurrent with an increase in developed land, likely changes to runoff and infiltration are not considered here. Similarly, lake water *quality* may be affected by on-site septic systems in the watershed, but residential wells and septic systems were not significant in this analysis of groundwater *quantity* in the region.

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Figures

Figure 1. Geneva Lake study region including nearby communities, tributary streams, surface watershed area, and municipal wells.

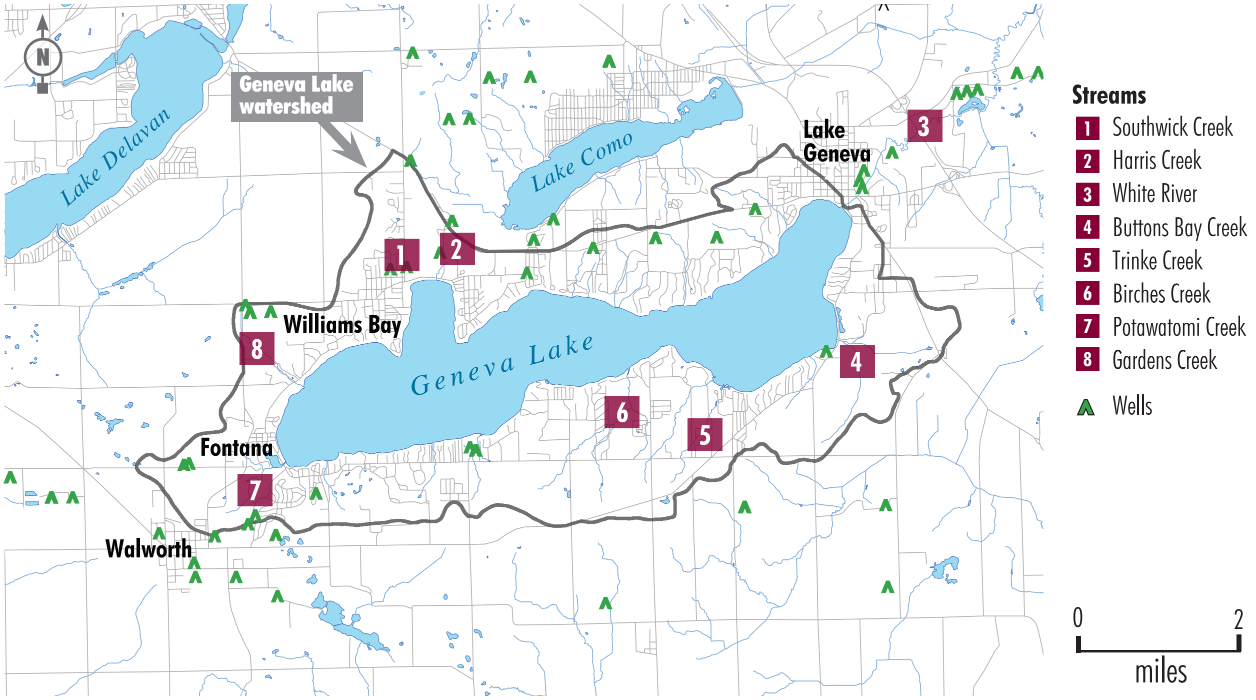


Figure 2. Grain size of surficial materials based on Ham and Attig's Pleistocene map (2004).

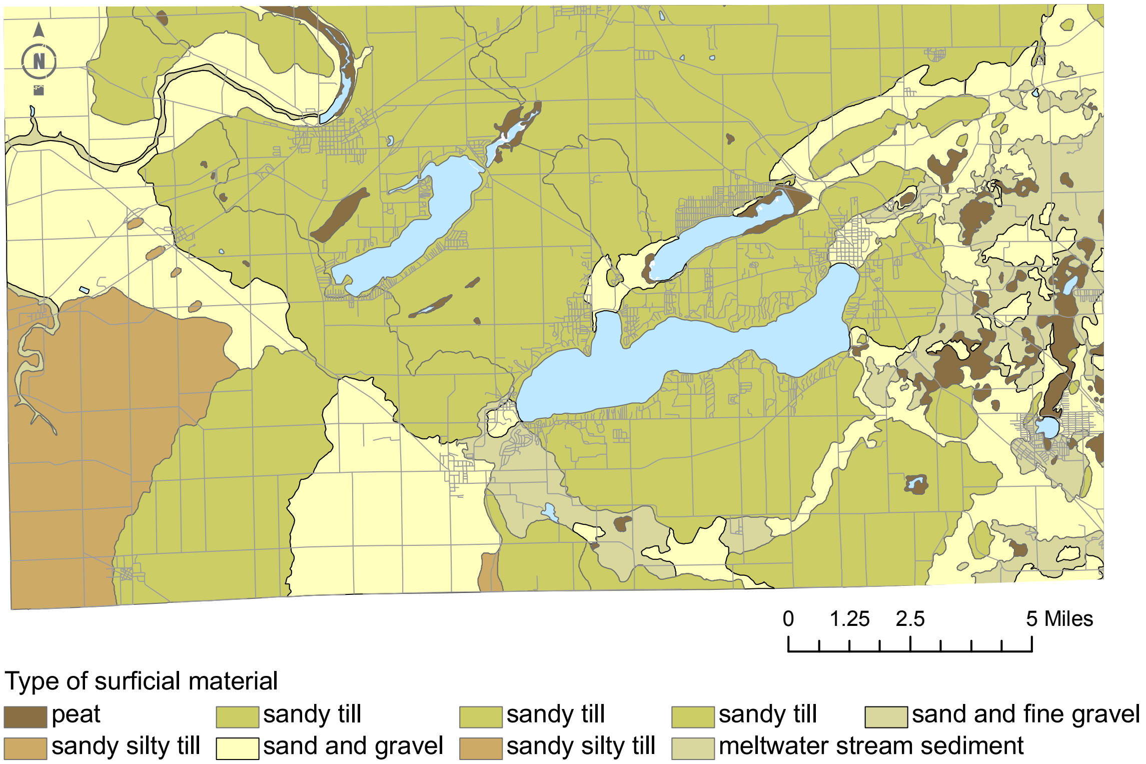
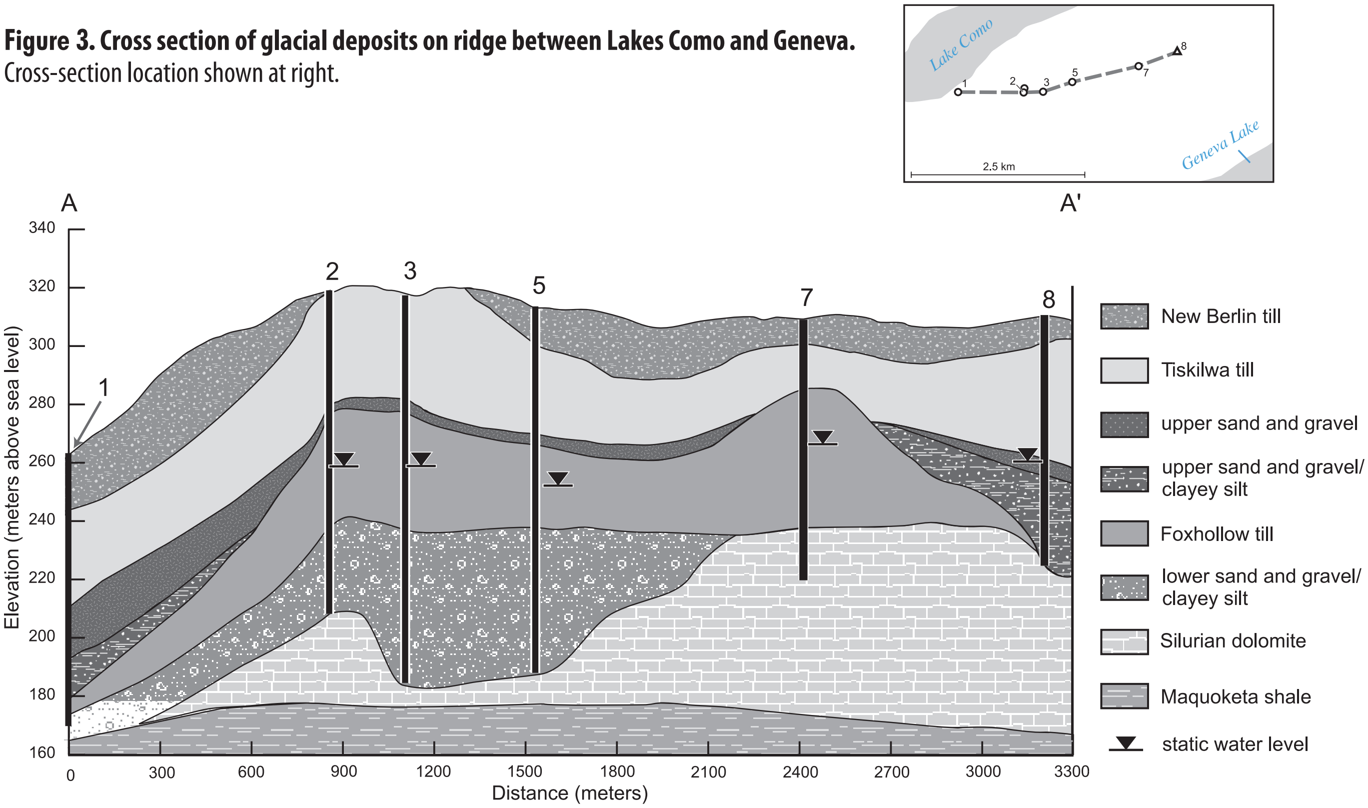
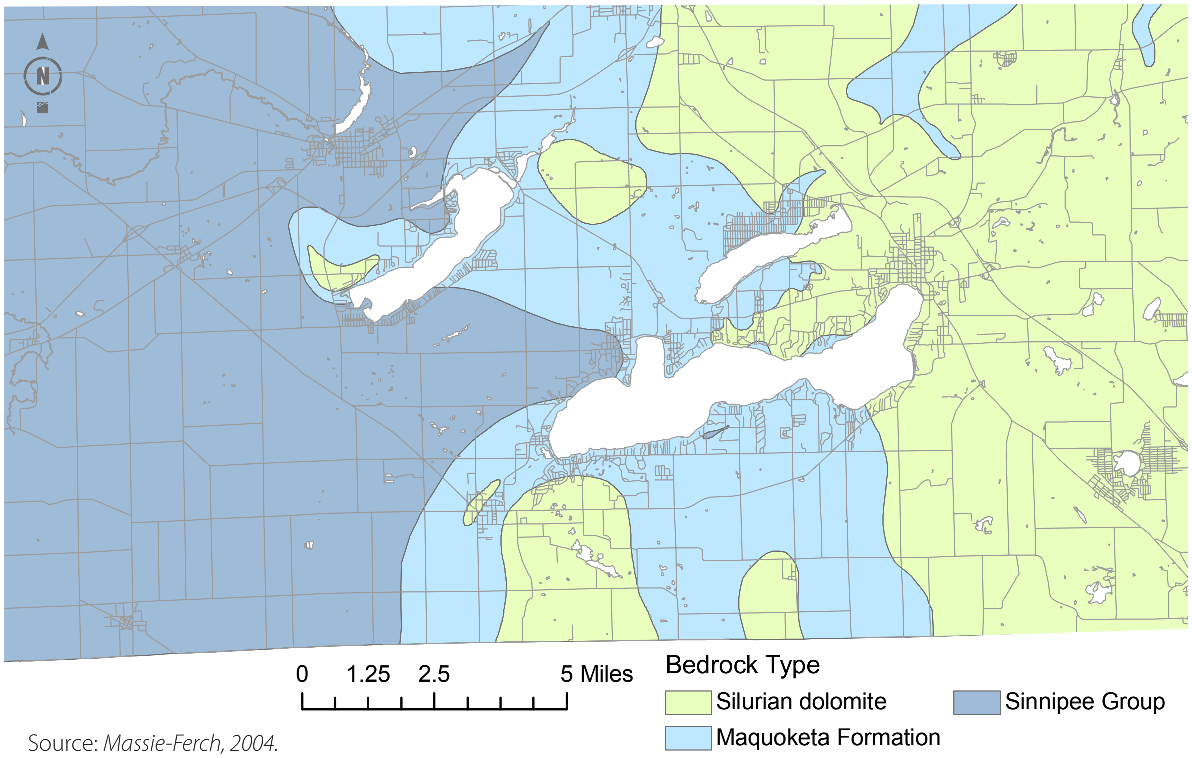


Figure 3. Cross section of glacial deposits on ridge between Lakes Como and Geneva. Cross-section location shown at right.



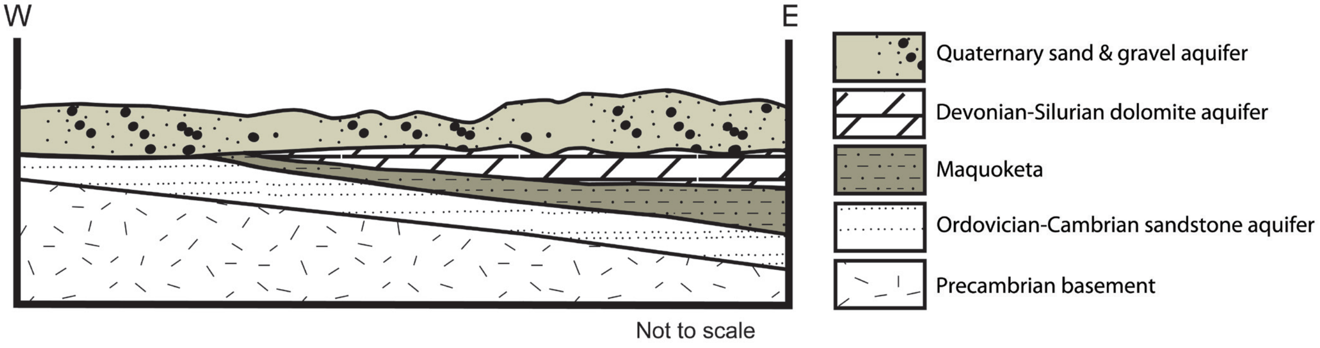
Source: *Root and others (in review).*

Figure 4. Bedrock geology in Geneva Lake area.



Source: *Massie-Ferch, 2004.*

Figure 5. General regional geologic cross section.



Source: *Root and others (in review).*

Figure 6. Model domain, grid and boundary conditions.

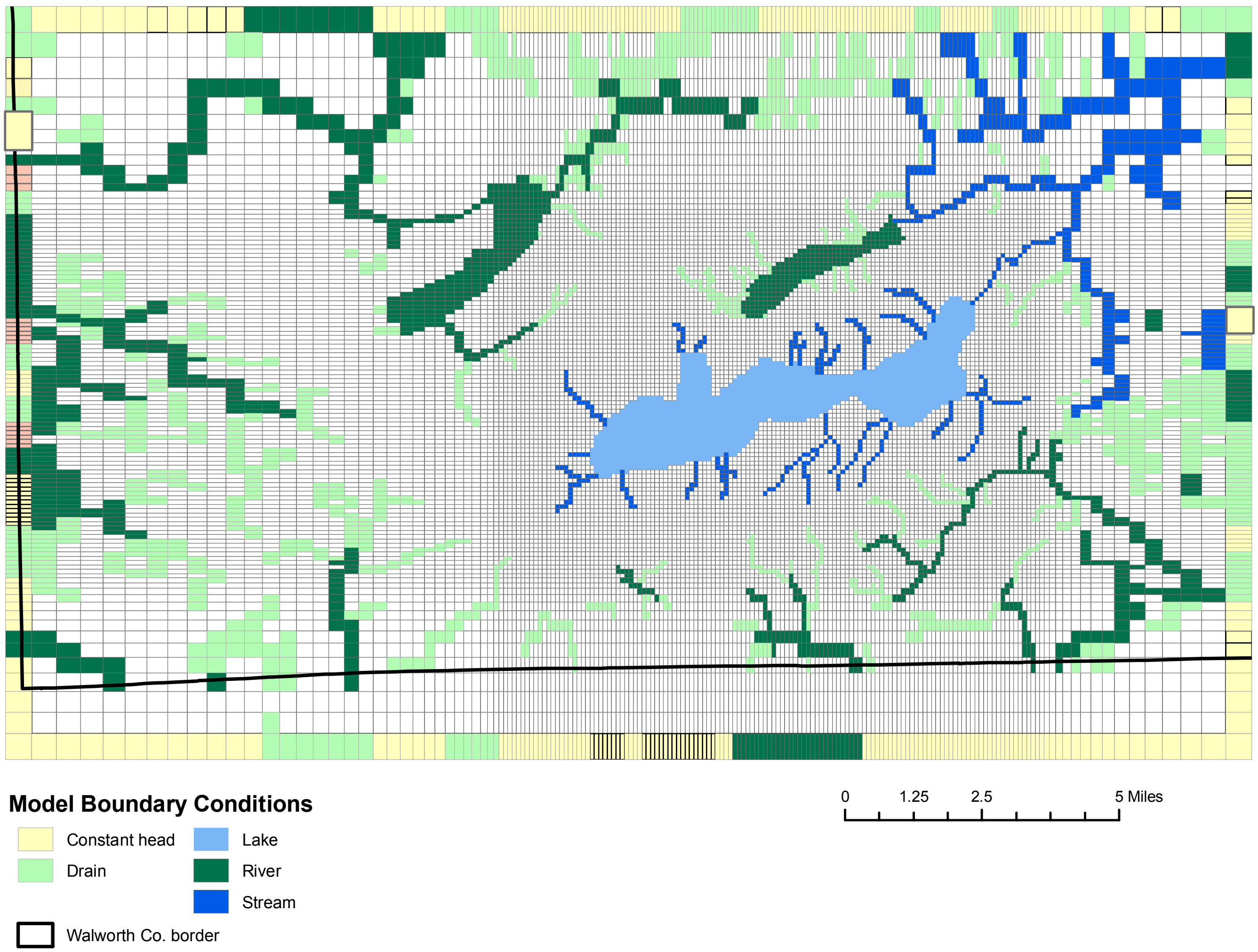


Figure 7. Cross section of model layers along model row 57.
Silurian dolomite and Maquoketa shale subcrop in the vicinity of Geneva Lake.

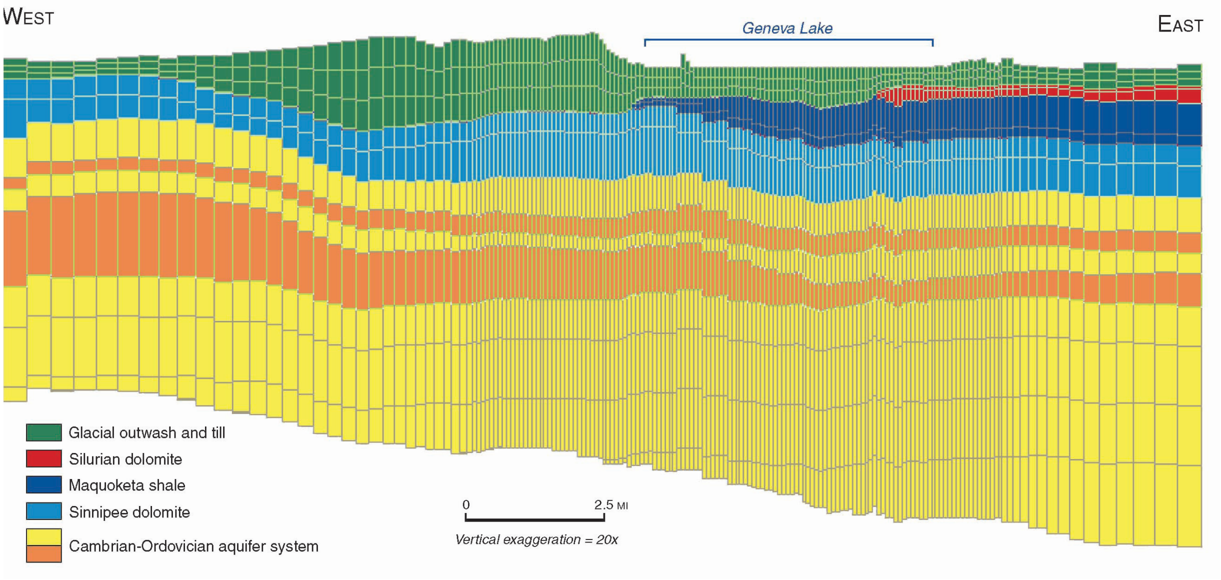
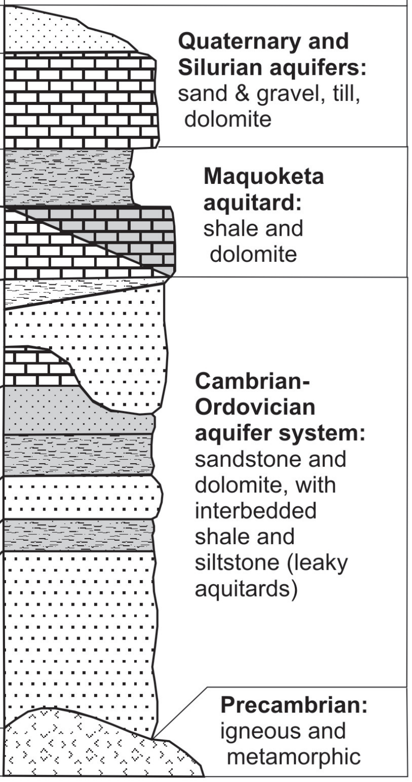


Figure 8. Hydrostratigraphy in Geneva Lake region.

Stratigraphic Nomenclature		Initial hydraulic values		Calibrated hydraulic values		Model Structure
Group	Formation	Kh (ft/d)	Kv (ft/d)	Kh (ft/d)	Kv (ft/d)	
Quaternary	(undiff.)	5-10	0.03-0.1	0.0001-236	0.30	Layers 1-3
Devonian*		–	–	–	–	Layers 4-5
Silurian	(undiff.)	1-4	0.001-0.01	1-6	0.0037-0.0041	
	Maquoketa	0.0003-0.3	0.00005-0.001	0.0003-0.3	0.000012-0.004	Layers 6-7
Sinnipee**	Galena	0.04-0.3	0.0005-0.01	0.04-0.3	0.0005-0.01	Layers 8-9
	Platteville					
Ancell	Glenwood	1.2-3.6	0.0004-0.004	1.2-3.6	0.0004-0.004	Layer 10
	St. Peter					
Prairie du Chien	(undiff.)					
Trempealeau	Jordan	0.6-1.2	0.0004-0.004	0.6-1.2	0.0004-0.004-	Layer 11
	St. Lawrence					
Tunnel City	(undiff.)					Layer 12
Elk Mound	Wonewoc	3.6-8.4	0.0004-0.004	3.6-8.4	0.0004-0.004	Layer 13
	Eau Claire	0.6-1.2	0.00004-0.0004	0.6-1.2	0.00004-0.0004	
	Mt. Simon	1.2-2.4	0.00012-0.004	1.2-2.4	0.00012-0.004	Layers 14-17
Precambrian		*not simulated*				

Lithology and Generalized Hydrostratigraphy



* The Devonian is absent in the Geneva Lake region and is not simulated in this model.

** The Sinnipee is an aquitard below the Maquoketa and an aquifer to the west. Where the Maquoketa is present, the upper layer of the Sinnipee Kh=0.04 and Kz=0.0005 ft/day. Where the Maquoketa is absent, the Sinnipee Kh=0.3 and Kz=0.01 ft/day. For the lower layer of the Sinnipee, Kh and Kz values depend on proximity to the unit's western subcrop.

Source: *Adapted from Feinstein and others, 2005.*

Figure 9. Hydrologic features in the model near-field. See appendix B for well names.

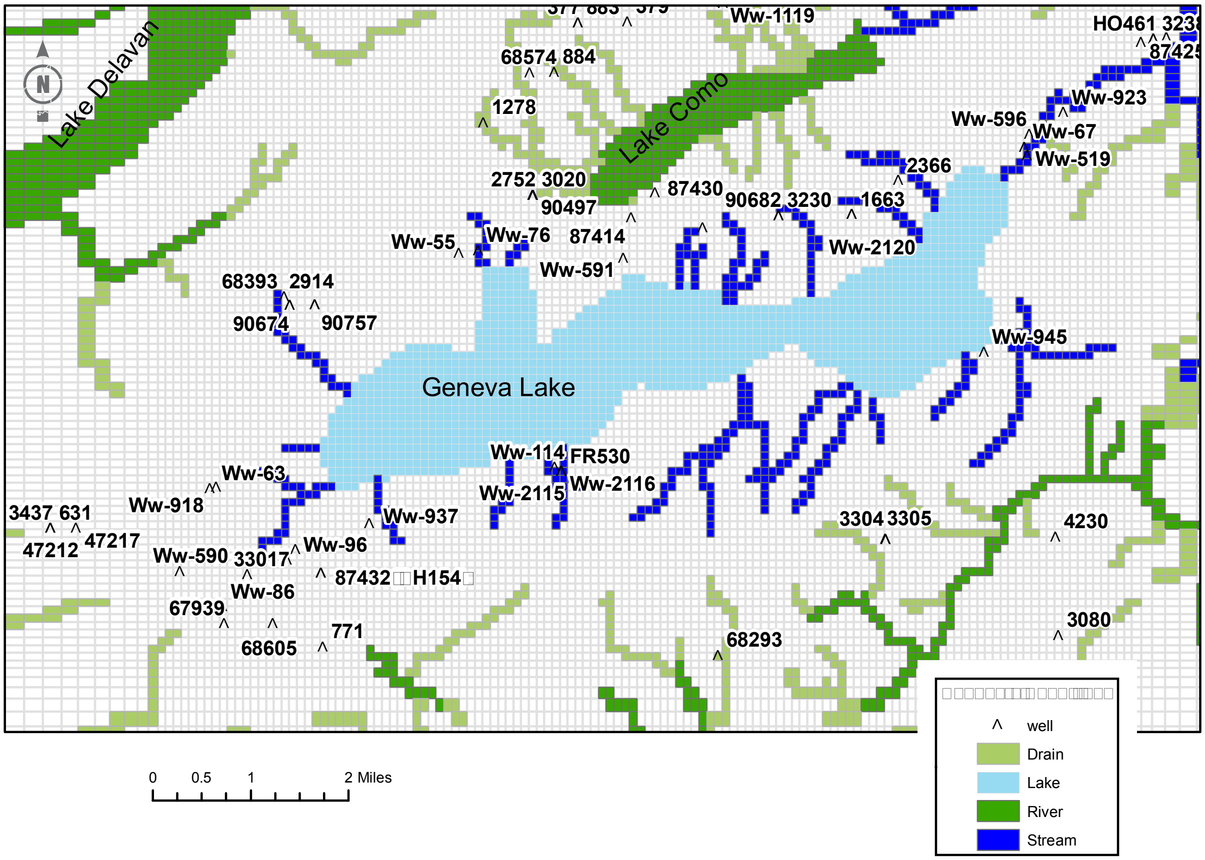


Figure 10. Recharge zones in the calibrated model.
Values shown are recharge in inches per year.

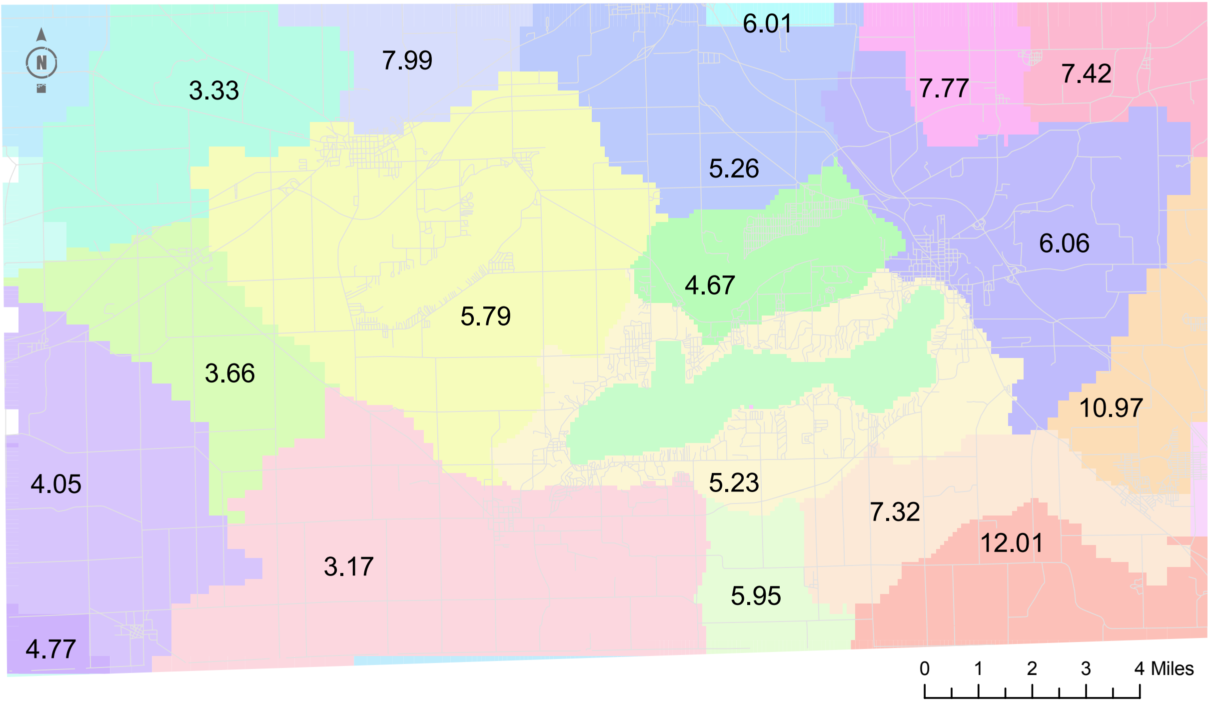


Figure 11. Model calibration results for head targets. Dashed line is the 1:1 line.

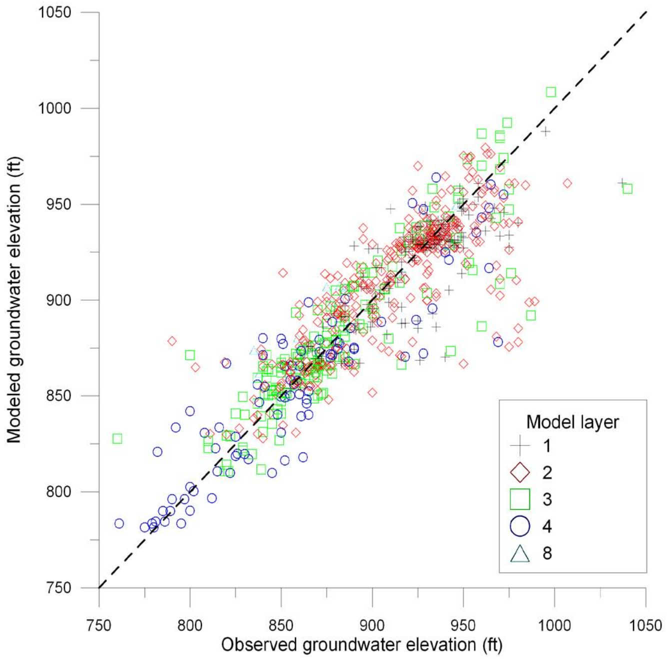


Figure 12. Difference (residual) between measured and simulated groundwater elevations. Positive difference indicates simulated value is less than measured; negative values indicate simulated value is higher than measured.

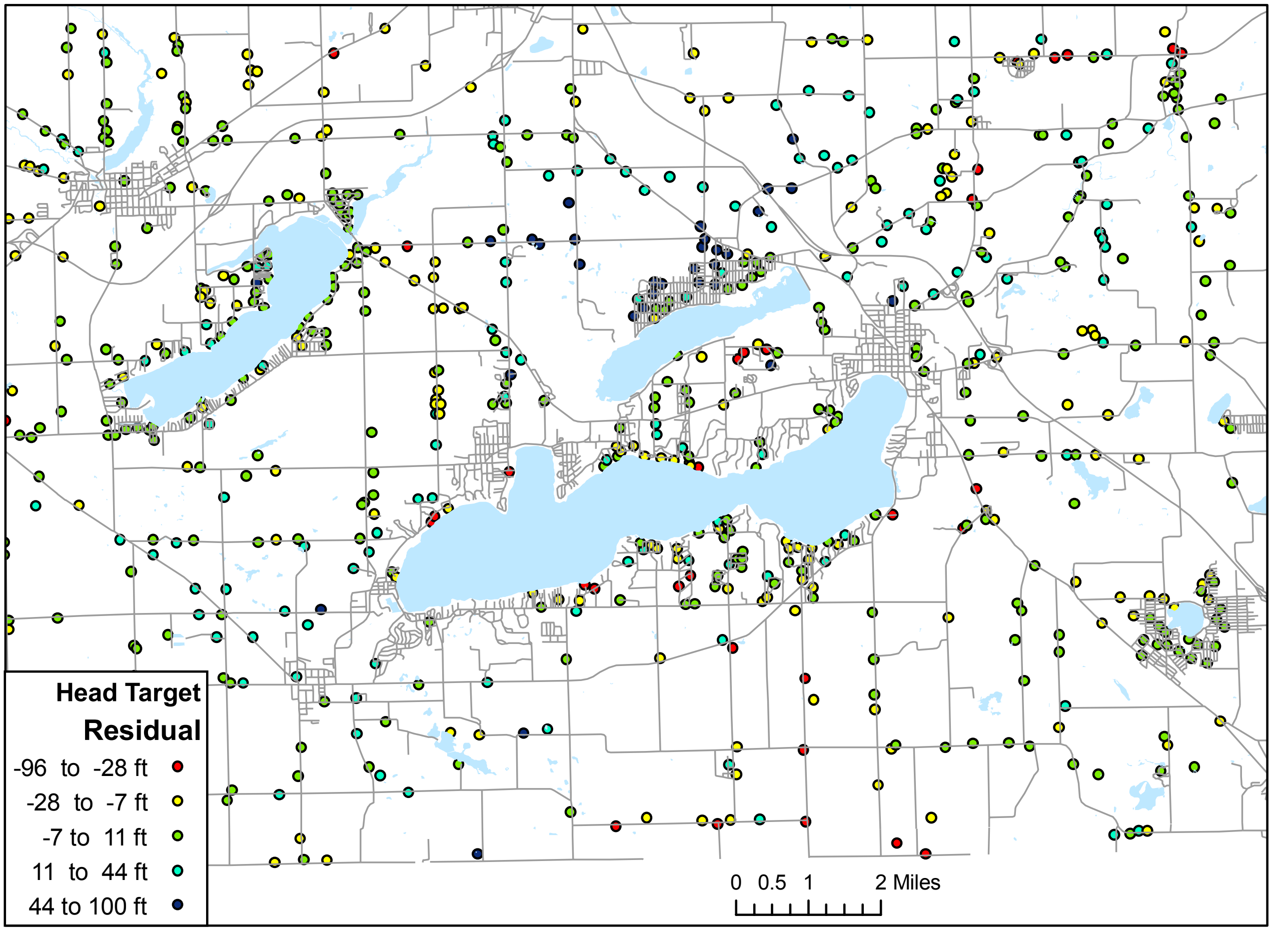
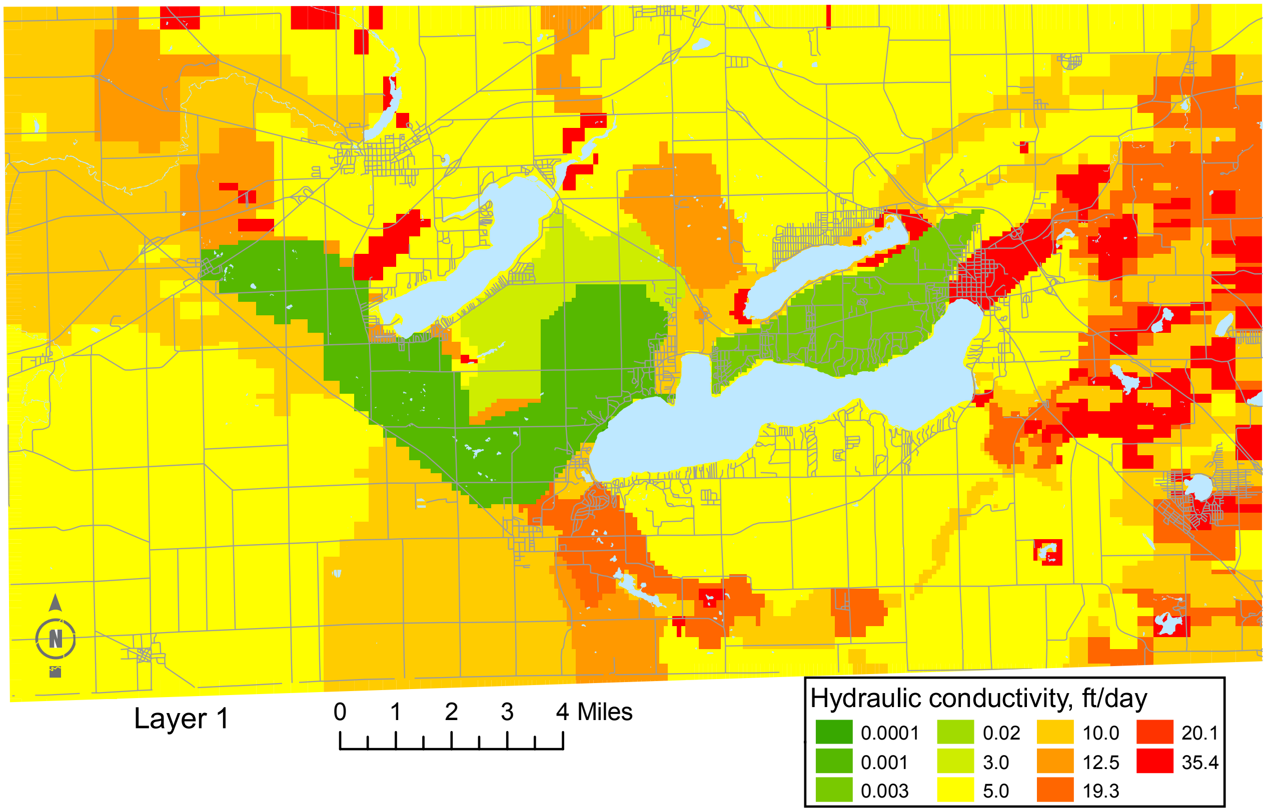
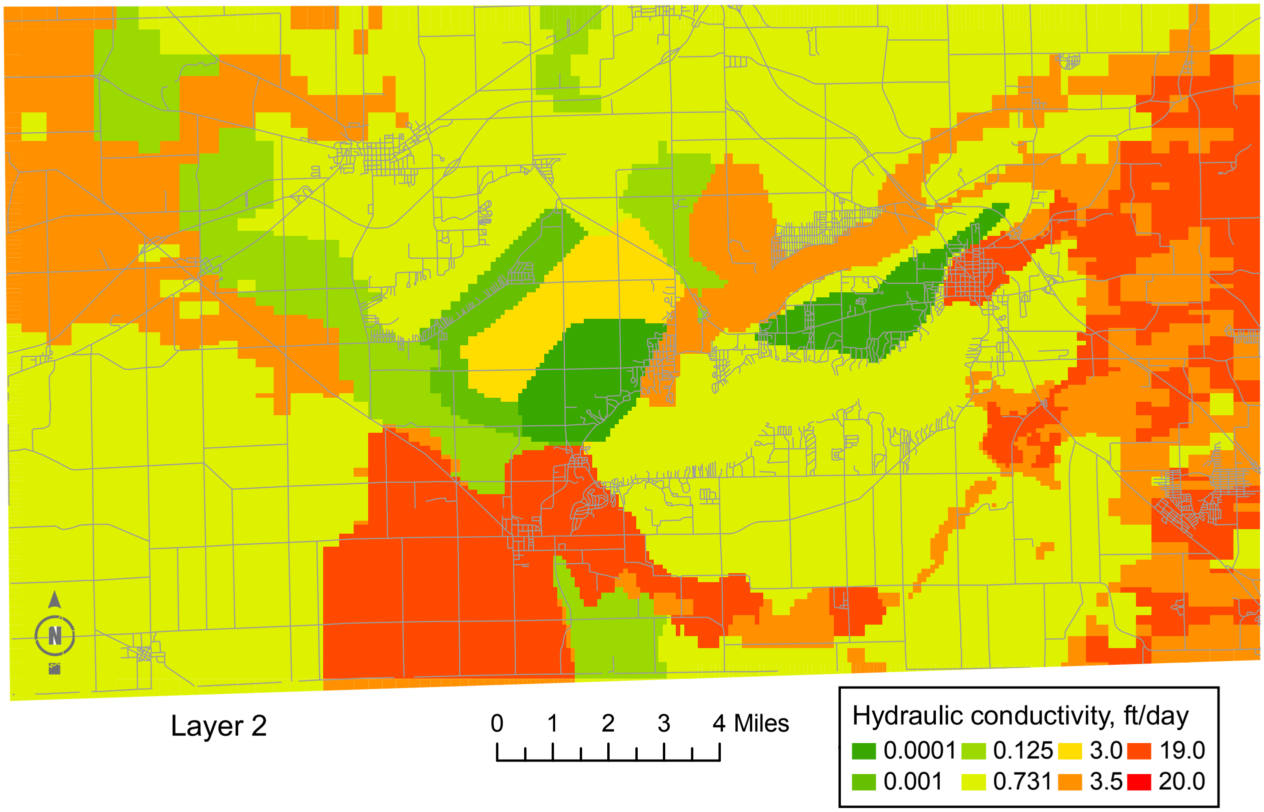


Figure 13. Distribution of hydraulic conductivity in models layers 1, 2 and 3.



Layer 1



Layer 2

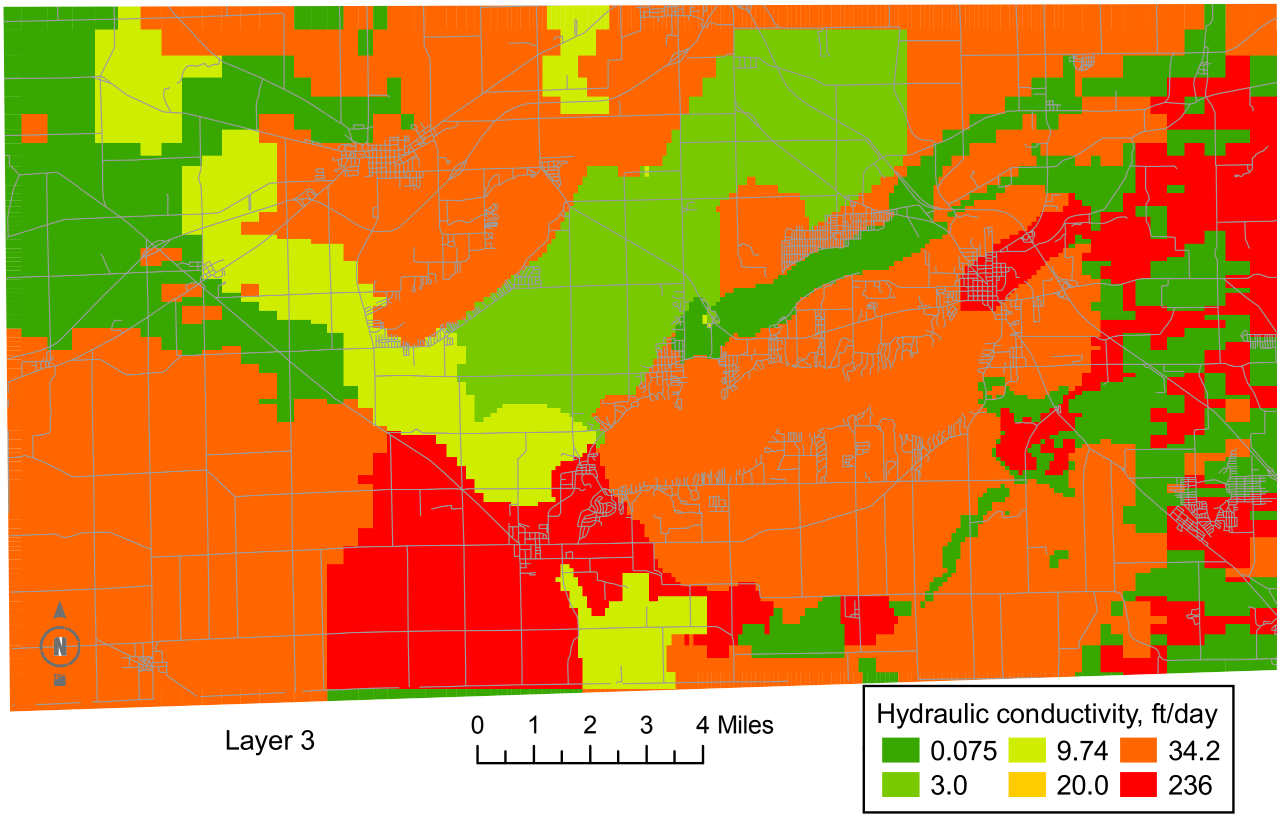


Figure 14. Simulated water table under current (2006) conditions.

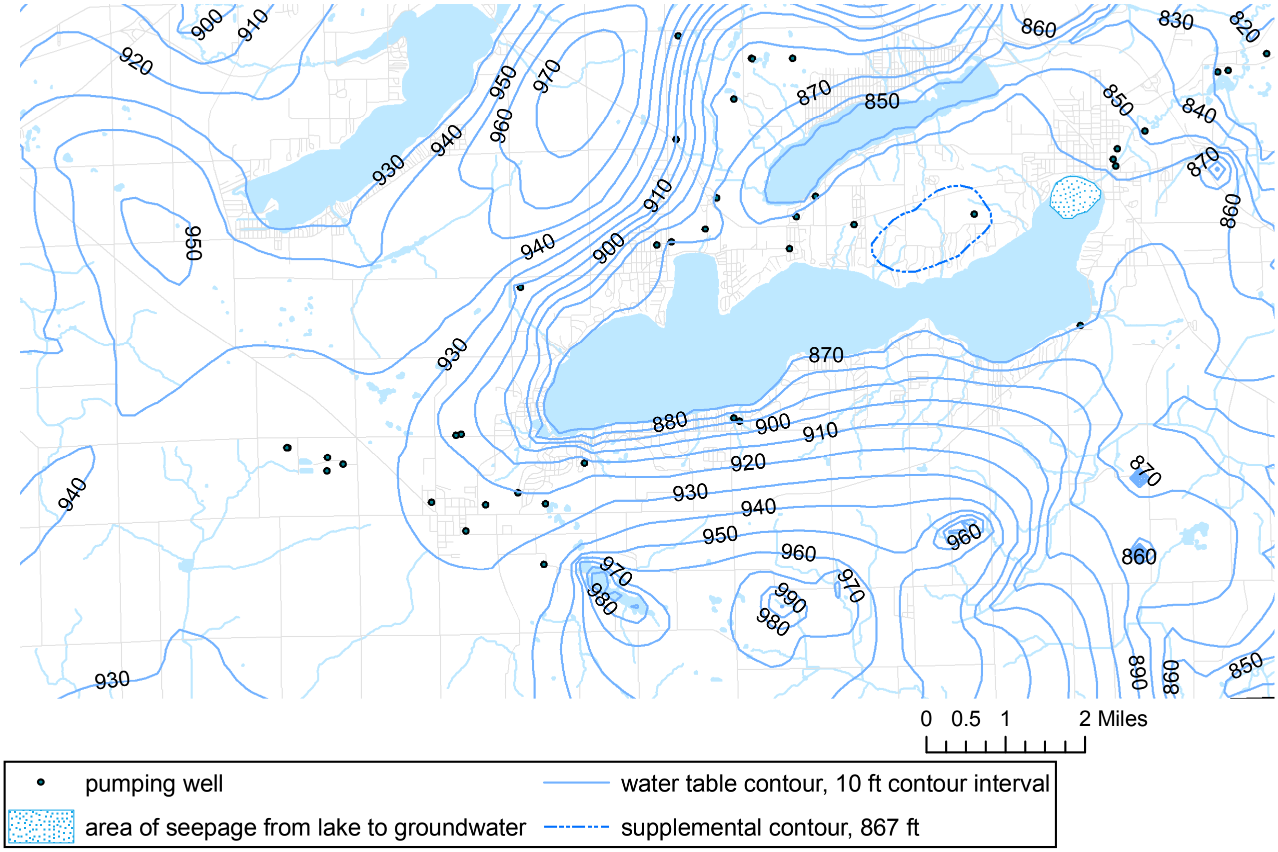


Figure 15. Simulated recharge areas of Geneva Lake.

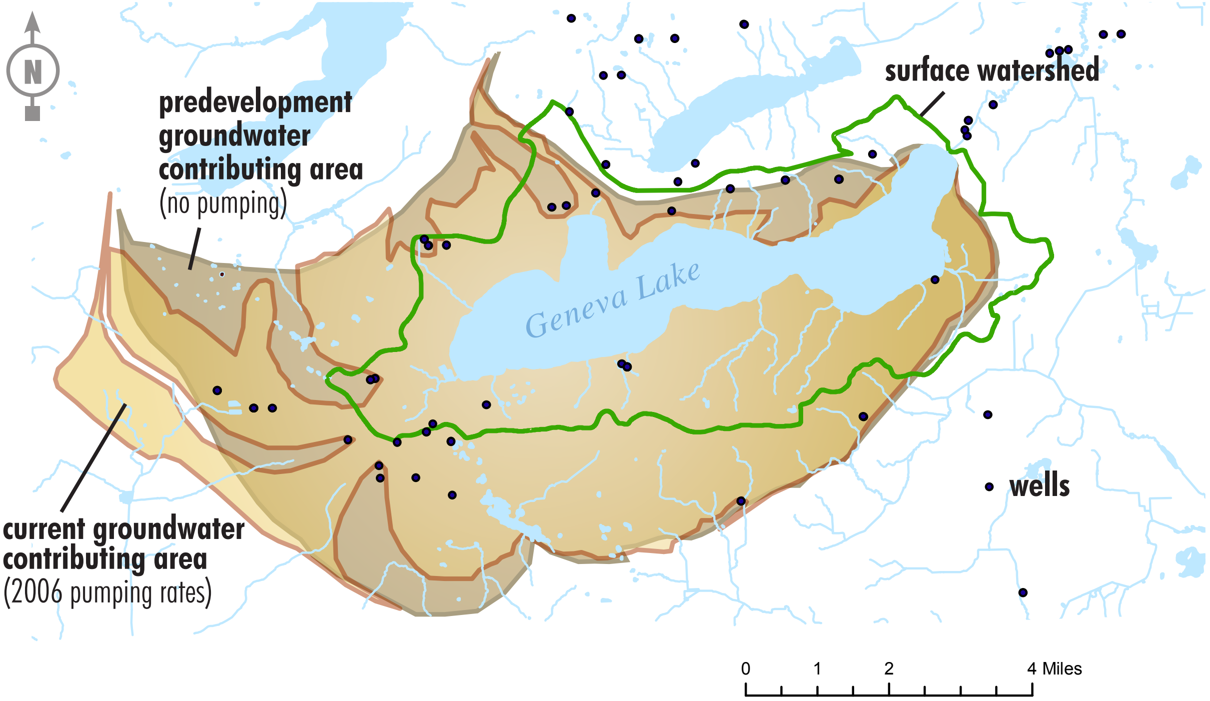


Figure 16. Simulated predevelopment water table, no dam. Lake stage is 857.3 ft.

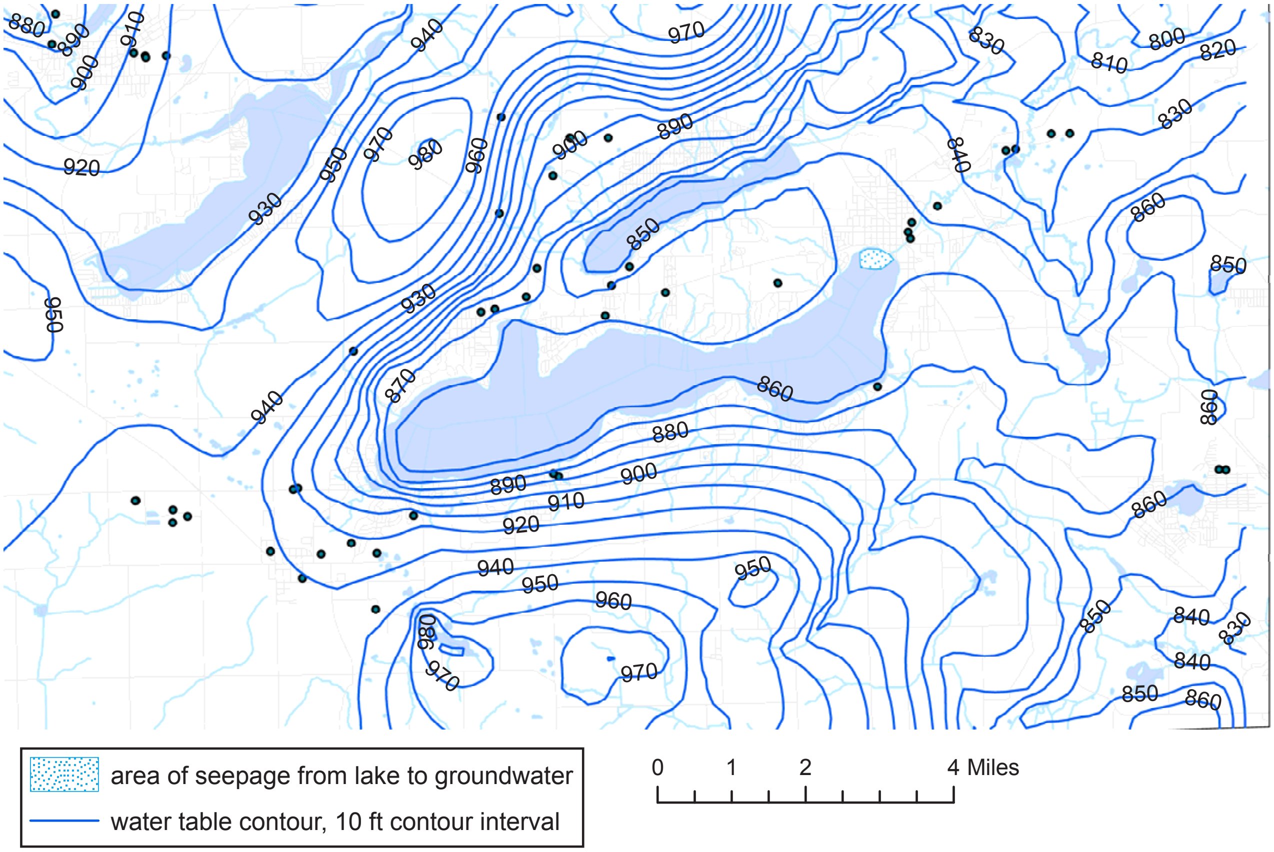
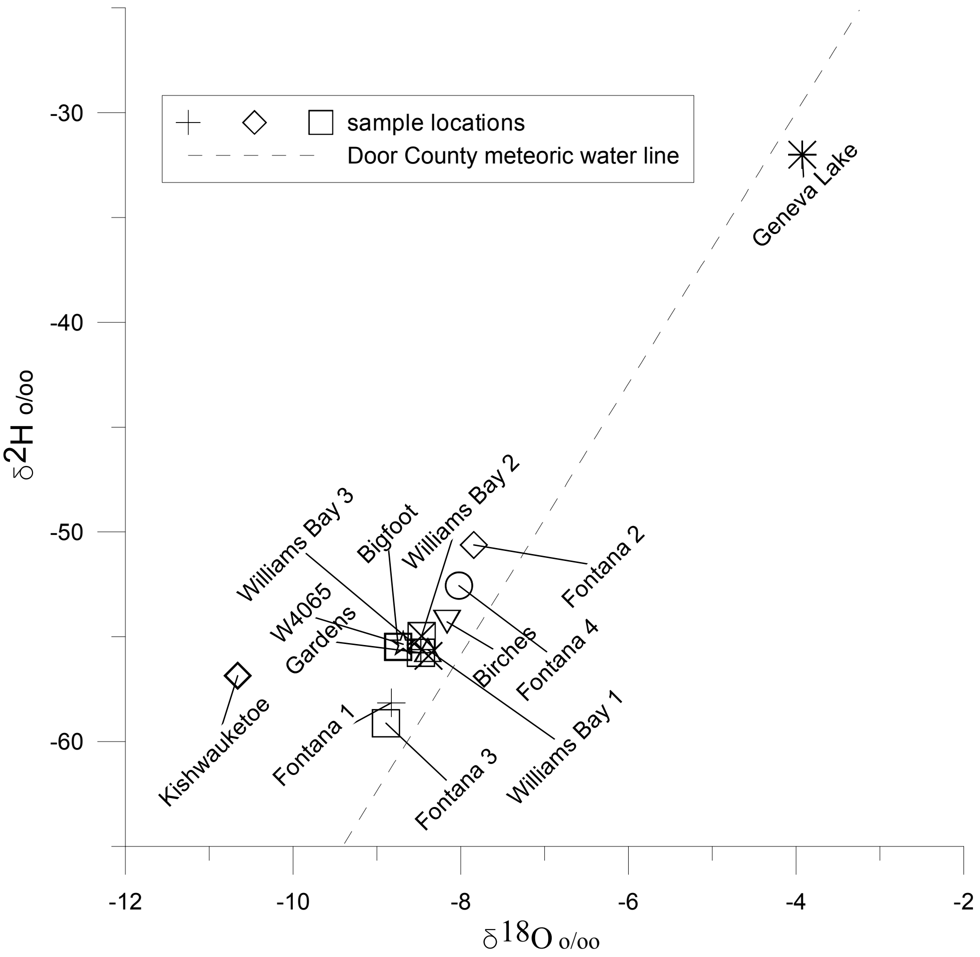
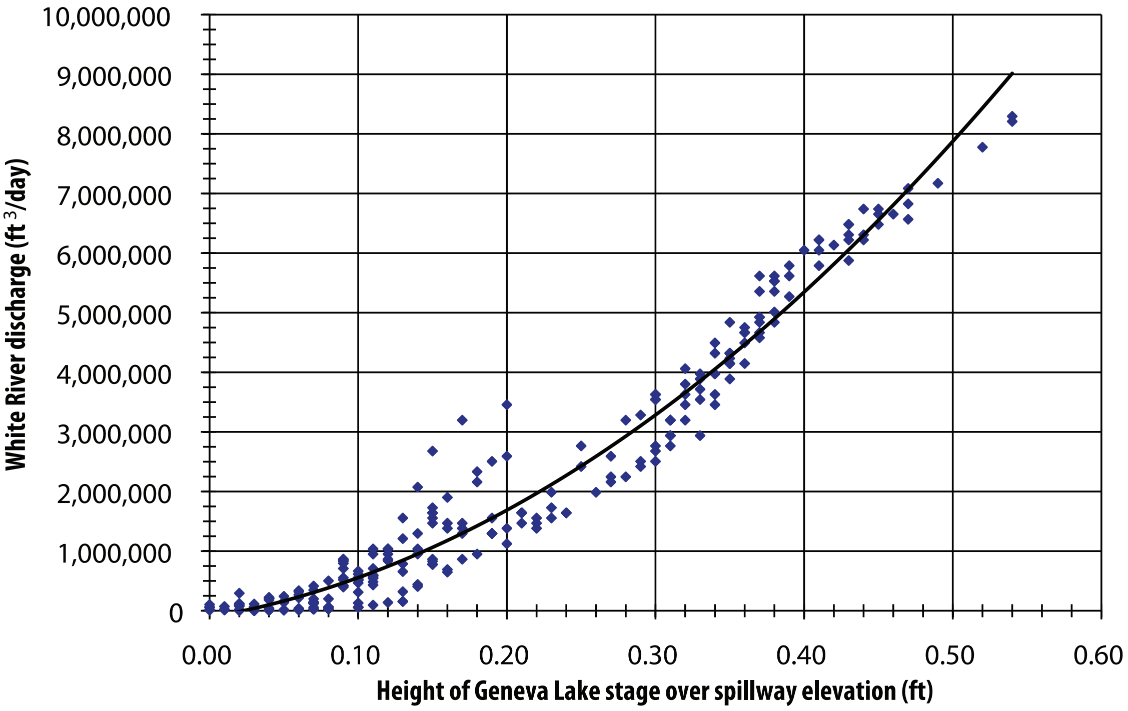


Figure 17. Oxygen-18 and deuterium results from Geneva Lake region.



Appendix A. Geneva Lake stage and discharge to White River

We constructed a rating curve from measured stage of Geneva Lake (USGS Station # 423525088260400) and discharge to the White River (USGS Station # 055451345) based on measurements collected in 1998 and presented below.



Appendix B. Wells and simulated pumping rates

					Calibration (1998)		Current (2006)		
Well ID in model	Wisconsin unique well number	WDNR permit number	WGNHS number	Well name / owner	gallons/ minute	Note[a]	gallons/ minute	Note[a]	Aquifer(s)[b]
377	CO552	377	—	Poloma Development # 3 - Irrig #2 (?)	30.0	3	30.0	3	SG
379	CO570	379	—	Poloma Development # 5 - Irrig #3 (?)	30.4	3	30.0	3	SG
631	AY373	631	—	Kikkoman #3	125.0	6	0.0	5	SG
701	EM118	701	—	Kincaid Farm	30.0	3	30.0	3	GP-UpS
771	EM218	771	—	Big Foot Farm	30.0	3	30.0	3	SG
883	CO567	883	—	Geneva National #2	550.0	1	550.0	1	SG
884	AX734	884	—	Geneva National #1	200.0	1	200.0	1	GP-UpS
1278	AR739	1278	—	Mercy Center #1	25.0	1	25.0	1	GP-UpS
1663	KQ027	1663	—	Foxwood Enterprises #1 (Wrigley Estate)	20.8	1	20.8	1	Sil
2366	MU167	2366	—	Hillmoor Golf Club #2	0.0	8	30.0	3	SG
2752	NO705	2752	—	Poloma Development #6 - Irrig #5 (?)	0.0	8	30.0	3	SG
2863	NX145	2863	—	Country Estates Sanitary Dist #5	0.0	8	8.2	4	GP-UpS-LowS
2900	OP792	2900	—	Country Estates Sanitary Dist #6	0.0	8	8.2	4	Sil
2914	QK217	2914	—	Inspiration Ministries #3	0.0	8	20.0	6	SG
3020	NO896	3020	—	Poloma Development #7 - Irrig #6 (?)	0.0	8	30.0	3	SG
3080	OT683	3080	—	Leedle, William #1	0.0	8	500.0	1	SG
3230	OT616	3230	—	Foxwood Enterprises #2 (Wrigley Estate)	0.0	8	30.0	6	Sil-GP
3238	OG484	3238	—	Mountain Top at Grand Geneva	0.0	8	30.0	3	SG
3304	QL742	3304	—	Merry Water Farms #3	0.0	8	1.4	3	SG
3305	QL770	3305	—	Merry Water Farms #4	0.0	8	27.8	3	SG
3437	SA198	3437	—	Kikkoman #4	0.0	8	125.0	5	GP-UpS-LowS
3919	SA442	3919	—	Hawks View Golf Club #2	0.0	8	30.0	3	GP-UpS
4230	RB747	4230	—	Leedle, William #2	0.0	8	500.0	1	SG
33017	AU058	33017	—	Big Foot Corp.	30.0	3	30.0	3	SG
47212	FH031	47212	—	Kikkoman #1	245.0	6	40.0	5	SG
47213	BE517	47213	—	Stolper Industries, Inc. / Tankcraft Corp. #1	2.8	1	2.8	1	SG
47214	BE518	47214	—	Stolper Industries, Inc. / Tankcraft Corp. #2	2.8	1	2.8	1	SG
47217	FH032	47217	—	Kikkoman #2	245.0	6	125.0	5	SG
67939	TT958	67939	—	Walworth #5	0.0	8	0.0	8	SG
68249	WJ278	68249	—	Geneva Lakes Cold Storage #3	0.0	8	17.4	1	LowS
68252	WJ279	68252	—	Geneva Lakes Cold Storage #4	0.0	8	86.8	1	GP-UpS
68293	UB012	68293	—	Crandall, Rick	0.0	8	100.0	6	SG
68392	RH960	68392	—	Inspiration Ministries #1	0.0	8	17.4	3	SG
68393	EL927	68393	—	Inspiration Ministries #2	10.0	1	10.0	1	SG
68574	SB750	68574	—	Geneva National #3	0.0	8	100.0	6	SG
68605	VK991	68605	—	Walworth #6	0.0	8	0.0	8	SG

(continued)

					Calibration (1998)		Current (2006)		
Well ID in model	Wisconsin unique well number	WDNR permit number	WGNHS number	Well name / owner	gallons/ minute	Note[a]	gallons/ minute	Note[a]	Aquifer(s)[b]
68713	WJ836	68713	—	Leedle, Tom	0.0	8	500.0	6	SG
87414	FX351	87414	—	Interlaken Lodge & Village #1	34.7	1	0.0	8	GP-UpS-LowS
87421	BH130	87421	—	Country Estates Sanitary Dist #4	100.0	1	0.0	4	GP-UpS-LowS
87425	BH134	87425	—	Americana Lake Geneva / Playboy Resort #2	0.0	7	0.0	7	GP-UpS
87426	BH135	87426	—	Americana Lake Geneva / Playboy Resort #3	30.0	3	30.0	3	GP-UpS
87427	BH136	87427	—	Americana Lake Geneva / Playboy Resort #4	200.0	1	200.0	1	Sil
87428	BH137	87428	—	Americana Lake Geneva / Playboy Resort #9	200.0	1	200.0	1	SG
87430	BH139, JD377	87430	—	Interlaken Lodge & Village #2	69.4	1	0.0	8	SG
90497	HO474	90497	—	Calvary Community Church	20.8	1	20.8	1	SG
90674	QK252	90674	—	Faith Christian School #1	0.0	8	2.1	3	SG
90682	RH985	90682	—	Woods Elementary School	0.0	8	1.4	1	SG
90757	QT989	90757	—	Faith Christian School #2	0.0	8	1.4	3	SG
87432_(BH141)	BH141	87432	—	Country Club Estates Assoc. #1	16.7	1	16.7	1	SG
87432_(BH154)	BH154	87432	—	Country Club Estates Assoc. #2	16.7	1	16.7	1	SG
FR530	FR530	—	—	Lake Geneva Yacht Club	25.0	6	25.0	6	Sil
HO461	HO461	—	—	Grand Geneva	30.0	3	30.0	3	SG
RG655	RG655	—	—	Darien #3	0.0	8	39.2	4	GP-UpS-LowS
Ww-1119	NA552	2314	Ww-1119	Lake Como #1	0.0	8	47.2	4	GP-UpS-LowS
Ww-114	—	—	Ww-114	Northwestern Military Academy	20.0	6	20.0	6	GP-UpS
Ww-129	BF010	66407	Ww-129	Bird's Eye Foods	684.7	1	684.7	1	UpS-LowS
Ww-185	BH170	87502	Ww-185	Delavan #3	141.4	2	121.2	4	SG
Ww-2104	NA553	2315	Ww-2104	Lake Como #2	0.0	8	47.2	4	GP-UpS-LowS
Ww-2115	RX244	2938	Ww-2115	South Shore Club #1	0.0	8	75.0	6	GP-UpS-LowS
Ww-2116	RX245	4329	Ww-2116	South Shore Club #2	0.0	8	75.0	6	GP-UpS-LowS
Ww-2120	OS500	3990	Ww-2120	Foxwood Enterprises #3 (Wrigley Estate)	0.0	8	30.0	6	Sil-GP-UpS
Ww-24	BH158	87449	Ww-24	Lakeland Nursing Home (Walworth Co.)	55.6	1	55.6	1	GP-UpS-LowS
Ww-396	MK404	2300	Ww-396	Williams Bay #3	9.4	2	79.9	4	GP-UpS-LowS
Ww-40	—	—	Ww-40	U.S. Army Radar Station #1	5.0	6	5.0	6	GP-UpS
Ww-41	—	—	Ww-41	Bradley Knitting Co.	5.0	6	5.0	6	UpS-LowS
Ww-45	—	—	Ww-45	Wisconsin School for the Deaf	20.0	6	20.0	6	SG-Sil-GP-UpS

Notes and aquifer abbreviations on page 32

(continued)

					Calibration (1998)		Current (2006)		
Well ID in model	Wisconsin unique well number	WDNR permit number	WGNHS number	Well name / owner	gallons/ minute	Note[a]	gallons/ minute	Note[a]	Aquifer(s)[b]
Ww-47	BH167	87499	Ww-47	Darien #1	28.8	2	9.8	4	UpS-LowS
Ww-519	BH184	87516	Ww-519	Lake Geneva #2	63.7	2	200.7	4	SG
Ww-538	—	—	Ww-538	Sunset Hills Subdivision	20.0	6	20.0	6	SG-Sil-GP-UpS
Ww-55	BH197	87529	Ww-55	Williams Bay #2	101.7	2	55.6	4	SG
Ww-590	BH191	87523	Ww-590	Walworth #4	122.4	2	139.9	4	SG
Ww-591	BH142	87433	Ww-591	Knollwood Subdivision #1	58.3	1	58.3	1	GP-UpS-LowS
Ww-596	BH186	87518	Ww-596	Lake Geneva #4	403.5	2	233.0	4	SG
Ww-603	BH133	87424	Ww-603	Americana Lake Geneva / Playboy Resort #1	279.9	1	279.9	1	Sil
Ww-63	BH180	87512	Ww-63	Fontana #1	181.3	2	69.0	4	SG
Ww-67	BH185	87517	Ww-67	Lake Geneva #3	316.4	2	233.0	4	SG
Ww-68	BH171	87503	Ww-68	Delavan #4	136.0	2	153.1	4	SG
Ww-740	BH188	87520	Ww-740	Sharon #3	47.6	2	38.9	4	SG
Ww-76	BH196	87528	Ww-76	Williams Bay #1	118.0	2	55.6	4	SG
Ww-832	BH172	87504	Ww-832	Delavan #5	113.1	2	152.6	4	SG
Ww-86	BH190	87522	Ww-86	Walworth #3	234.8	2	215.7	4	SG
Ww-903	BH168	87500	Ww-903	Darien #2	43.5	2	19.6	4	SG
Ww-918	CU130	510	Ww-918	Fontana #3	169.2	2	69.0	4	SG
Ww-919	AX010	723	Ww-919	Sharon #4	29.6	2	38.9	4	UpS
Ww-923	AY367	719	Ww-923	Lake Geneva #5	127.5	2	303.0	4	SG
Ww-936	EQ931	1088	Ww-936	Delavan #6	355.0	2	317.7	4	UpS-LowS
Ww-937	EQ928	938	Ww-937	Abbey Springs Condo. Assoc.	30.0	3	30.0	3	SG
Ww-945	LI564	2127	Ww-945	Geneva Inn #2	17.4	1	17.4	1	Sil
Ww-954	KW633	2039	Ww-954	Pell Lake #1	27.0	9	73.5	4	UpS-LowS
Ww-955	KW634	2040	Ww-955	Pell Lake #2	27.0	9	73.5	4	UpS-LowS
Ww-96	BH181	87513	Ww-96	Fontana #2	93.8	2	22.2	4	SG
Ww-988	LW428	2289	Ww-988	Fontana #4	0.0	8	103.5	4	UpS-LowS

[a] Notes:

1	high cap permit normal pumping rate converted to gpm
2	SEWRPC model 1990s rate
3	golf course-- assume each well serves 18 holes; 16mgal/yr/18-hole course
4	2006 PSC utility report; pumping distributed by well capacity
5	reported by owner
6	estimated
7	standby well
8	well out of use during time period
9	1999 PSC utility report

[b] Aquifer abbreviations:

SG	Sand and gravel
Sil	Silurian dolomite
GP	Galena - Platteville
UpS	Upper Sandstone
LowS	Lower Sandstone

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