U.S. Department of the Interior
U.S. Geological Survey

Simulation of the Shallow Hydrologic System in the Vicinity of Middle Genesee Lake, Wisconsin, Using Analytic Elements and Parameter Estimation

Water-Resources Investigations Report 00–4136

Prepared in cooperation with the

Middle Genesee Lake Management District
Wisconsin Department of Natural Resources

USGS
science for a changing world

Simulation of the Shallow Hydrologic System in the Vicinity of Middle Genesee Lake, Wisconsin, Using Analytic Elements and Parameter Estimation

By R.J. Hunt, Y. Lin, J.T. Krohelski, and P.F. Juckem

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 00–4136

Prepared in cooperation with the
Middle Genesee Lake Management District
Wisconsin Department of Natural Resources

Middleton, Wisconsin
2000

USGS
science for a changing world

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, *Secretary*

U.S. GEOLOGICAL SURVEY
Charles G. Groat, *Director*

For additional information write to:

District Chief
U.S. Geological Survey
8505 Research Way
Middleton, WI 53562-3586

Copies of this report can be purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286
Denver, CO 80225-0286

CONTENTS

FIGURES

TABLE

CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To Obtain
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
acre (A)	0.4047	hectare
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer
	Volume	
cubic foot (ft^3)	7.4805	gallon
	Hydraulic conductivity*	
foot per day (ft/d)	0.3048	meter per day

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

***Hydraulic conductivity:** The standard unit for hydraulic conductivity is cubic foot per day per square foot of aquifer cross-sectional area $(ft^3/d)/ft^3$. In this report, the mathematically reduced form, feet per day (ft/d), is used for convenience.

Other abbreviations:

gal/min	gallons per minute
ft^3/s	cubic feet per second
in/yr	inches per year
ft/d	feet per day

The stratigraphic nomenclature used in this report is that of the Wisconsin Geological and Natural History Survey and does not necessarily follow usage of the U.S. Geological Survey.

Simulation of the Shallow Hydrologic System in the Vicinity of Middle Genesee Lake, Wisconsin, Using Analytic Elements and Parameter Estimation

By R.J. Hunt, Y. Lin, J.T. Krohelski, *and* P.F. Juckem

Abstract

Middle Genesee Lake is a ground-water flow-through lake located in a developing area in southeastern Wisconsin. Because the lake is in good connection with the shallow ground-water system, hydrologic stresses to the shallow ground-water system could adversely affect the lake system. In order to assess the effects of potential stresses on the lake, a study was completed by the U.S. Geological Survey, in cooperation with the Middle Genesee Lake Management District. The objective of the study was to identify areas that contribute ground water to the lake and estimate the hydrologic budget of the lake and hydraulic parameters affecting ground-water flow. A two-dimensional, steady-state analytic element model of the lake and surrounding area was developed using the computer code GFLOW. A parameter estimation model, UCODE, was used to optimize the calibration to measured water levels and streamflow.

The calibrated model was used to evaluate the effect of three hypothetical stress scenarios on the stage of Middle Genesee Lake; the simulations were linked to UCODE, which formally incorporated parameter uncertainty into 95-percent confidence intervals around the simulated value. The scenarios included: (1) pumping from upgradient irrigation wells, (2) pumping from Lower Genesee Lake to lower lake levels, and (3) reduction in recharge resulting from development. The results of the simulations demonstrated that lake levels could be affected by hydrologic stresses in the shallow hydrologic system, with effects ranging from a 2.7 feet decline in lake stage resulting from pumping in Lower Genesee Lake to a 0.1 feet decline in lake stage from development in part of the upgradient recharge area. The range of lake stage decline increased when parameter uncertainty was included, from a decline of 3.1 feet for pumping from Lower Genesee Lake to no reduction in lake stage for the development in the recharge area. Whereas these simulated effects are within the natural variation in lake stage, they represent a systematic reduction of ground-water flow to the lake. Therefore, these hypothetical stresses are expected to establish a new, lower, baseline lake stage over which the natural variation due to climatic effects are added and subtracted.

INTRODUCTION

Middle Genesee Lake is a ground-water flow-through lake located in a developing area in southeastern Wisconsin (fig. 1). Because the lake is in good connection with the ground-water system, hydrologic stresses in the shallow ground-water system could adversely affect the lake. In order to assess the effects of stresses on the lake, a study was completed by the U.S. Geological Survey, in cooperation with the Middle Genesee Lake Management District. The study was initiated in 1999 with the following goals: (1) identification of the ground-water recharge area that contributes water to the lake, (2) estimation of the hydrologic budget of the lake and, (3) estimation of hydraulic parameters affecting ground-water flow. In addition to these goals, the study also included evaluating effects of potential hydrologic stresses to the lake, and formally addressed the issue of uncertainty in the hypothetical simulations. The hypothetical stresses assessed included: (1) nearby pumping of irrigation wells, (2) the artificial lowering of lake levels of Lower Genesee Lake and (3) reduction in recharge resulting from potential development in the basin.

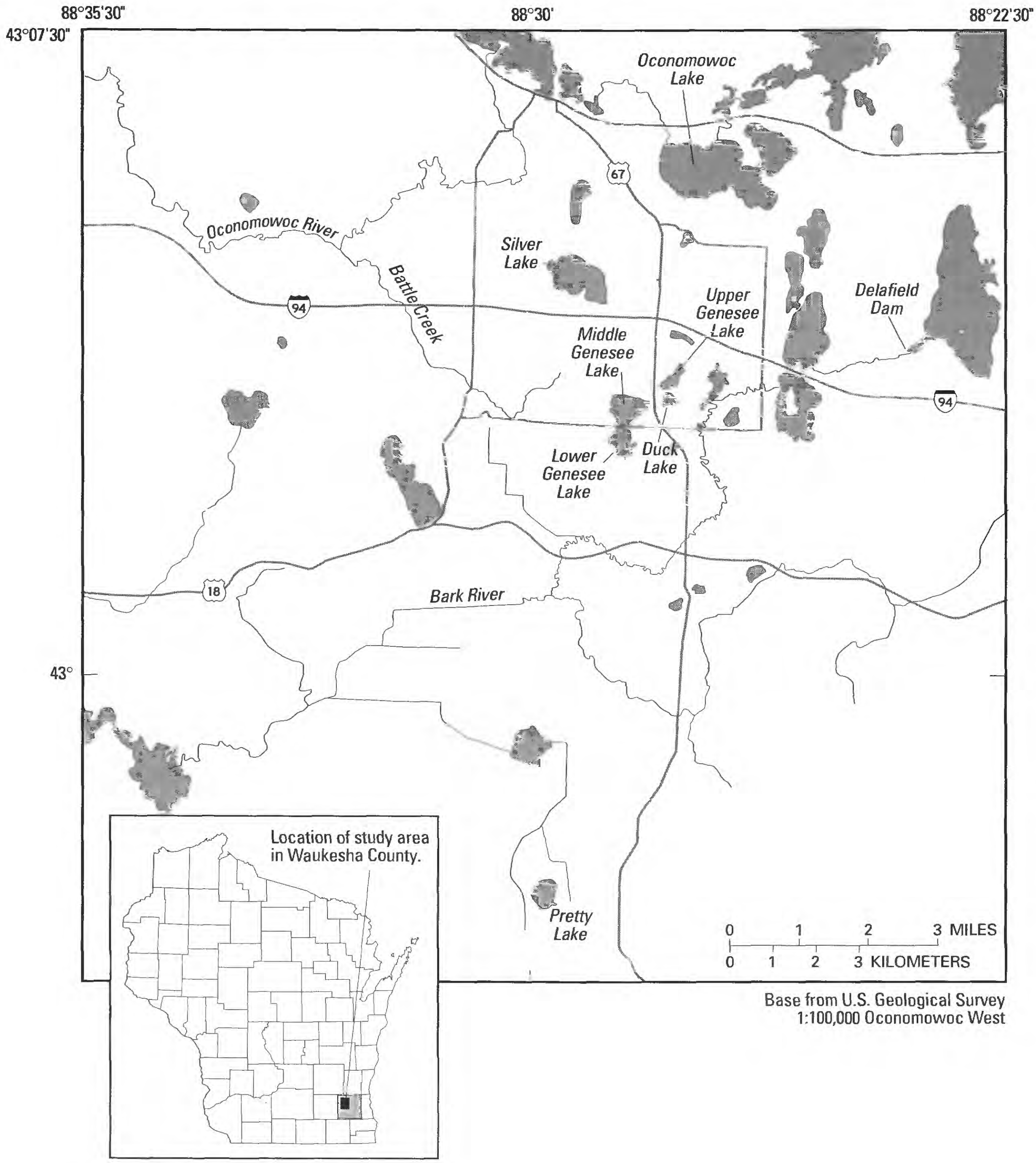


Figure 1. Location of Middle Genesee Lake and study area, Waukesha County, Wisconsin.

Purpose, Scope, and Data Sources

The purpose of this report is to present the results of flow modeling of the hydrologic system in the vicinity of Middle Genesee Lake. Because the ground-water and surface-water systems are in good hydrologic connection in this area, the hydrologic system simulated in this study encompasses the lakes, streams and shallow ground-water system. Only existing geologic and hydrologic data were used during this study. The ground-water-flow model complexity was commensurate with the extent of the existing data set. That is, the data set did not include vertical gradients or ground-water elevation (head) data over time; therefore, the system was simulated using an areal, two-dimensional, steady-state model. Two-dimensional assumptions are appropriate because the shallow ground-water-flow system is thin and areally extensive. Steady-state assumptions are appropriate because the system has high hydraulic conductivity and relatively small distances between surface-water features helping to ensure that periodic transient stresses are mitigated quickly within the system. In order to describe the largest effect on the shallow hydrologic system, hypothetical stress simulations also were simulated using steady-state conditions.

Geologic data consisted of interpretive maps presented by Gonthier (1975) and well-construction reports (Wisconsin Department of Natural Resources-Bureau of Drinking Water and Groundwater, 1998). These data were used to estimate saturated thickness of the shallow aquifer and provided estimates of water-table elevation. Streamflow measurements from the USGS gaging station on the Bark River at Rome, Wisconsin, were used to estimate flow duration. USGS 7.5 minute topographic maps were used to locate and estimate elevations of surface-water features for model development.

Methods

An analytic element ground-water-flow model, using the computer program GFLOW (Haitjema, 1995), was developed to simulate the shallow ground-water system and its interaction with surface-water features. A complete description of analytic elements is beyond the scope of this report; a brief description is given below.

An infinite aquifer is assumed in analytic element modeling. The problem domain does not require a grid or involve interpolation between cells. To construct an analytic element model, features important to ground-water flow (for example, wells) and surface-water features are entered as mathematical elements or strings of elements. The amount of detail specified for the features depends on distance from the area of interest. Each element is represented by an analytic solution. The effects of these individual solutions are superposed or added together to arrive at a solution for the ground-water-flow system. Because the solution is not confined to a grid, heads and flows can be computed anywhere in the model domain without nodal averaging. In the GFLOW model used here, the analytic elements are two-dimensional and are used to only simulate steady-state conditions (that is, heads do not vary with time). The analytic element method, and the comparison of analytic element to finite-difference numerical model techniques, have been discussed by others (Strack, 1989; Haitjema, 1995; and Hunt and Krohelski, 1996; Hunt and others 1998, respectively).

The GFLOW model was calibrated using parameter estimation techniques. The use of parameter estimation for calibration is a relatively new advancement for the science. There are numerous publications detailing the advantages of parameter estimation models (for example, Hill 1992; Poeter and Hill, 1997; Hill 1998). Briefly, the primary benefit of a properly prepared parameter estimation model over typical "trial-and-error" calibration is the ability to automatically calculate parameter values (for example, hydraulic conductivity and recharge) that are a quantified best fit between simulated model output and observed data (for example, ground-water levels and streamflows). Other benefits also result, such as the quantification of the quality of the calibration and a statistically rigorous measure of the uncertainty (or confidence interval) of hypothetical simulations made using the optimized model. In addition, parameter correlation (for example, hydraulic conductivity and recharge) and parameter sensitivity can be quantified and assessed. In this study, the GFLOW model was coupled with the parameter estimation code UCODE (Poeter and Hill, 1998). This report is among the first published application linking an analytic element model to a multi-objective function parameter estimation code.

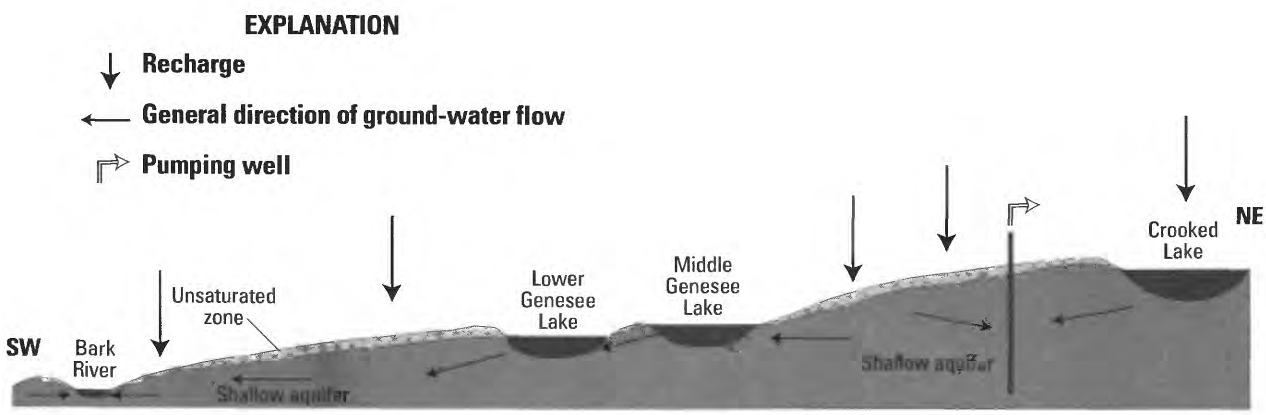


Figure 2. Conceptual model of shallow hydrologic system in the vicinity of Middle Genesee Lake, Waukesha County, Wisconsin.

Physical Setting

Middle Genesee Lake, located in west-central Waukesha County, Wisconsin (fig. 1), is a 109-acre seepage lake (a lake without stream inlets or outlets). Four other lakes are located in the vicinity. Lower Genesee Lake, which is similar in size and shape to Middle Genesee Lake, is closest and is located to the south. The two lakes are separated by a thin strip of land only slightly wider than the width of a road constructed between the two lakes. The shorelines of both lakes are developed with year-round homes. Rapid development—both commercial and residential—is occurring and is expected to continue throughout the region. Ground water is the source of all domestic and municipal water supplies in the area of the lakes. An area of irrigation, known locally as Pabst Farms, is located approximately 1 mi to the north of the lakes. Local streams in the area include the Oconomowoc River, Battle Creek, and the Bark River (fig. 1).

CONCEPTUAL MODEL

Prior to simulating the ground-water system using a flow-modeling code, a conceptualization of the hydrologic system is essential because it forms the framework for model development. The conceptualization reduces the ground-water system into important component parts. This reduction is a necessary *simplification* of the hydrologic system because inclusion of all of the complexities into a model is not feasible. Steps in the development of the conceptual model include: (1) definition of the aquifer(s), (2) identification of sources and sinks of water, and (3) identification and delineation of hydrologic boundaries present in the area of interest. The conceptualization of the shallow hydrologic system in the vicinity of Middle Genesee Lake used in this study is shown in figure 2.

The shallow ground-water system consists of a laterally extensive unconsolidated deposit of varying thickness. Within these sediments, saturated outwash (sand and gravel) about 100 ft thick forms a shallow aquifer (Gonthier, 1975). Although the underlying bedrock unit could be considered an aquifer, the ability of this unit to transmit water is much less than the overlying unconsolidated sediments. Therefore, the model included only the most transmissive upper sediments. The depth to ground water (water table) in the vicinity of the Genesee Lakes is generally less than 10 ft. The depth to water increases as land-surface elevation increases.

Ground water moves from higher to lower potentials (areas of higher ground-water levels to areas of lower ground-water levels). As a result, ground water generally discharges to surface-water features and recharges in areas away from these features. Due to the position of Middle Genesee Lake in the ground-water basin, it is likely that the lake receives ground-water flow on the upgradient side (the side with higher ground-water levels) and the lake contributes flow to the ground-water system on the downgradient side (the side with lower ground-water levels). Therefore, ground water flows through the lake. This conceptualization of the interaction of ground water and surface water also was observed at nearby Pretty Lake, which is located about 6 mi to the south of the Genesee Lakes (fig. 1), by Hunt and Krohelski (1996). In the two-

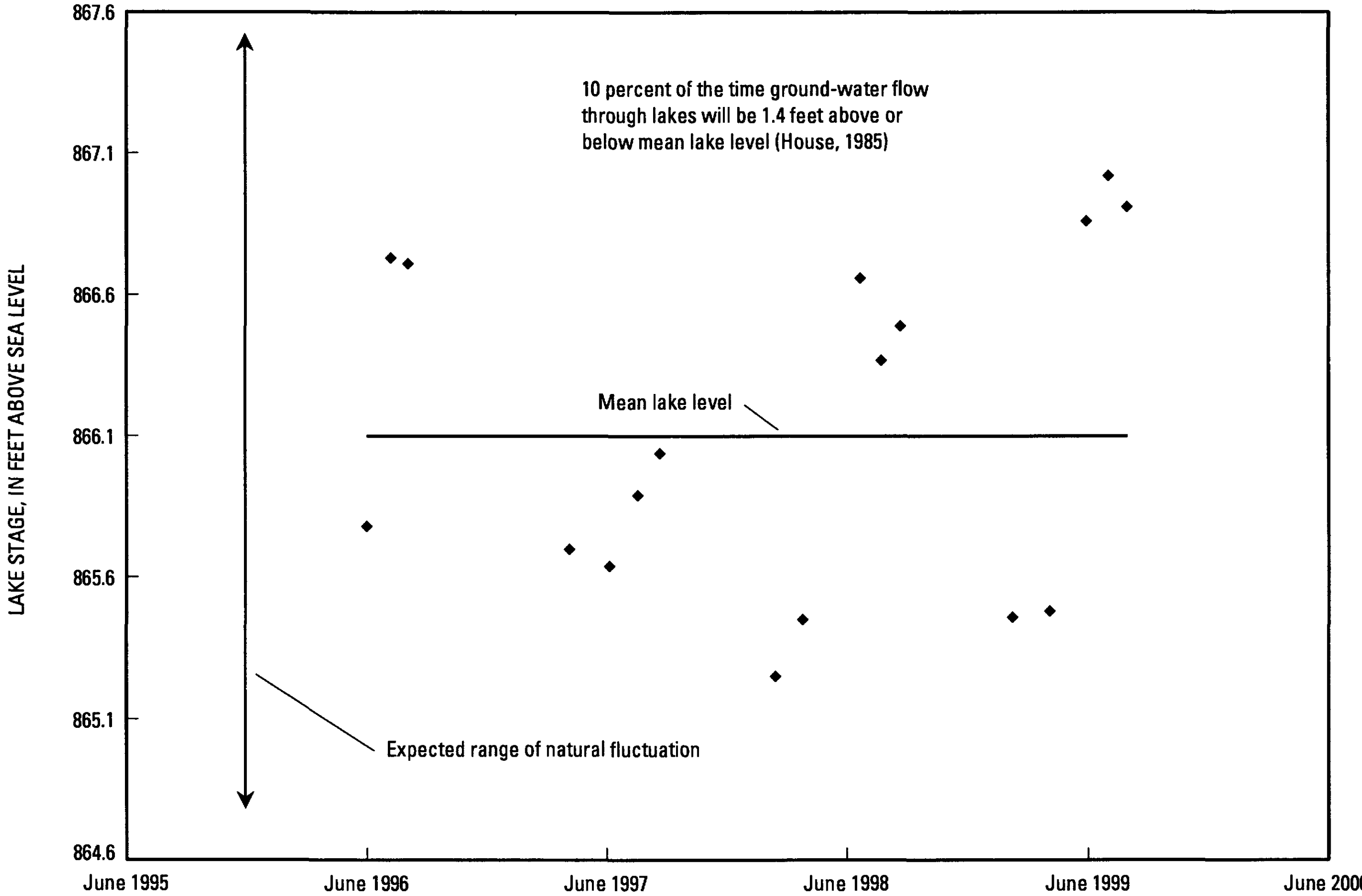


Figure 3. Lake stage and expected range of fluctuation for Middle Genesee Lake, Wisconsin, June 1995–June 2000.

dimensional model used in this study, it was assumed that all upgradient ground water discharges into the lake. That is, no ground water flows beneath Middle Genesee Lake; thus, the lake acts as a fully penetrating boundary.

Middle Genesee Lake is a seepage lake as there are no surface-water outlets out of the lake. Lake levels have been measured intermittently during the period 1995–99; the mean lake level was 866.1 ft above sea level and fluctuated about 0.9 ft above and below the mean (fig. 3). From these data collected to date, it appears that Middle Genesee Lake levels fluctuate in the range expected for a ground-water flow-through, seepage lake. The water level of a typical ground water flow-through lake in Wisconsin can be expected to be 1.4 ft above or below the long-term mean level of the lake about 10 percent of the time (House, 1985).

In addition to ground-water flow, other hydrologic budget components for Middle Genesee Lake include precipitation falling on the lake and water evaporating from the lake surface. In southeastern Wisconsin, annual precipitation exceeds evaporation by about 2 in/yr (Novitzki, 1982). Overland flow is assumed to be insignificant because infiltration rates of the sandy surface deposits are rarely exceeded by precipitation rates. Thus, overland flow is not included as a budget component in the hydrologic conceptual model.

DEVELOPMENT OF THE GFLOW MODEL

Initial model development included estimating the elevation of the base of the shallow aquifer system, a global recharge rate, and a horizontal hydraulic conductivity. The base of the model approximates the bottom of the high conductivity unconsolidated sediments (about 800 ft above sea level). The recharge rate and horizontal hydraulic conductivity were considered calibration parameters; thus, these parameters were varied during model calibration. Initially, recharge was set to

5.9 in/yr and horizontal hydraulic conductivity set to 250 ft/d based on previous modeling results in the area by Hunt and Krohelski (1996).

The ground-water flow model consists of the "far-field" and "near-field" elements. Based on the conceptual model, the location and elevation of far-field surface-water features were added to the model (fig. 4a). These are rivers and lakes distant from Middle Genesee Lake that are simulated with coarse linesinks and little or no resistance between the surface-water features and the ground-water system (that is, simulated as having good hydraulic connection). The purpose of simulating the far-field features is to have the model explicitly define the regional ground-water-flow field around Middle Genesee Lake area (called the "near field"). The near field is the primary area of interest and in this study encompasses the Upper, Middle, and Lower Genesee Lakes, as well as other nearby features that affect the hydrology of the lakes (fig. 4b).

Streambed sediment resistance in the near and far field was set equal to 0.3 days. Resistance in analytic element modeling is calculated by dividing the streambed sediment thickness by the vertical hydraulic conductivity. For this model, the value of 0.3 days corresponds to a 1-ft sediment thickness and a vertical hydraulic conductivity of 3.3 ft/d. The width of the stream was assigned according to stream order, and ranged from 10 to 50 ft. Parameter sensitivity assessments within UCODE demonstrated that the model results are not sensitive to changes in stream resistance when varied over reasonable ranges; therefore, the values for specific streams were fixed in all model runs.

Streams in the far field are not used for flux calibration; thus, streams are simply modeled as individual linesinks. In near-field streams a special type of linesink was used, called a "stream element" (Mitchell-Bruker and Haitjema, 1996). This element consists of linked linesinks that route water from high elevation linesinks to low elevation linesinks. During the routing through the stream network, the amount of water captured from and lost to the shallow ground-water system by the stream is tabulated. This accounting allows easy determination of fluxes from any linesink in the stream network that includes flows from all the upstream linesinks. More importantly, the accounting also ensures that the amount of stream water lost to the ground-water system is restricted to the amount of water available (that is, water delivered from upgradient linesinks in the network). For streams where the headwaters are not included in the model domain, a headwater inflow term can be specified. This option was utilized for the Bark River – a stream with a large flow duration data set and one that includes an appreciable headwater reach that is not in the model domain. Based on field measurements at the Delafield Dam, the amount of headwater inflow was set to 28.3 ft^3/s, and was added to the stream element immediately downgradient of the dam (fig. 4b).

Lakes where simulation of lake stage is not desired (lakes not adjacent to Middle Genesee Lake) were simulated using linesinks with resistance. Drainage lakes in the near field were linked to the stream network by stream elements based on the methodology of Hunt and others (1998). The value of resistance was assigned according to the lake's geologic setting (for example, in sandy sediments, near wetlands). The resulting resistance varied over a small range (from 0.3 to 2.0 days). Similar to Hunt and Krohelski (1996), simulation of Duck Lake, and Upper, Middle, and Lower Genesee Lakes used inhomogeneities (change in aquifer properties) rather than the linesinks used to simulate the streams and the far-field lakes. This formulation allows the model to account for the average rate of precipitation and evaporation and directly solve for lake stage, whereas linesinks require the input of a fixed lake stage. Use of inhomogeneities required the specification of a hydraulic conductivity in the lake three orders of magnitude larger than the aquifer to represent the equipotential surface (Hunt and Krohelski, 1996; Chung, 1998). Lakes simulated with inhomogeneities ensure that the water table in the vicinity of Middle Genesee Lake is allowed to fluctuate and is not overspecified by head-dependent flux boundaries.

MODEL CALIBRATION

The model solution using the initial parameter values resulted in a water-table configuration (fig. 4b) similar to the water table presented by Gonthier (1975) with water flowing from the northeast to the southwest in the Middle Genesee Lake area. In order to determine the "best fit" of model results to measured values of water-table elevation and streamflows, a more formal calibration process was used (described below).

Calibration targets are measured field data, which are used to evaluate how well the model represents the hydrologic system. The targets used here include both ground-water levels and streamflows (fig. 4b). Only existing field data were used in this study; no additional data were collected. Ground-water levels for 17 existing

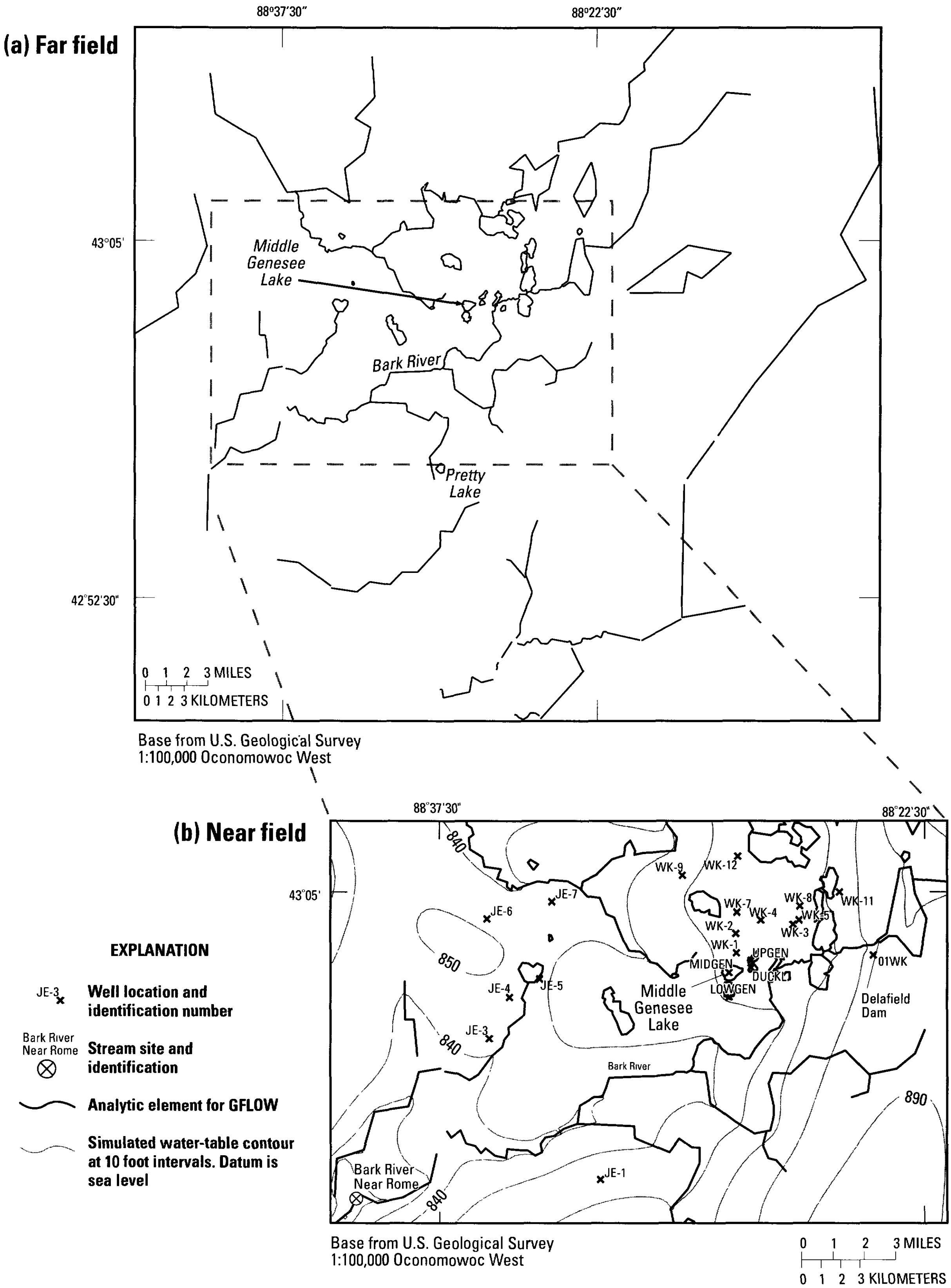


Figure 4. Simulated hydrologic features with analytic elements, initial water-table elevation and calibration targets, (a) far field elements (Global recharge is applied for the entire far field); (b) near field elements.

Table 1. Measured and simulated values and weight of calibration targets

[Lake stage and ground-water levels are in feet above sea level and streamflow is the 50-percent flow duration in cubic feet per second. Weights for targets are reported as standard deviations. Head targets are divided into near-field targets (standard deviation equal or less than five feet) and far-field targets (standard deviation equal 10 feet). Lake locations are shown in figure 1; ground-water level and flux target locations are shown in figure 4b.]

Calibration target	Measured	–	Simulated	=	Residual	Weight
Lake stage (feet above)						
Middle Genesee	863		862.62		0.38	1
Lower Genesee	862		861.85		.15	4
Upper Genesee	864		865.07		-1.07	4
Duck Lake	864		864.47		-.47	4
Ground-water level (feet above)						
JE_1	845		859.85		-14.85	10
JE_3	839		844.89		-5.89	10
JE_4	830		849.52		-19.52	10
JE_5	836		849.55		-13.55	10
01WK	889		884.29		4.71	5
WK_1	865		863.86		1.15	5
WK_2	869		864.89		4.12	5
WK_3	864		868.71		-4.71	5
WK_4	870		867.17		2.83	5
WK_5	868		868.99		-.99	5
JE_6	834		852.02		-18.02	10
WK_7	868		865.33		2.67	5
WK_8	867		868.95		-1.95	5
JE_7	841		845.95		-4.95	10
WK_9	857		858.30		-1.30	5
WK_11	869		874.51		-5.51	5
WK_12	869		863.23		5.77	5
Streamflow (cubic feet per second)						
Bark River near Rome, Wisconsin	77		77.3		-0.3	2.3

wells were obtained from well-construction reports. In addition to the ground-water levels, calibration targets representing the lake levels for Duck Lake as well as Upper, Middle, and Lower Genesee Lakes also were used. Data from a historical streamflow gaging station on the Bark River gaging station at Rome, Wisconsin, also were used as a calibration target. This target was used to constrain the simulated fluxes and associated regional recharge. Average conditions (here defined as the "Q_{50}" or flow that occurs 50 percent of the time) were used for calibration; the Q_{50} flow duration was estimated to be 77 ft^3/s for the Bark River gaging station. The relation of the target to the model calibration is such that lower values of the streamflow target result in lower rates of recharge and lower corresponding horizontal hydraulic conductivity.

The GFLOW model was coupled to UCODE (Hill and Poeter, 1998) to formulize the selection of an optimal set of parameters (a set that best matches observed ground-water levels and flows). One of the most important operations in using a parameter estimation technique such as that used in UCODE is assigning weight to the observations. The weights assigned to each calibration target and results of the optimized model solution are shown in table 1. Distant calibration targets and those with higher uncertainty were assigned lower weight for the calibration process. Lake stage and ground-water levels are in feet above sea level and streamflows are in cubic feet per second (ft^3/s). Weights for ground-water level, lake stage, and streamflow targets are expressed as a standard deviation. Hill (1998) gives a detailed explanation of the use of these statistics to represent uncertainty. Ground-water levels are divided into far-field targets (standard deviation equal to 10 ft) and near-field targets (standard deviation equal to 5 ft). The assigned standard deviation reflects uncertainty associated with well locations, concerns with how well the measurements reflect average conditions, and the qualitative desire for a better goodness of fit in the near-field targets than far-field targets during parameter estimation. Streamflow for the gaging station at Rome, Wisconsin was assigned a standard deviation of 2.3 ft^3/s (table 1). This value corresponds to a high weight for this problem and reflects (1) the long-term flow record at the gaging station, and (2) that additional weight is needed to offset the higher number of water-table elevation targets.

During calibration, horizontal hydraulic conductivity and recharge were adjusted in the model to obtain the best fit to the observed heads and streamflows. Although initial model runs included combinations of hydraulic conductivity zonation and recharge zonation, UCODE parameter sensitivity evaluations demonstrated that the field data did not support this level of complexity and the model could be adequately calibrated using one global hydraulic conductivity and one global recharge rate. This parsimonious design also corresponds to the homogeneous geological structure expected in the outwash sediments and uniform precipitation conditions expected in the study area. The optimized model indicated horizontal hydraulic conductivity and recharge rate of 112 ft/d and 6.7 in/yr, respectively. Unweighted statistics comparing measured ground-water levels to calibrated modeled values include an average difference of –3.2 ft, a mean absolute error of 5.2 ft and the root mean square error of 7.7 ft. The streamflow in the Bark River also was well simulated (77.3 ft^3/s simulated flow versus 77.0 ft^3/s measured flow). The optimized values for horizontal hydraulic conductivity and recharge (112 ft/d and 6.7 in/yr) are similar to the values used near the southern boundary of the model at Pretty Lake (250 ft/d and 5.9 in/yr, respectively) by Hunt and Krohelski (1996).

HYDROLOGIC BUDGET

An annual hydrologic budget for Middle Genesee Lake can be described by

$$\Delta S = P - E + GW_{in} - GW_{out},$$

where

- ΔS is change in lake storage,
- P is volume of precipitation falling directly on the lake,
- E is volume of water evaporated from the lake surface,
- GW_{in} is volume of ground-water flow into lake, and
- GW_{out} is volume of flow out of the lake to the ground-water system.

Various assumptions were made in the application of this equation. Overland flow is assumed to be negligible because infiltration rates of the sandy surface deposits are rarely exceeded by precipitation rates. Annual evaporation is assumed to be about 2 in/yr less than precipitation (Novitzki, 1982). Average precipitation is 32 in/yr for the period 1961 to 1990; climatological data are available at http://www.crh.noaa.gov/mkx/data/wipcpn.gif. It is assumed that lake storage does not change with time; that is, the hydrologic system is at a steady state. In addition, it is assumed that Middle Genesee Lake acts as a fully penetrating boundary; thus, ground water does not flow under the lake.

The calibrated model results (fig. 5) were used to estimate GW_{in}; the GW_{out} term is estimated as a residual. The width of the simulated contributing area was used, in conjunction with Darcy's law, to estimate the volume of ground-water flow into the lake. Ground-water flow into the lake is equal to the cross-sectional area, which is the width of the contributing area multiplied by the saturated aquifer thickness, multiplied by the model-simulated gradient and the horizontal hydraulic conductivity. The contributing area of the lake is the land area with the same horizontal extent as that part of the aquifer from which ground-water flow is diverted to the lake. The contributing area of the lake was delineated by backward particle tracking from the lake edge. Mathematical particles of water were placed around the edge of the lake at the bottom of the aquifer and traced backwards to the water table. Using a porosity value typical of sand (0.25 – Freeze and Cherry, 1979), estimates of the time required for a particle of water located in the contributing area to reach the lake also can be calculated (fig. 5).

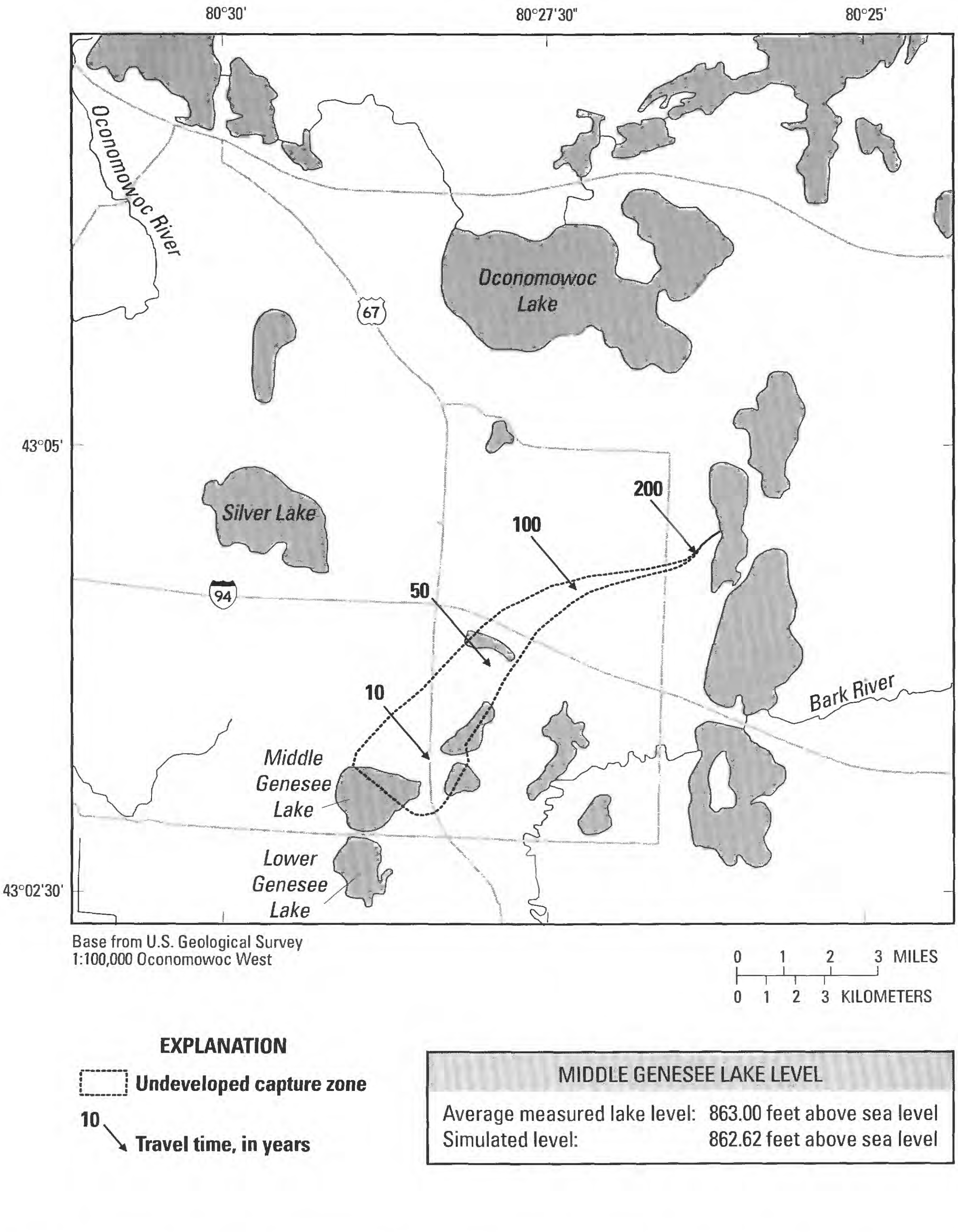


Figure 5. The ground-water capture zone of Middle Genesee Lake, Wisconsin simulated using the calibrated model region without development.

Using this approach, estimates of the hydrologic budget components of Middle Genesee Lake are:

$P = 32$ in/yr,

$E = 30$ in/yr,

$GW_{in} = 25.2$ in/yr, and

$GW_{out} = P - E + GW_{in} = 27.2$ in/yr.

APPLICATION OF MODEL TO SIMULATE CHANGES IN LAKE STAGE DUE TO HYDROLOGIC STRESS

Three hypothetical hydrologic stress scenarios were assessed with the calibrated model. These include the effects on the lake stage of Middle Genesee Lake due to: (1) pumping of nearby irrigation wells, (2) the artificial lowering of lake levels of Lower Genesee Lake, and (3) reduction in recharge to the shallow ground-water system resulting from development in the basin. These three hypothetical scenarios were simulated using the calibrated ground-water flow model by adding nine pumping wells in the vicinity of the contributing area with each well pumping at a steady-state rate of 50 gal/min (scenario number 1), pumping from Lower Genesee Lake at a steady-state pumping rate of 500 gal/min (scenario number 2), and reducing recharge rate by 25 percent within an area to the northeast of Middle Genesee Lake (scenario number 3).

The scenarios described above were assessed by comparing calibrated lake stages and lake contributing areas to simulated lake stages and contributing areas after the hypothetical stresses were added. A range in the simulated lake stage is determined by applying parameter-estimation techniques, and is provided to describe the uncertainty present in the model due to uncertainty in selected underlying parameters (horizontal hydraulic conductivity and recharge). The uncertainty is reported as a 95-percent confidence interval around the simulated value; if the underlying assumptions are met, this range can be considered a good representation of the extreme values that are expected given the uncertainty in the model parameters. It should be noted that the range of uncertainty could be reduced by lowering the uncertainty within the model. Lowering the uncertainty would require refining existing data such as improving well locations, elevations, and average water levels and average flows, or collecting additional long-term data in areas near Middle Genesee Lake.

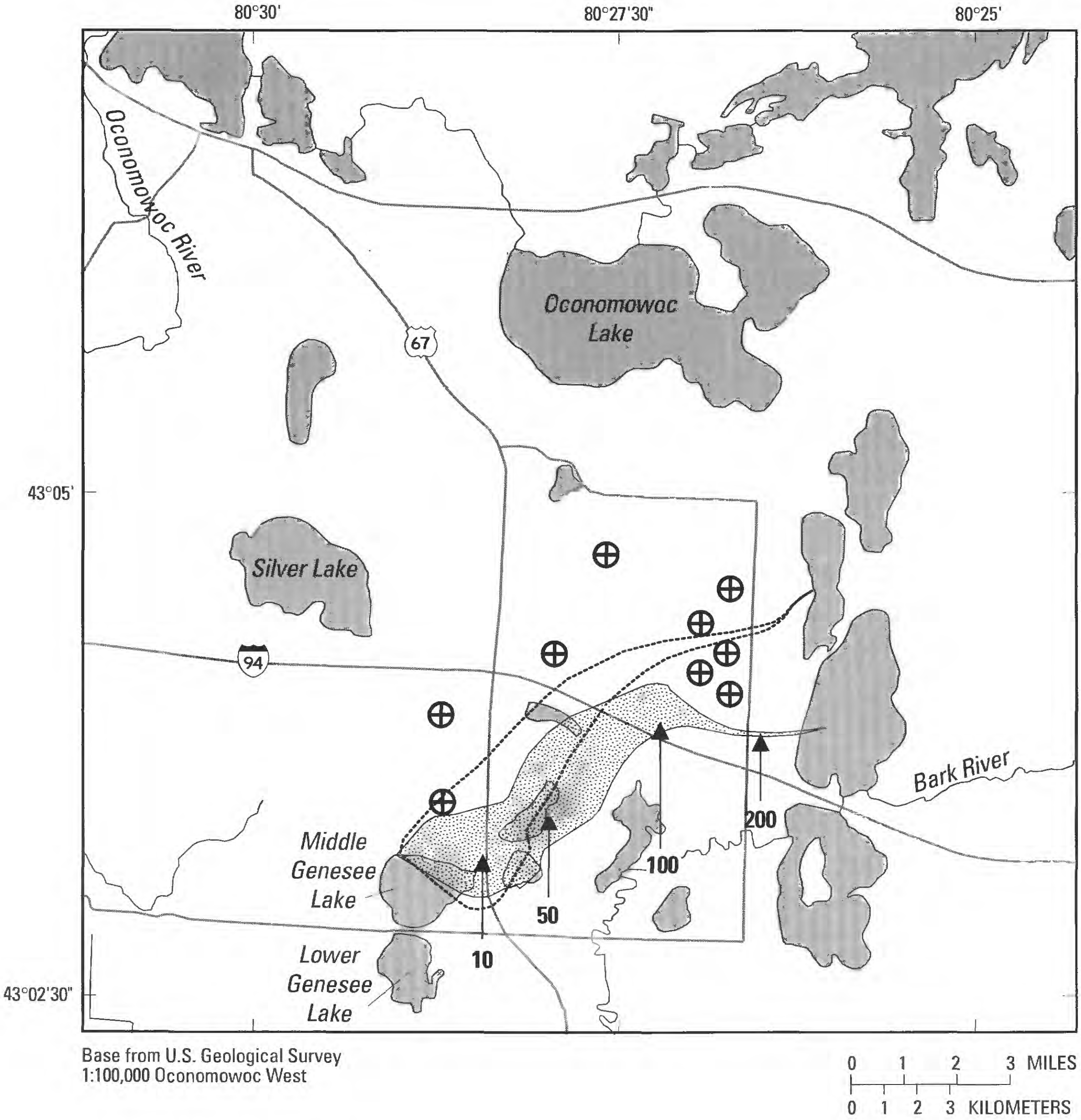
Scenario Number 1—Addition of Nine Pumping Wells

The addition of nine pumping wells to the north of Middle Genesee Lake with a pumping rate of 50 gal/min would reduce the lake stage by 0.4 ft with a possible range of no effect (no lowering of lake level) to a maximum of 2.0 ft. Because the lake and wells draw water from the same source, the amount of lake stage decrease is sensitive to the pumping rate assigned to the pumping wells. The 50 gal/min rate used in this simulation is based on withdrawals reported to the Wisconsin Department of Natural Resources for 1988, a drought year when irrigation water use was extremely high. The annual withdrawal rate for the nine irrigation wells when averaged was equal to 70 gal/min. The consumptive use (the amount of water not returned to the groundwater system) was assumed to be 70 percent (Weeks and Strangland, 1971). Applying the consumptive use rate to the annual irrigation rate for the nine wells in 1988 gives a withdrawal rate of about 50 gal/min. This rate should be considered a high end of expected withdrawals because pumping is not expected to be this high in non-drought years.

The effect of pumping the irrigation wells is to shift the lake contributing area to the south (fig. 6). Averaging of higher growing-season pumping over the year to obtain an average annual pumping rate for the steady-state model may underestimate short-term effects near the pumping wells. That is, the shifting of the contributing area and the amount of lake stage reduction may be greater when the wells are pumping during the irrigation season than the effects reported by a model simulating steady-state conditions. However, the hydrologic system recovers during the non-growing season when the wells are not pumping, and the long-term average effect on the hydrologic system is expected to be that simulated by the steady-state model.

Scenario Number 2—Pumping from Lower Genesee Lake

A proposal to lower the stage of Lower Genesee Lake also was evaluated using the model. A pumping station on Lower Genesee Lake was simulated using a well in the lake pumping at a steady-state rate of 500 gal/min. In this simulation, Middle Genesee Lake stage declined by 2.7 ft, with a range of 2.2 to 3.1 ft at the 95-percent confidence interval. An important



EXPLANATION

- Undeveloped capture zone
- Developed capture zone
- 10 — Travel time, in years
- Pumping well

MIDDLE GENESEE LAKE LEVEL CHANGE	
Undeveloped lake level:	862.6 feet
Developed lake level:	862.2 feet (Δh = 0.4 feet)
95% C.I. (+)lake level:	863.7 feet (Δh = 0.0 feet)
95% C.I. (-) lake level:	860.6 feet (Δh = 2.0 feet)

Δh is change in lake stage;
95% C.I. is 95-percent confidence interval

Figure 6. The ground-water capture zone of Middle Genesee Lake region for scenario number 1 (9 wells pumping at 50 gallons per minute each well).

assumption in this scenario is that the water pumped for Lower Genesee Lake is conveyed away from the lakes so that it cannot re-enter the lake systems (that is, conveyed to a down gradient surface-water body by a non-leaking channel or storm sewer). The contributing area is in about the same position with or without pumping but is larger during pumping (fig. 7).

Scenario Number 3—Reduction in Recharge Rate

A 0.1-ft decline in lake levels was simulated by reducing recharge rate by 25 percent within an area of potential development to the north of Middle Genesee Lake, with a range of 0.0 to 2.0 ft at the 95-percent confidence interval. A reduction in recharge is assumed because paved areas due to development will limit recharge and increase runoff, which may not be infiltrated or recharged to the shallow ground-water system. The contributing areas have a similar shape with or without the reduction in recharge (fig. 8). The larger capture zone resulting from reduced recharge reflects the need to encompass a larger area to offset the lower recharge rate. If the reduction in recharge encompasses more of the contributing area, a greater reduction in lake stageand shifting of the contributing area is expected.

Effect on Middle Genesee Lake

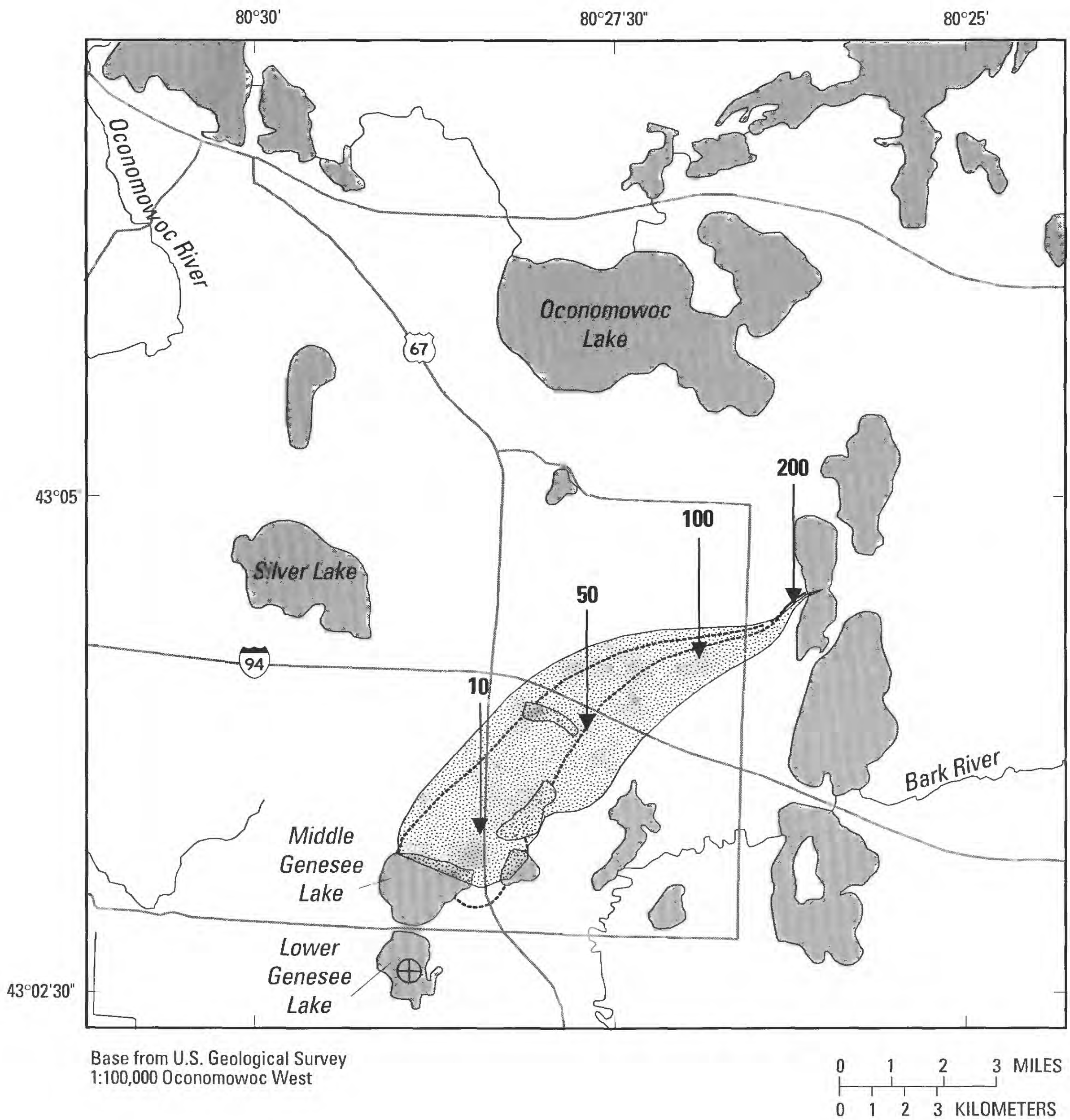
The range of the simulated effects shown above is similar to natural variations in lake stage (a 2-ft fluctuation or approximately one foot above or below the mean lake stage). Whereas it might be concluded that the simulated reductions in lake stage are within the natural fluctuation of lake stage, the hydrologic stresses simulated here differ from normal climatic variation in one important way. Pumping stresses and recharge reduction are *systematic changes* to the hydrologic system. That is, whereas normal changes in climate include both wet and dry years, the hydrologic stresses simulated here always reflect a one-directional stress toward less water entering the lakes. Therefore, although the normal climatic variation would still occur and lake levels would continue to fluctuate, the normal fluctuations would be overlain on a new, lower, average lake level. Thus, both wetter and drier years would have lower lake levels than if the hydrologic stress was not present.

SUMMARY AND CONCLUSIONS

Middle Genesee Lake is a ground-water flow-through seepage lake located in a developing area in southeastern Wisconsin. The lake is in good connection with the ground-water system; thus, hydrologic stresses in the shallow ground-water system could adversely affect the lake system. A study was completed by the U.S. Geological Survey, in cooperation with the Middle Genesee Lake Management District, to identify areas that contribute ground water to the lake and estimate the hydrologic budget of the lake and hydraulic parameters affecting ground-water flow.

A two-dimensional, steady-state, analytic element ground-water model of the shallow hydrologic system was developed and calibrated using the computer code GFLOW. The model provides identification of the area that contributes water to Middle Genesee Lake and estimates the hydrologic budget of the lake and the hydraulic parameters affecting ground-water flow. The model was calibrated to an existing data set that included ground-water levels measured in 17 wells, four lakes, and the average (Q_{50}) flow duration for a stream gaging station on the Bark River located in Rome, Wisconsin. The parameter estimation model UCODE was coupled to the GFLOW model to automate and optimize the calibration. This report represents one of the first efforts to link an analytic element code to a multi-objective function parameter estimation code.

Parameter estimation techniques also allowed estimation of uncertainty in model simulations of hypothetical hydrologic stressors. The stresses simulated included withdrawals from nearby pumping of irrigation wells, the artificial lowering of lake levels of Lower Genesee Lake, and reduction in recharge in an area of potential development. The simulation results indicate that Middle Genesee Lake stage would be reduced—ranging from 0.1 for the reduction in recharge to 2.7 ft by pumping from Lower Genesee Lake. Decreases in lake stage resulting from these hydrologic stresses ranged between 0 and 3.1 ft when parameter uncertainty was included. The range in simulated values represents the uncertainty in the underlying model construction and calibration data, and can only be quantified using parameter estimation techniques. Whereas these simulated effects are within the natural variation in lake stage, they represent a systematic reduction of ground-water flow to the lake. Therefore, these hypothetical stresses are expected to establish a new, lower, baseline lake stage over which the natural variation due to climatic effects are added and subtracted.



EXPLANATION

Undeveloped capture zone

Developed capture zone

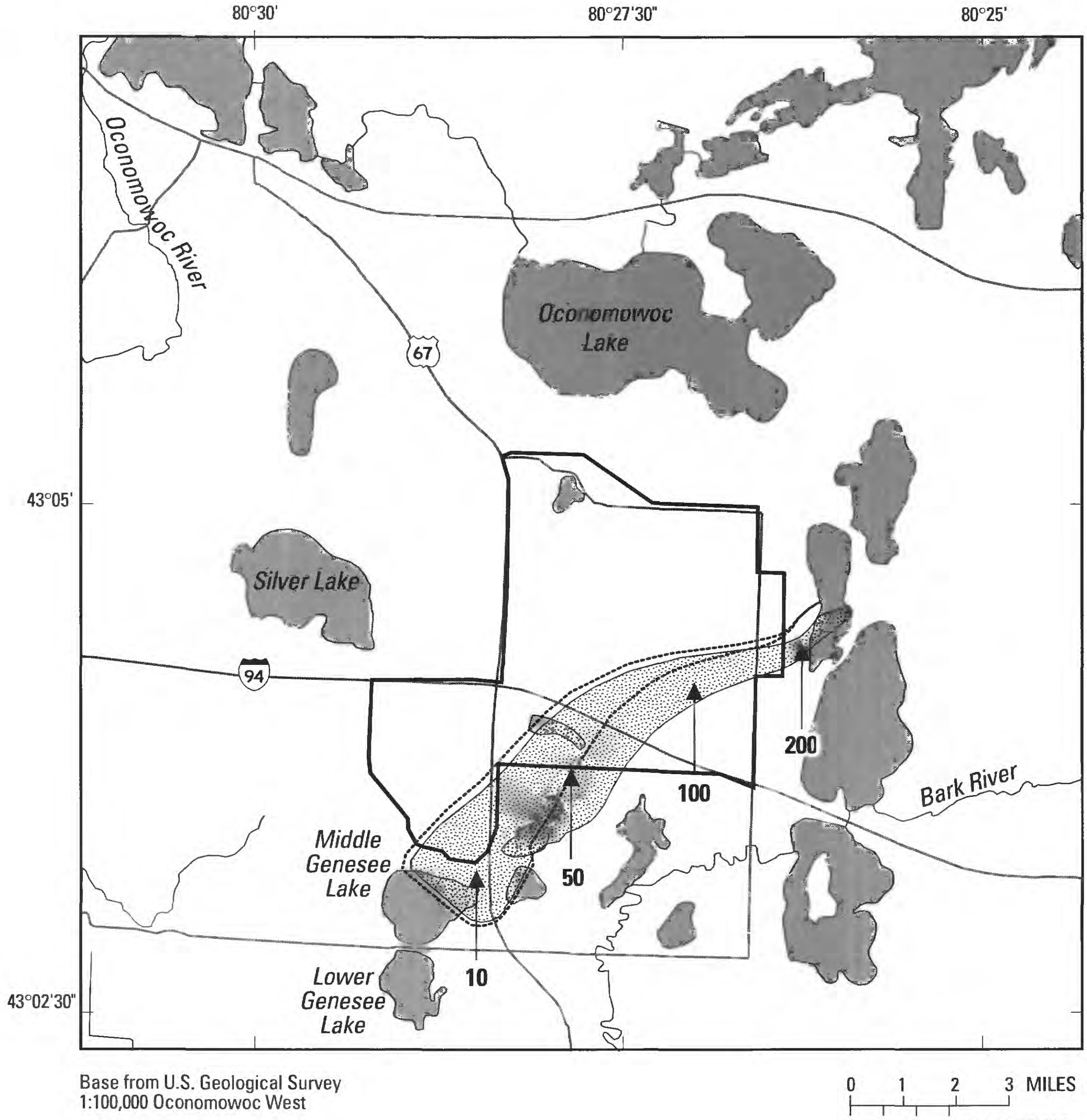
10 Travel time, in years

⊕ Pumping well

MIDDLE GENESEE LAKE LEVEL CHANGE	
Undeveloped lake level:	862.6 feet
Developed lake level:	859.9 feet (Δh = 2.7 feet)
95% C.I. (+)lake level:	860.4 feet (Δh = 2.2 feet)
95% C.I. (-) lake level:	859.5 feet (Δh = 3.1 feet)

Δh is change in lake stage;
95% C.I. is 95-percent confidence interval

Figure 7. The ground-water capture zone of Middle Genesee Lake region for scenario number 2 (500 gallons per minute pumping from Lower Genesee Lake).



Base from U.S. Geological Survey
1:100,000 Oconomowoc West

0 1 2 3 MILES
0 1 2 3 KILOMETERS

EXPLANATION

- Original capture zone
- Developed capture zone
- 10 Travel time, in years
- Recharge reduced area

MIDDLE GENESEE LAKE LEVEL CHANGE	
Original lake level:	862.6 feet
Developed lake level:	862.5 feet (Δh = 0.1 feet)
95% C.I. (+)lake level:	864.4 feet (Δh = 0.0 feet)
95% C.I. (-) lake level:	860.6 feet (Δh = 2.0 feet)

Δh is change in lake stage;
95% C.I. is 95-percent confidence interval

Figure 8. The ground-water capture zone of Middle Genesee Lake region for scenario number 3.

REFERENCES

Chung, K., 1998, Zones of high hydraulic conductivity to represent lakes in a groundwater flow model: Unpublished MS thesis, University of Wisconsin-Madison, 76 p.

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

Gonthier, J.B., 1975, Ground-water resources of Waukesha County, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular Number 29, 47 p.

Haitjema, H.M., 1995, Analytic Element Modeling of Groundwater Flow: San Diego, Calif., Academic Press, 394 p.

House, L.B., 1985, Stage fluctuations in Wisconsin lakes: Wisconsin Geological and Natural History Survey Information Circular Number 49, 84 p.

Hill, M.C., 1992, A computer program (MODFLOWP) for estimating parameters of a transient, three-dimensional, ground-water flow model using nonlinear regression: U.S. Geological Survey Open-File Report 91–484, 358 p.

____1998, Methods and guidelines for effective model calibration: U.S. Geological Survey Water-Resources Investigation Report 98–4005, 90 p.

Hunt, R.J., and Krohelski, J.T., 1996, The application of an analytic element model to investigate groundwater-lake interactions at Pretty Lake, Wisconsin: Journal of Lake and Reservoir Management, v. 12, no. 4, p. 487–495.

Hunt, R.J., Anderson, M.P., and Kelson, V.A., 1998, Improving a complex finite-difference ground water flow model through the use of an analytic element screening model: Ground Water, v. 36, no. 6, p. 1011–1017.

Mitchell-Bruker, S., and Haitjema, H., 1996, Modeling steady state conjunctive groundwater and surface water flow with analytic elements: Water Resources Research, v. 32, no. 9, p. 2725–2732.

Novitzki, R.P., 1982, Hydrology of Wisconsin Wetlands: Wisconsin Geological and Natural History Survey Information Circular Number 40, 22 p.

Poeter, E.P., and Hill, M.C., 1997, Inverse models—A necessary next step in ground-water modeling: Ground Water, v. 35, no. 2, p. 250–260.

____1998, Documentation of UCODE, a computer code for universal inverse modeling: U.S. Geological Survey Water-Resources Investigation Report 98–4080, 116 p.

Strack, O.D.L., 1989, Groundwater Mechanics: Englewood Cliffs, N.J., Prentice-Hall, 732 p.

Weeks, E.P., and Stangland, H.G., 1971, Effects of irrigation on streamflow in the central sand plains of Wisconsin: U.S. Geological Survey Open-File Report, 113 p.

Wisconsin Department of Natural Resources-Bureau of Drinking Water and Groundwater, 1998, Water Well Data—Well Construction Reports by County, CD ROM.

Simulation of the Shallow Hydrologic System in the Vicinity of Middle Genesee Lake, Wisconsin, Using Analytic Elements and Parameter Estimation WRIR 00–4136