U.S. Department of the Interior
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Simulation of Fish, Mud, and Crystal Lakes and the Shallow Ground-Water System, Dane County, Wisconsin

Water-Resources Investigations Report 02–4014

Prepared in cooperation with the
Dane County Lakes and Watershed Commission
Wisconsin Department of Natural Resources

USGS
science for a changing world

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2002

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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		
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer
Volume		
cubic foot (ft^3))	28.31	liter
gallon (gal)	3.79	liter
Hydraulic Conductivity*		
feet per day (ft/d)	0.3048	meters per day

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by use of the following equation:
°F = 1.8 (°C) + 32.

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)— 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^2. In this report, the mathematically reduced form, feet per day (ft/d), is used for convenience.

Other Abbreviations Used in this Report:

ft^3/d	cubic feet perday
gpm	gallons per minute
in/yr	inch per year

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Abstract

A new MODFLOW lake package (LAK3) that simulates ground-water/lake interaction was used in simulation of Fish, Mud and Crystal Lakes—three shallow seepage lakes located in northwestern Dane County, Wis. The simulations were done to help determine the cause of increasing lake stages and provide a tool to estimate the effect of pumping water from Fish Lake on future lake stages. The ground-water-flow model was developed using a telescopic-mesh refinement of the Dane and southwestern Columbia Counties regional model previously developed by the U.S. Geological Survey and the Wisconsin Geological and Natural History Survey. The parameter estimation model, UCODE, was coupled to the steady-state ground-water model to automate and optimize the calibration procedure. The steady-state model was calibrated to measured ground-water levels, Spring Creek streamflow measured at Lodi, and Fish and Crystal Lake stages. The results of the steady-state model were used as initial conditions in a transient simulation beginning in 1966 and ending in 1998. Recharge based on annual baseflow in Black Earth Creek, runoff based on measured coefficients, and precipitation and evaporation from the lake surfaces, were varied during the transient simulation. Measured Fish Lake stage was matched to simulated stage to calibrate the transient model.

Model results suggest that the increase in regional ground-water recharge resulted in increased ground-water flow to the lake, which in turn resulted in increased lake stages. Simulation results of withdrawal of water from Fish Lake at 500 gallons per minute, assuming 1990–98 climatic conditions, indicate that after 1 year of pumping the stage of Fish and Mud Lakes would be reduced more than 1 foot and the stage of Crystal Lake would be reduced by less than 0.2 foot. When pumping is stopped, the lake stages would recover to near pre-pumping levels within about 3 years. When pumping is extended to 5 years, Fish and Mud Lake stage would be reduced by a maximum of 3.8 feet and Crystal Lake stage is reduced a maximum of 0.8 feet. After 4 years of recovery, Fish and Mud Lake stages are within 0.9 foot of prepumping levels and Crystal Lake stage is within 0.7 foot.

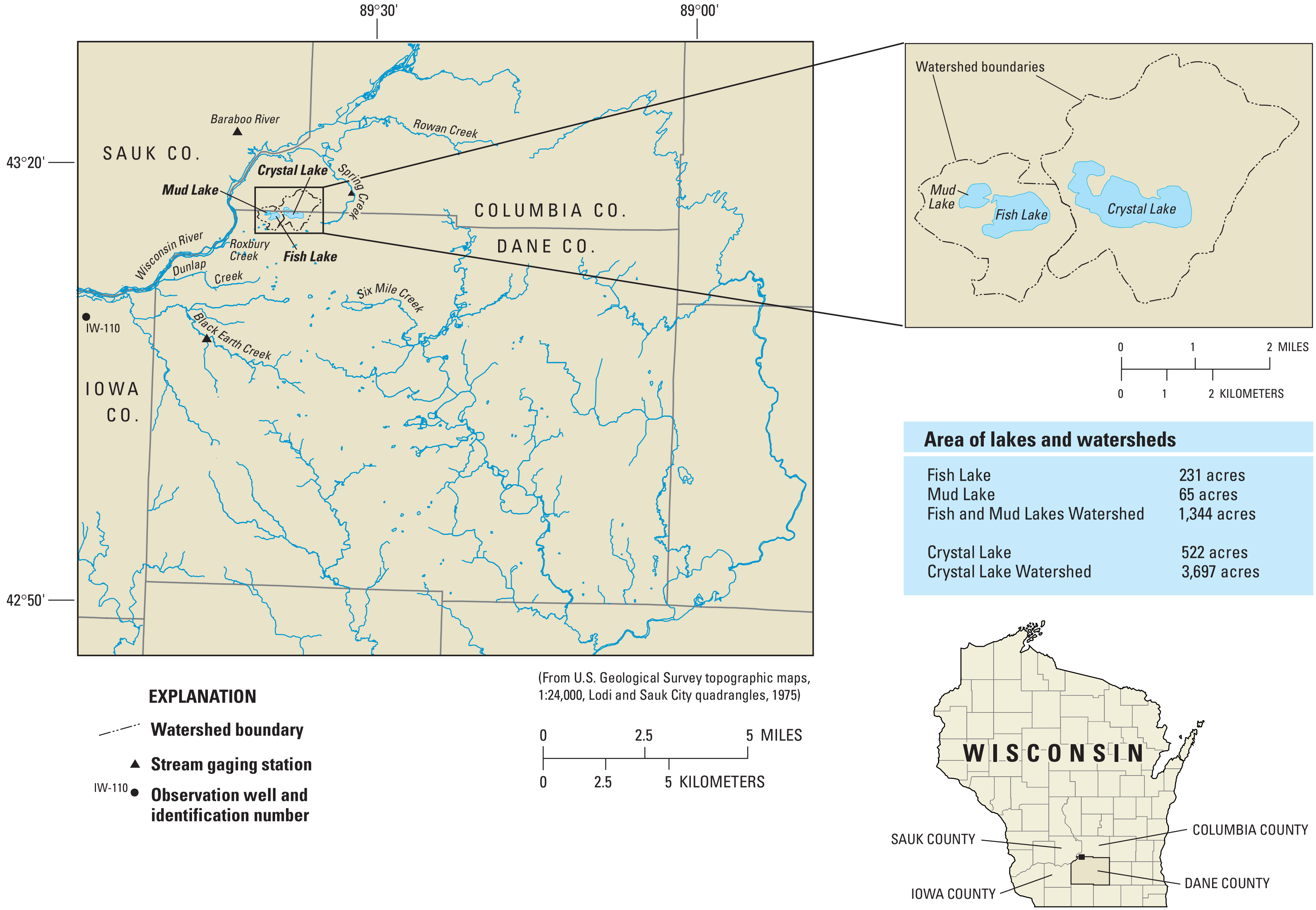
INTRODUCTION

The stage of Fish Lake located in northwestern Dane County, Wis. (fig. 1), has risen about 9 ft since 1966. High water levels have caused flooding of roads and some near-shore residences. The Fish Lake Association has contemplated withdrawing water from Fish Lake and adjoining Mud Lake during high-stage periods. However, before decisions concerning pumping can be made, an understanding of the hydrology of the lake/ground-water system and of the long-term effect of withdrawing lake water on lake stages are needed. In addition, it is not known whether the stage of nearby Crystal Lake, Dane and Columbia Counties, will be adversely or advantageously affected if water is withdrawn from Fish and Mud Lakes.

In 2001, the U.S. Geological Survey (USGS), in cooperation with the Dane County Lakes and Watershed Commission and the Wisconsin Department of Natural Resources (WDNR) (through a Lake Management Planning Grant), completed a 2-year study that described the hydrology of these lakes, their watersheds, and their relation to the shallow ground-water system. This report describes the findings of that study.

Purpose and Scope

This report describes the hydrology of Fish and Crystal Lakes (fig. 1) through the development and calibration of a ground-water-flow model. The model simulates lake stage using estimated hydrologic-budget



(From U.S. Geological Survey topographic maps, 1:24,000, Lodi and Sauk City quadrangles, 1975)

Area of lakes and watersheds

Fish Lake	231 acres
Mud Lake	65 acres
Fish and Mud Lakes Watershed	1,344 acres
Crystal Lake	522 acres
Crystal Lake Watershed	3,697 acres

Figure 1. Location of Fish, Mud, and Crystal Lakes and their associated watersheds, Dane and Columbia Counties, Wisconsin.

components and hydraulic parameters. The calibrated model is used to simulate the effect of pumping water from Fish Lake on future lake stages. Most data needed for this study were available from a previous, unpublished USGS study of Fish Lake or from USGS hydrologic databases. A 1-year (November 1990–October 1991) water-budget and phosphorus-loading study provided information for estimating surface-runoff coefficients. Historical streamflow records for Black Earth Creek provided the basis for estimating ground-water recharge. Stage records for Fish Lake were available for most of the period since 1966 to present. Data collected specifically for this study were recent (1999 to 2001) stage data and a bathymetric survey to define the morphometry of Crystal Lake.

Lake Description and Hydrologic Budgets

Fish and Crystal Lakes are seepage lakes. That is, these lakes do not have surface-water inlets or outlets (fig. 1). The northwest basin of Fish Lake, which is referred to as Mud Lake, is separated artificially from the main basin of Fish Lake by Fish Lake Road. However, Fish and Mud Lakes are connected hydraulically by at least three culverts. Hence, hereafter most references to Fish Lake are references to the Fish and Mud Lakes combination.

The surface areas of these lakes have increased with increasing lake stage. For example, based on USGS topographic maps constructed using photogrametric methods from 1974 photography (Lodi and Sauk City 7.5 minute quadrangles, 1975) the stage of Fish and Mud Lake, was about 854 ft above sea level and the areas were 231 and 65 acres, respectively. The average Fish and Mud Lake stage in January 1991 was 856.9 ft above sea level. Bathymetric maps constructed in January 1991 (Wisconsin Department of Natural Resources, 1991) indicate that Fish Lake had an area of 251 acres and Mud Lake had an area of about 76 acres. Therefore, compared to 1974, lake stage was about 3 ft higher in 1991 than in 1974 and Fish and Mud Lakes increased in area by 20 and 11 acres, respectively.

The change in Crystal Lake stage and area are not as well known as for Fish and Mud Lakes. Fish Lake stage has been measured intermittently since 1966 but the only measurement of stage available for Crystal Lake is from the USGS topographic maps constructed in 1959 (Baraboo 15-minute quadrangle, 1959) and 1974 (Lodi and Sauk City 7.5-minute quadrangles, 1975); these maps indicate Crystal Lake's stage was about 7 ft higher than Fish Lake's stage in 1959 and 9 ft higher in 1974. Assuming a 9 ft difference in stage between Fish and Crystal Lake, Crystal stage would have been 868.8 ft above sea level with an area of 594 acres in 1999. Compared to 1974 the stage of Crystal Lake was about 4.8 ft higher in 1999 than in 1974 and area increased by about 72 acres.

The Fish Lake watershed area (1,344 acres), was determined by delineation on USGS topographic maps and field verified by USGS personnel in 1991. The Crystal Lake watershed area is 3,697 acres (fig. 1) as delineated on the 1975 USGS topographic maps and field verified (Richard Lillie, Wisconsin Department of Natural Resources, oral commun., 2001).

The hydrologic budget of the lakes can be described by the following equation:

$$\Delta S = P + SW_{in} - E - (GW_{out} - GW_{in}), \qquad (1)$$

where

ΔS is the change in lake storage,
P is precipitation falling directly on the lake,
SW_{in} is surface-water runoff into the lake from overland flow,
E is water evaporated from the lake surface, and
$(GW_{out} - GW_{in})$ is net ground-water seepage, or ground-water seepage out of the lake minus ground-water seepage into the lake.

Each budget component was determined independently for the 1-year period, November 1, 1990 to October 31, 1991. The results of this part of the study are discussed later (table 1) but it should be noted here that the results underscore the importance of ground-water flow to lake stage and support the assumption that the lakes are well connected to the ground-water system.

Study Methods

The water-budget components for Fish Lake for the November 1, 1990 to October 31, 1991 period were determined as follows. Change in lake storage (ΔS) was determined from data obtained at a continuously recording lake-stage gage. Precipitation (P) was measured by use of an automatic-recording rain gage, and augmented by manually measured precipitation at a site near the southwestern side of the lake. Evaporation (E) was estimated from evaporation-pan data from a weather station near Arlington, Wisconsin, in conjunction with lake/pan evaporation coefficient of 0.8. An analysis of lake-stage recession rates during periods of no precipitation and surface runoff was used to estimate net ground-water seepage ($G_{out} – G_{in}$). Surface water runoff (SW_{in}) was determined by a storm-by-storm water mass-balance using equation (1) for the duration of precipitation and storm runoff, and calculating (SW_{in}) as the residual in equation (1) with all other components measured or estimated.

Table 1. Measured and simulated annual hydrologic budget components for Fish Lake, Dane County, Wisconsin

[Units are feet of water on the lake surface]

Component: ΔS, change in lake storage; P, precipitation falling directly on the lake; SW_{in}, surface-water runoff into the lake from overland flow; E, water evaporated from the lake surface; ($GW_{out} – GW_{in}$), net ground-water seepage, or ground-water seepage out of the lake minus ground-water seepage into the lake.

Component (steady state)	Measured[1]	Simulated
ΔS	-0.02	0.0
SW_{in}	.88	.92
P	2.84	2.67
E	2.10	2.50
GW_{out}-GW_{in}	1.64	1.08 (GW_{out} = 1.52; GW_{in} = 0.44)

[1] Measured values are for the period November 1990 through October 1991.

Meteorological data were obtained from weather stations in Prairie du Sac, Madison, Baraboo, and Arlington, Wis. for assessment of trends in precipitation and other model input for the area in the vicinity of the lakes. Trends in precipitation, snowfall and baseflow were determined using linear regression. Daily values (1966 to 1998) of precipitation from Prairie du Sac and daily pan evaporation for non-freezing periods from the Arlington Experimental Station were used in model simulations. Daily evaporation from the lake surfaces was estimated using the daily pan evaporation data multiplied by a typical lake/pan coefficient (0.8) for Wisconsin (Chow, 1964). Average values of the years 1966–98 were used as input to model the steady-state simulations.

Runoff coefficients for the Fish Lake watershed were estimated for the period November 1, 1990 to October 31, 1991, using measured precipitation and calculated surface runoff values. These coefficients were determined for selected hydrologic periods as follows: Winter, December–March, 0.12; Spring, April–June, 0.06; Summer, July–September, 0.03; Fall, October–November, 0.07. The coefficients were assumed to be representative of coefficients for both the Fish and Crystal Lake watersheds.

A flux target for the ground-water model was obtained using 11 miscellaneous streamflow measurements collected during the period 1962–76 for Spring Creek at Lodi. This target was estimated by correlating these flow measurements to two nearby stream-gaging stations, Black Earth Creek at Black Earth and the Baraboo River near Baraboo. By estimating Q_{80} and Q_{50} flow durations for these continuous-record stream-gaging stations an estimate of the Q_{80} and Q_{50} flow durations for Spring Creek at Lodi was made. Flow duration refers to the portion of time a given flow is exceeded. For example, the Q_{80} flow is the flow that is exceeded 80 percent of the time. Baseflow, the portion of streamflow due to ground-water discharge is assumed to fall between the Q_{50} and Q_{80} flow duration (Krohelski and others, 2000).

Baseflow at the Black Earth Creek at Black Earth stream gaging station was estimated with a baseflow separation program (White and Sloto, 1990). Briefly, the program determines if a daily discharge is the lowest in a given time interval. If the daily discharge meets the interval criteria, it is connected by straight lines to adjacent local minimums. The baseflow discharge values for each day between local minimums are calculated by using the slope of the connecting line. Based on the daily baseflows, an annual average for baseflow then can be calculated.

The recently completed Dane County hydrologic study and ground-water flow model (Krohelski and others, 2000) provided the framework for development of a computer model that couples the lakes to the ground-water system. The model provides the tool to simulate the possible effects of pumping water from Fish Lake on future lake stages. A new lake package, LAK3, (Merritt and Konikow, 2000), developed for the USGS ground-water flow model computer code (MODFLOW) (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996; and Harbaugh and others, 2000), was used to simulate Fish, Mud and Crystal Lakes. The lake package can calculate changes in lake stage caused by variations in water-budget components including ground-water flow. The lake package requires the input values of precipitation, evaporation and runoff along with the morphometry of the lakes and lakebed leakance (leakance is defined as lakebed hydraulic conductivity divided by thickness). Discretization of the lakes to the ground-water flow model grid was based on bathymetric maps (Fish and Mud Lakes, Wisconsin Department of Natural Resources, 1991; Crystal Lake, Elizabeth Mergener, U.S. Geological Survey, written commun., 2000).

The parameter-estimation model UCODE (Poeter and Hill, 1998) was coupled to the steady-state ground-water-flow model. The UCODE model systematically varies model parameters until the differences between measured and model-calculated values of ground-water levels, stream flow and lake stage are minimized. A transient calibration in which a "best fit" (minimize the difference between simulated and measured values) to measured Fish Lake stage for the period 1966–98 was accomplished through trial-and-error. After calibration, the model was used in the transient mode to simulate the effects of hypothetical or proposed pumping on lake stages.

Acknowledgments

Richard Lillie (WDNR) recorded Fish Lake stage measurements. Without these measurements, the model used to simulate lake stage could not have been developed. Vincent Marx, local resident, measured precipitation at his residence near the lake from November 1990 through October 1991. Dale Robertson (USGS) provided the analysis of snowfall amount and its correlation to Black Earth Creek baseflow.

SIMULATION OF LAKE/GROUND-WATER SYSTEM

The steps involved in developing the three-dimensional model are: (1) selection of aquifers and confining units, (2) designation of boundary conditions, (3) construction of the finite-difference grid, (4) assembly of input data (for example, aquifer and confining unit geometry, and hydraulic conductivities, recharge rate, and leakance of streams and lakes) and, (5) series of calibration runs until there is reasonable match between measured and simulated ground-water levels, and measured and simulated surface-water flows. The model development is discussed in more detail below.

Conceptual Model

Prior to simulating the ground-water system, a conceptualization of the system is essential because it forms the basis for model development. The conceptualization is a necessary simplification of the natural flow system because inclusion of all of the complexities of the natural system into a computer model is not feasible. Figure 2 shows a conceptualization of the shallow ground-water system in the vicinity of the lakes.

Three aquifers and one confining unit underlie the Dane County area (Bradbury and others, 1999). A shallow sand and gravel aquifer is made up of glacial and alluvial materials overlying the bedrock. Except in narrow alluvial valleys, the sand and gravel aquifer is thin or absent in western Dane County. The upper bedrock aquifer underlies the sand and gravel aquifer and overlies the Eau Claire confining unit. The upper bedrock aquifer is made up of Cambrian sandstone and dolomite. The Eau Claire confining unit is present throughout northwestern Dane County and effectively restricts flow between the deep sandstone aquifer and the shallow unconfined ground-water system. Because of the presence and lateral extent of this confining unit in the study area, the third aquifer, the lower sandstone aquifer, was not included in this study. The system above the Eau Claire confining unit has extensive interaction with the area lakes. To avoid unwarranted complexity in this study, these two aquifers (sand and gravel aquifer and the Upper Bedrock aquifer) were grouped and designated as the shallow aquifer and assumed to have similar hydraulic properties (fig. 2).

Ground water flows from areas of high elevation that generally are recharge areas, to areas with low elevation (fig. 2). Ground water flows into Crystal or Fish Lake on the upgradient side of the lakes. Ground water discharges to the ground-water system on the downgradient side of the lakes. The ultimate ground-water discharge area in the vicinity of the lakes is the Wisconsin River (fig. 2).

Precipitation and Ground-Water Recharge

Information on the amount of water added into the system is needed to simulate the nearly 9 ft increase in Fish Lake stage over the last 34 years (fig. 3). Although there is no trend in annual precipitation at Prairie du Sac, the closest precipitation station to the lakes (within 2 mi), positive trends do occur at other precipitation sta-

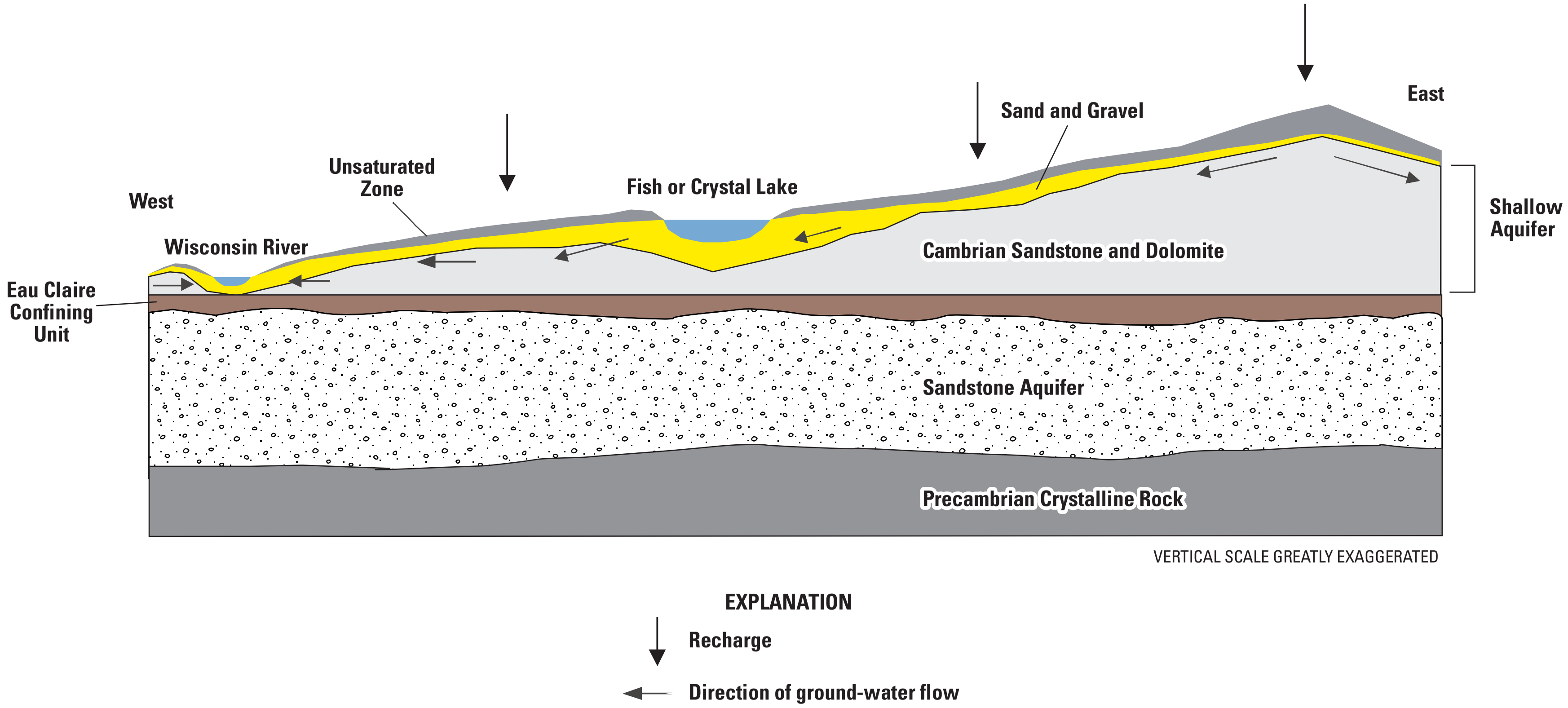


Figure 2. Conceptual model of the shallow ground-water/lake system, Dane and Columbia Counties, Wisconsin.

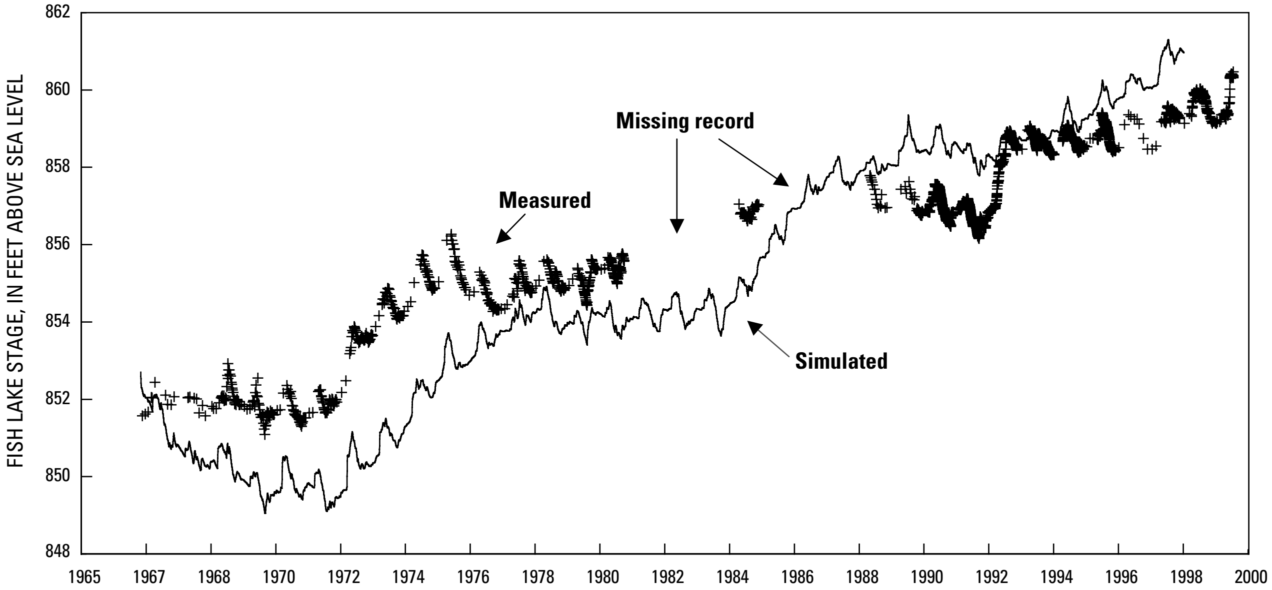


Figure 3. Measured (1966–2000) and simulated Fish Lake stage (1996–98), Dane County, Wisconsin.

tions such as Baraboo, Arlington and Madison that are located within 15 mi of the lakes (fig. 4). Depth to the water-table measured from land surface at Well IW-110 near Arena (fig. 1), which is approximately 17 mi southwest of Fish Lake, decreased about 5 to 6 ft over the same period of time that Fish Lake stage increased almost 9 ft (fig. 5). Significant increases in baseflow of various nearby streams have been documented (Gebert and Krug, 1996) during this period.

One of the closest stream-gaging stations to Fish Lake with an adequate period of record to estimate baseflow is Black Earth Creek at Black Earth (fig. 1), which is located approximately 11 miles southwest of Fish Lake. Baseflow at this station has increased about 30 percent since 1966 as shown by the regression line in figure 6. In the shallow unconfined ground-water-flow system there often is an excellent hydraulic connection between streams and ground water. The increase in Black Earth Creek baseflow has been attributed to increased ground-water seepage (Field and Graczyk, 1990). In order to increase ground-water seepage to a stream, ground-water recharge to the aquifer providing baseflow to the stream also must increase.

Recharge rates could increase by increasing the rate of infiltration or the amount of time infiltration takes place. Most recharge to the ground-water system takes place in the spring after frost leaves the ground but before evapotranspiration depletes soil moisture (Steuer and Hunt, 2001). A good correlation ($R^2 = 0.71$) results between the 5-year moving averages of baseflow at Black Earth Creek and snowfall at Madison (fig. 7), the closest weather station with available snowfall record. R^2, coefficient of determination, is an indicator that ranges from 0 to 1 and reveals how closely the estimated values for the trendline correspond to the actual data. A trendline is most reliable when its R^2 is at or near 1.

Generally, snowfall provides a source of recharge water and acts as an insulator against frost. It is postulated that during years with relatively more snowfall, more water is available for recharge over a longer period of time and the smaller amount of frost in the ground is expected to redistribute the snow water by reducing overland flow and increasing recharge to the ground-water system.

Model Assumptions and Development

A telescopic-mesh refinement of the Dane County ground-water-flow model (Krohelski and others, 2000), was used as a framework for the ground-water-flow model used to simulate the stage of Fish, Mud and Crystal Lakes (figs. 8A and B). As previously described, the sand and gravel and the upper bedrock aquifers, as defined in the Dane County ground-water-flow model, were grouped into a shallow aquifer and assumed to have similar hydraulic properties. For model simulations this shallow aquifer then was divided into two layers of equal thickness except under Fish, Mud and Crystal Lakes (fig. 8C). This division ensured that the

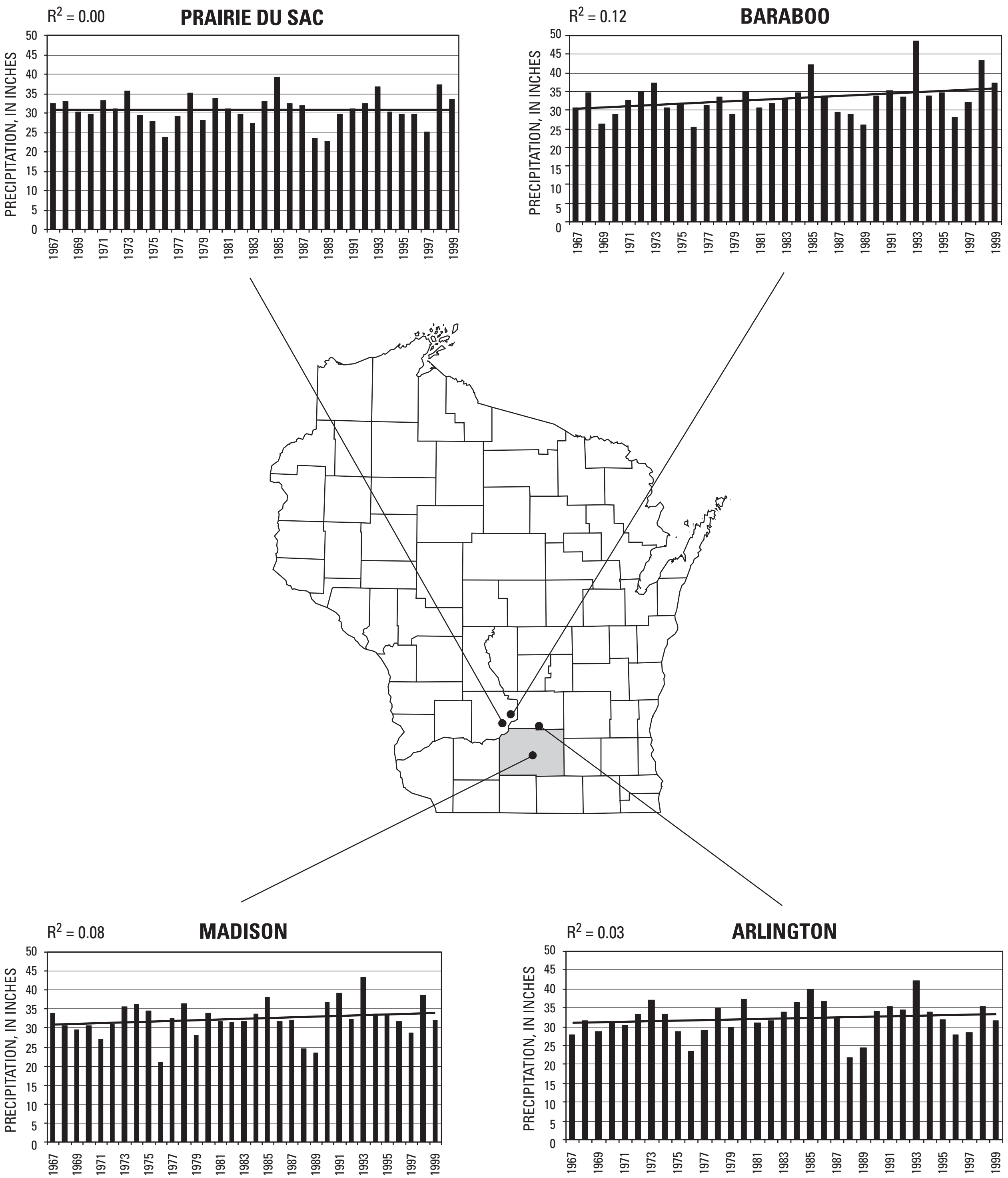


Figure 4. Average annual precipitation at Prairie du Sac and Baraboo—Sauk County, Madison—Dane County, and Arlington—Columbia County; Wisconsin, 1967–99. (Data are from Midwestern Climate Center, http://mcc.sws.uiuc.edu). [R^2, coefficient of determination, is an indicator that ranges from 0 to 1 and reveals how closely the estimated values for the trendline correspond to the actual data. A trendline is most reliable when its R^2 is at or near 1].

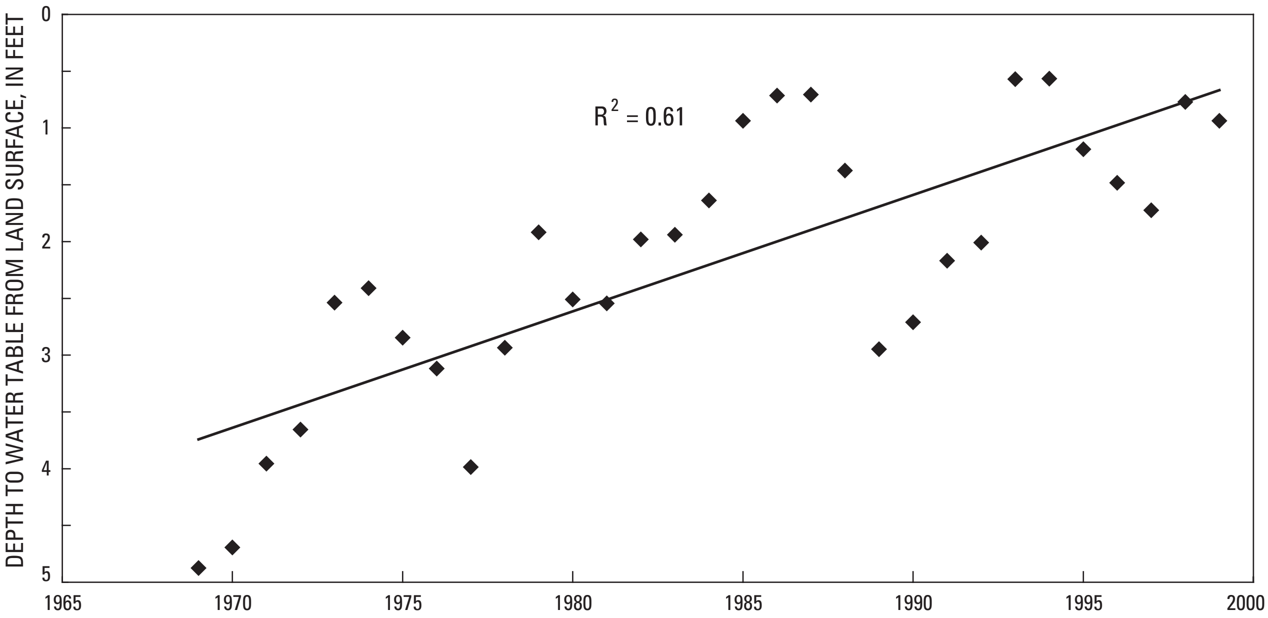


Figure 5. Depth to water table from land surface in well IW-110, 1966–99, Iowa County, Wisconsin.

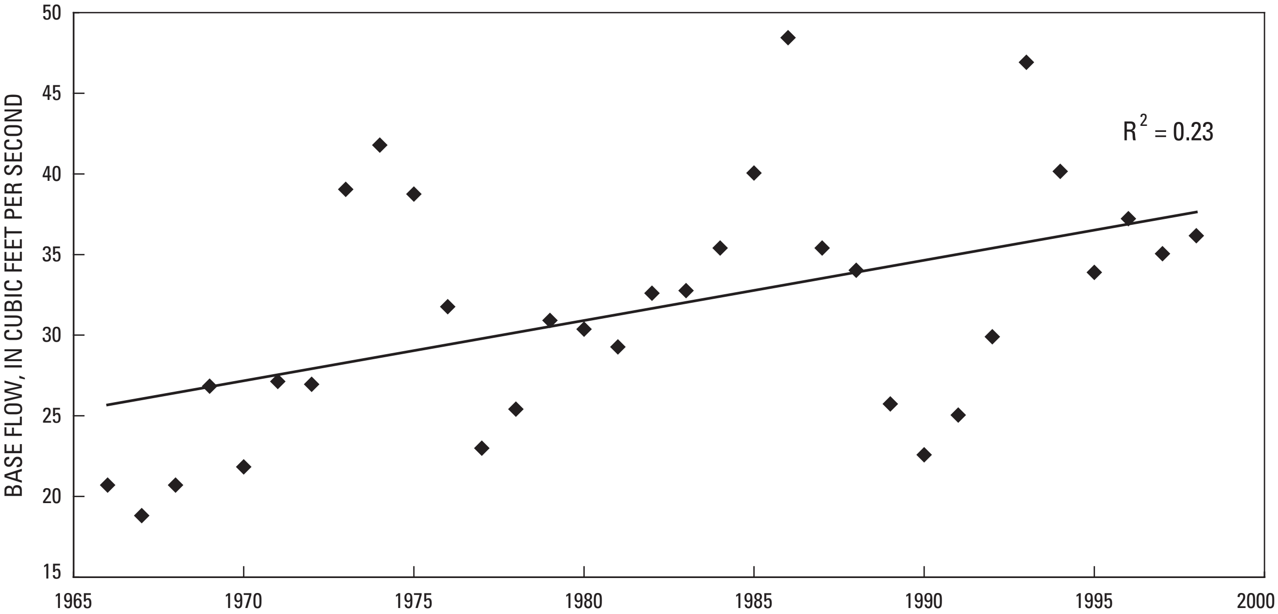


Figure 6. Black Earth Creek at Black Earth annual baseflow, 1966–98, Dane County Wisconsin.

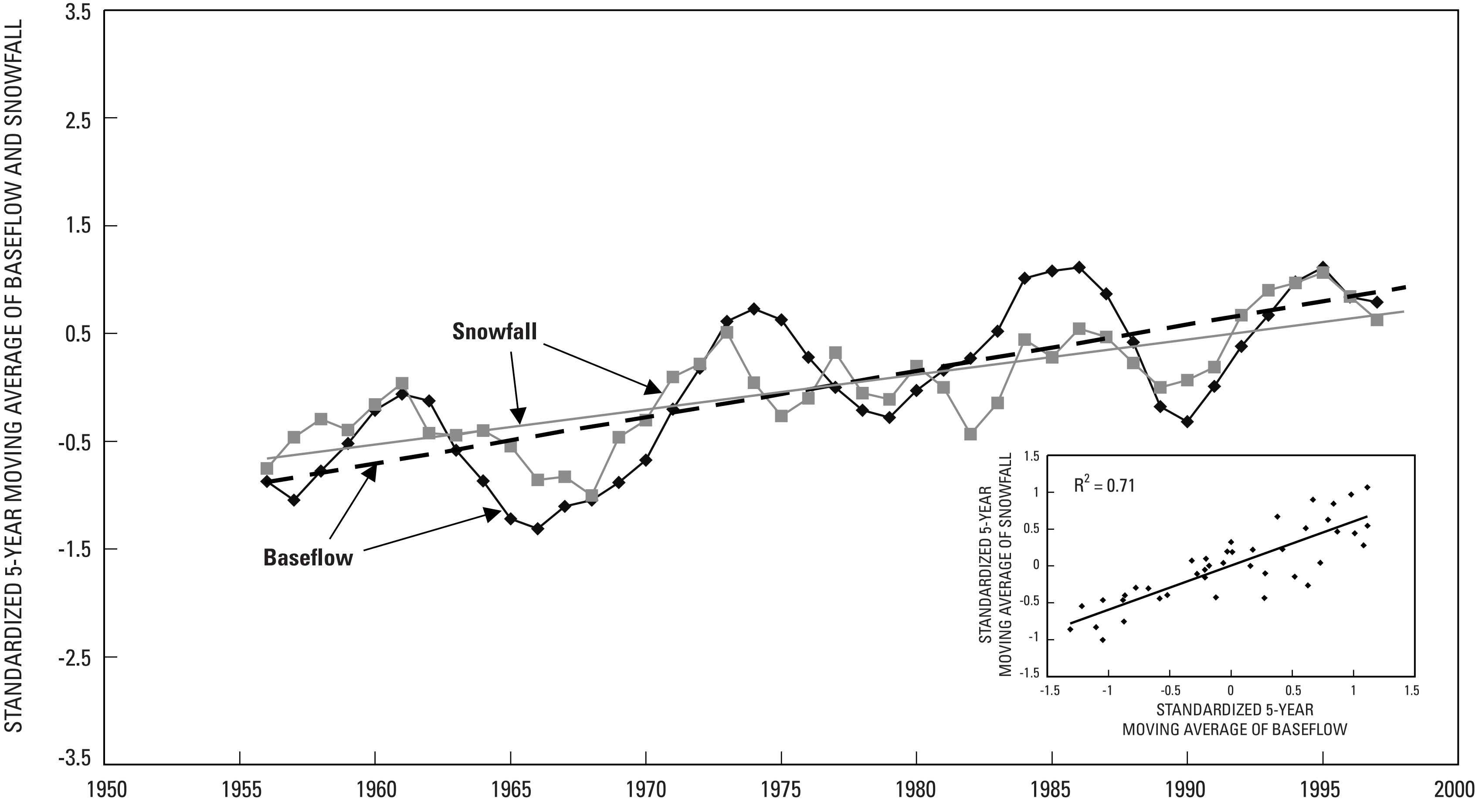


Figure 7. Standardized 5-year moving average of annual baseflow at Black Earth Creek at Black Earth and snowfall at Madison, Dane County, Wisconsin, by year and as a linear regression (inset graph). Standardized values were obtained by dividing the difference of a value and its mean by its standard deviation.

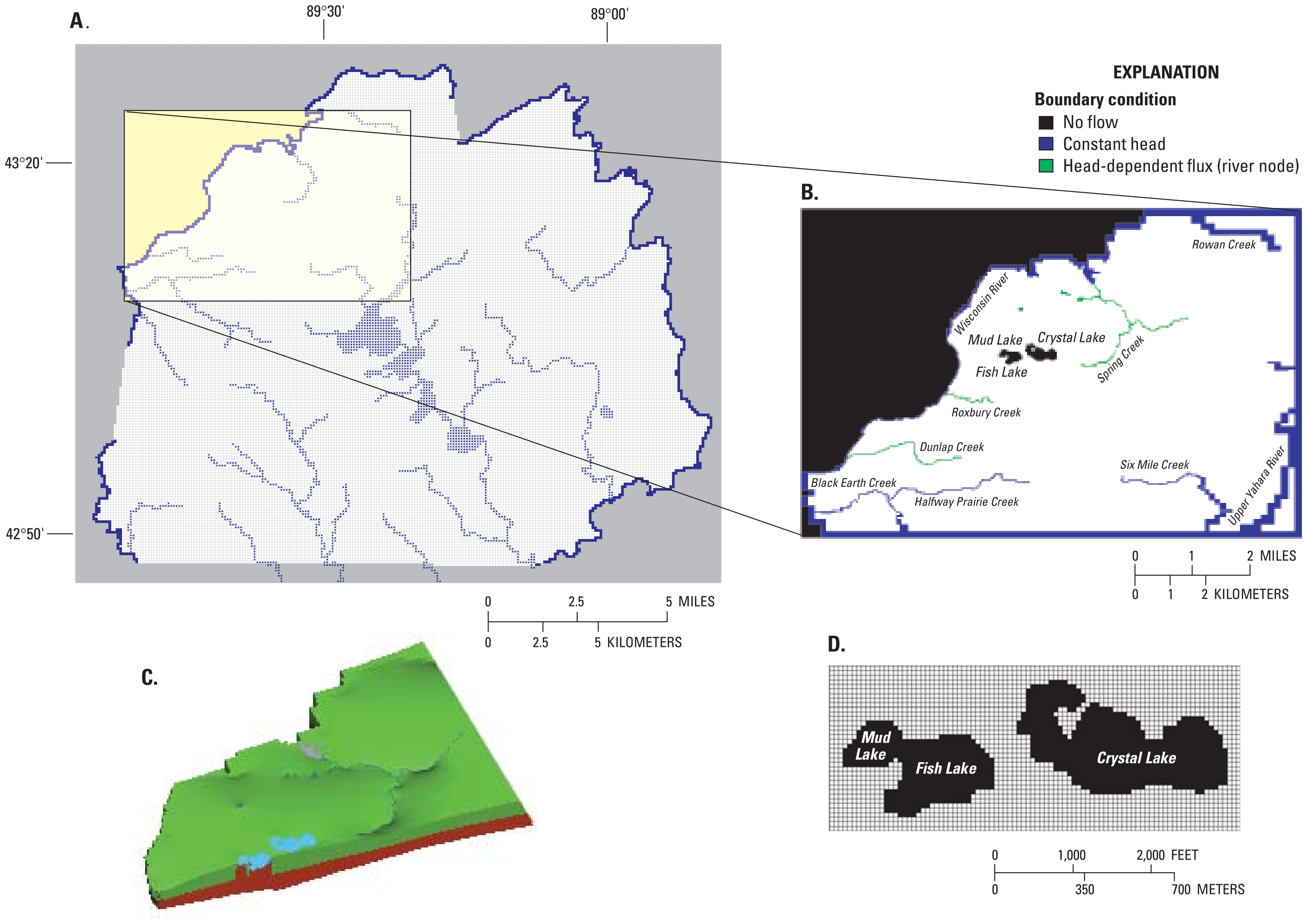


Figure 8. (A) Dane County, Wisconsin regional model grid, (B) Telescopic mesh refinement or local model area with boundary conditions, (C) Block diagram of a portion of the local model showing two model layers, and (D) Grid in the vicinity of the lakes showing a resolution of 200 feet on a side.

uppermost layer was not excessively thin and, therefore, would not dry out during simulation of a fluctuating water table; this formulation increased model stability. The division into two layers also allowed simulation of potential underflow beneath the lakes. The model nodes that represented the lakes are present only in layer one of the grid and were assigned “no flow” boundaries as required by the lake package.

Model Grid, Boundaries, and Runoff

The three-dimensional, finite-difference ground-water-flow model grid was subdivided into 386,232 nodes (363 rows, 532 columns, and 2 layers) of which 303,957 were active. Model nodes in the vicinity of the lakes were 200 ft on a side or slightly less than one acre in area (fig. 8D). The grid spacing was variable near the model perimeter. The 200-ft equal node spacing encompassed most of the major surface-water boundaries away from the model perimeter, including the Wisconsin River, Halfway Prairie Creek, Black Earth Creek, Six Mile Creek, and the Upper Yahara River.

A variety of boundary conditions were used (fig. 8B). The model area to the northwest of the Wisconsin River was considered “no flow”. This depiction represented the Wisconsin River as fully penetrating; thus, flow from north of this river did not affect flow in the area of the lakes. Model nodes in both layers representing the Wisconsin River and the model perimeter to the southeast of the Wisconsin River are constant head and were estimated based on the calibrated Dane County model (Krohelski and others, 2000). Surface-water features close to the lakes (Spring, Roxbury, and Dunlap Creeks) and various ponds are simulated using the river package, whereas surface-water features farther away from the lakes (Halfway Prairie Creek, Black Earth Creek, Six Mile Creek, and the Upper Yahara River) were considered constant-head nodes. The constant-head and river nodes were assigned to layer one with elevations based on USGS topographic maps (Lodi and Sauk City quadrangles, 1975). The upper model boundary was a specified-flux boundary, representing recharge to the ground-water system. For steady-state simulations (simulations in which flow into and out of the ground-water system is in equilibrium), one global value of recharge was applied to the highest active model cell. For transient simulation (simulations in which flow changes with time), recharge was varied annually using baseflow estimates from the stream gaging station at Black Earth Creek to formulate the appropriate recharge rate.

Surface-water runoff from the Fish and Mud and Crystal Lake watersheds contributed to these lakes, so was, therefore, entered into the lake package. For the steady-state model, a volume of runoff was estimated by multiplying an average precipitation rate for the period 1966–98 by watershed area by 0.07, an average runoff coefficient. For the transient simulations, runoff coefficients were grouped by hydrologic period (Winter, December–March, 0.12; Spring, April–June, 0.06; Summer, July–September, 0.03; Fall, October–November, 0.07), and then multiplied by watershed area and by the precipitation rate occurring during a transient stress period.

Model Calibration

The ground-water flow model was calibrated to both steady-state and transient conditions. In the steady-state calibration, ground-water levels and streamflow values were emphasized in order to estimate the hydraulic properties of the ground-water system. In the transient calibration, Fish Lake stage was emphasized to determine if reasonable changes in recharge could be responsible for the Fish Lake stage increase. In addition to the Fish, Mud and Crystal Lake stages, a set of 382 measured ground-water levels from driller’s well-construction reports were used for the steady-state calibration. Baseflow (Q_{80} and Q_{50}) for Spring Creek at Lodi were used to compare with model-calculated values. The Q_{50} and Q_{80} flow durations for Spring Creek at Lodi were estimated to be 18 ft^3/s and 17 ft^3/s, respectively. An optimum steady-state calibration was achieved by coupling the ground-water flow model to UCODE. The model was also calibrated to transient conditions using approximately 2,500 daily Fish Lake stage measurements from 1966 to 1998. The transient calibration was a trial-and-error “best fit” of measured Fish Lake stage to simulated stage. Details of these calibrations are described below.

Steady-State Calibration

UCODE automatically calculates parameter values (for example, hydraulic conductivity) that are a quantified best fit between simulated model output and data measured in the real world (for example, ground-water level, stream baseflow). Also, parameter correlation (for example, hydraulic conductivity to recharge) and parameter sensitivity can be quantified and assessed.

One of the most important operations in parameter estimation is the selection of observations and associated weight given to these observations in the optimization routine. The weights were input as standard deviations, which means that the higher the value is, the less emphasis is placed on fitting measured to simulated values for the calibration targets. Fish, Mud and Crystal Lake stages were given weights of 0.125, which represents a 95-percent confidence interval of plus-or-minus 0.25 ft around the observed value. Ground-water levels obtained from 382 driller's well construction reports were given weights of 20 ft and the average of the Q_{50} and Q_{80} flow durations for Spring Creek at Lodi (17.4 ft^3/s) was given a weight of 0.1 ft^3/s. Therefore, lake stage and streamflow for Spring Creek at Lodi were the most emphasized and important calibration targets.

Results from UCODE were used to determine the correlation and sensitivity among horizontal hydraulic conductivity, recharge and lake bed leakance. UCODE results indicate a strong correlation ($R^2 = 0.83$) between recharge and hydraulic conductivity. Both the recharge rate and hydraulic conductivity were very sensitive to model results, whereas lake bed leakance was insensitive. The best fit determined by UCODE indicated a hydraulic conductivity of 27.8 ft/d for the aquifer and 5.5 in/yr for the baseline recharge rate, that is, the recharge rate for the period used to estimate the Q_{50} and Q_{80} flow durations (1962–76). The water-table configuration using these optimized parameter estimates and a graph showing simulated to measured values of ground-water levels are shown in figures 9 and 10, respectively. Unweighted statistics for the calibrated model comparing measured and simulated values of the calibration targets had an average difference of -10.6 ft, a mean absolute difference of 18.5 ft and a root mean square difference of 27.2 ft. The streamflow in the Spring Creek at calibration was 17.3 ft^3/s. The mass-balance error for the steady-state calibration was close to zero. Simulated steady-state budget components for Fish Lake (table 1) compared favorably to measured and estimated for 1991.

Transient Calibration

A transient calibration was obtained through a trial-and-error comparison of measured Fish Lake stage to simulated stage. The same perimeter and head-dependent flux boundary conditions and hydraulic parameters used in the steady-state model were used in the transient model. The objective of the transient calibration was to match the trend in Fish Lake stage for the period 1966–98. Initial conditions (starting heads) for the transient run were from the calibrated steady-state model. The transient calibration used recharge rates that varied annually and were equal to 80 percent of baseflow. A recharge rate of less than 100 percent of baseflow is reasonable because it is likely a portion of baseflow does not represent global recharge. For example, baseflow because of bank storage and short ground-water flow paths will reduce the amount of baseflow that can be attributed to global recharge.

The transient simulation consisted of 1,958 6-day periods (about 32 years total time). Starting in 1966, precipitation, runoff and evaporation were totaled for each 6-day period and applied to Fish, Mud and Crystal Lakes. Recharge was estimated and varied annually and ranged from 4.6 in/yr to 9.7 in/yr. No adjustments were needed to runoff coefficients or any other model parameters from the steady-state calibration to achieve a satisfactory transient calibration. The transient calibration was accomplished visually and was not statistically based. The mass-balance error for each period of the transient simulation was near zero.

The transient calibration resulted in the simulated Fish Lake stage being lower than the measured lake stage early in the simulation but higher than the measured lake stage late in the simulation (fig. 3). The measured simulated stages were very close to one another during the mid-1970s and mid-1990s. The model is a simplification and is meant to approximate the actual lake/ground-water system. Therefore, the model cannot reproduce the measured lake stage exactly.

SIMULATED EFFECTS OF WITHDRAWING FISH LAKE WATER ON LAKE STAGES

The calibrated transient model was used to simulate the effects of withdrawing lake water on lake stages. If the other lake hydrologic budget components remain the same as during the 1990s, withdrawing lake water is expected to lower the stages of all the lakes. After withdrawal ceases the lake levels are expected to recover relatively quick because the lakes are hydraulically connected to the ground-water-flow system and the prior stress from pumping will be offset by ground-water flow from the aquifer.

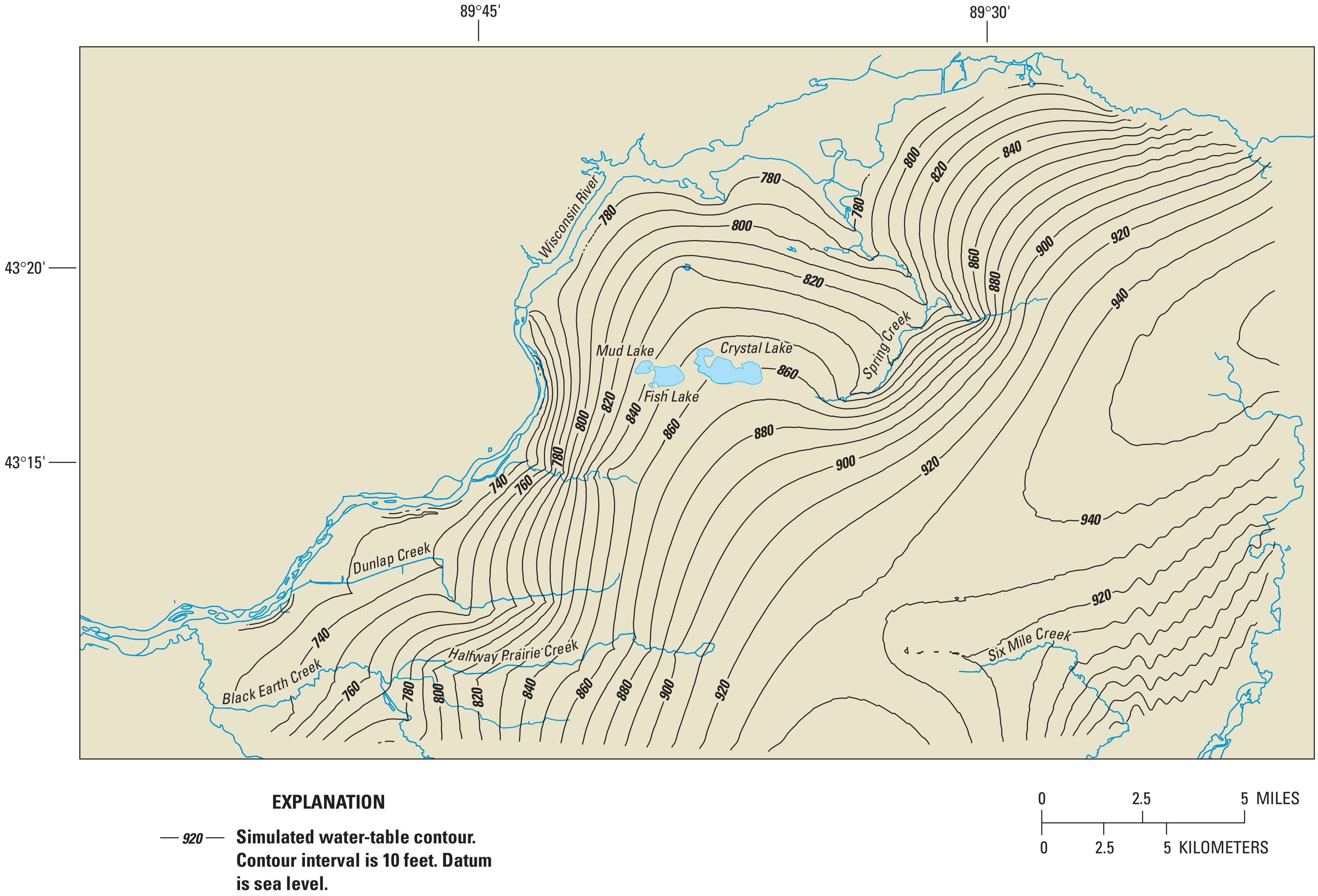


Figure 9. Calibrated steady-state water table configuration, Dane and Columbia Counties, Wisconsin. FIsh and Mud Lake stage is 853.07 feet above sea level and Crystal Lake is 865.44.

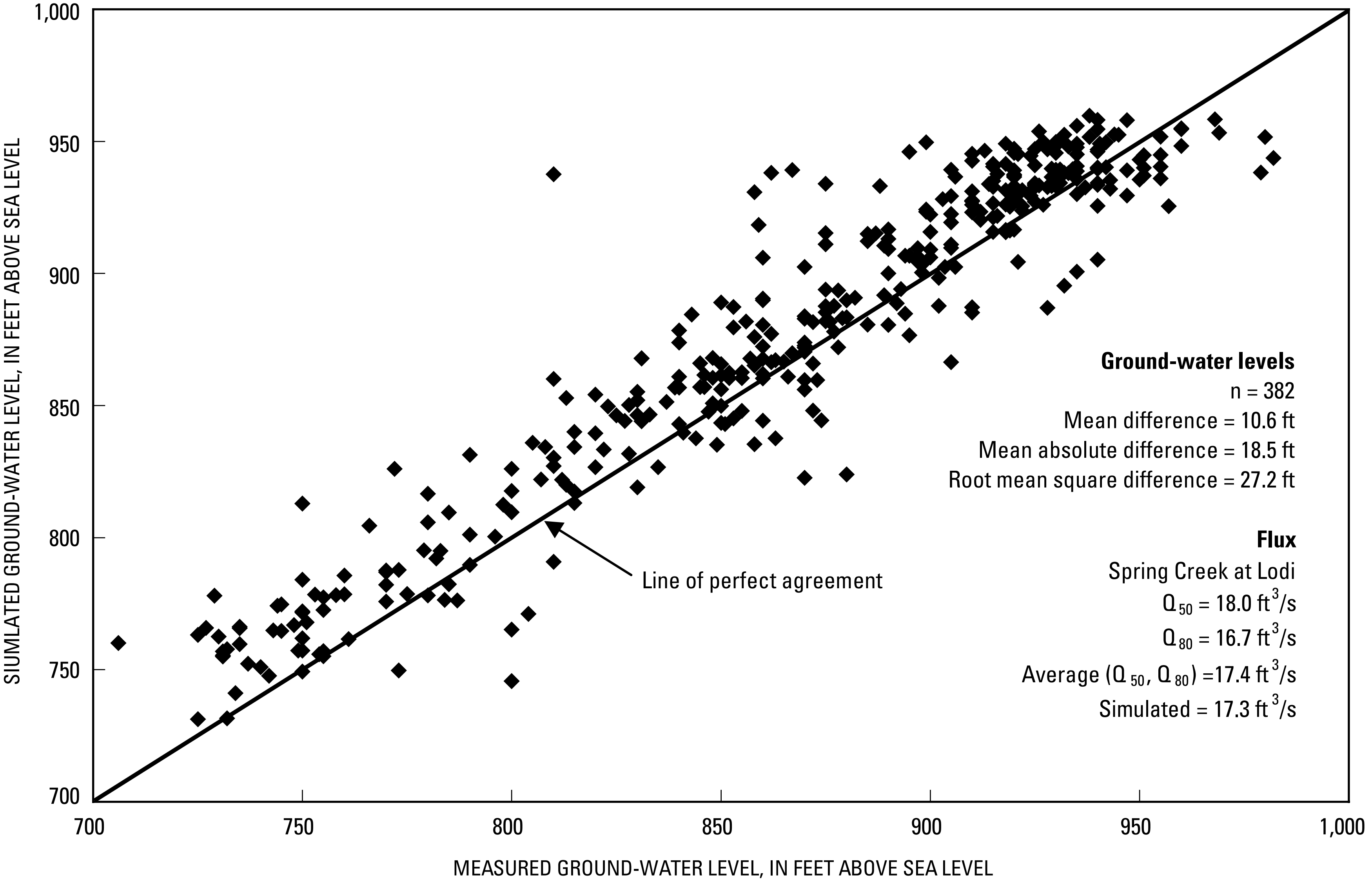


Figure 10. Steady state simulated and measured ground-water levels, Dane and Columbia Counties, Wisconsin.

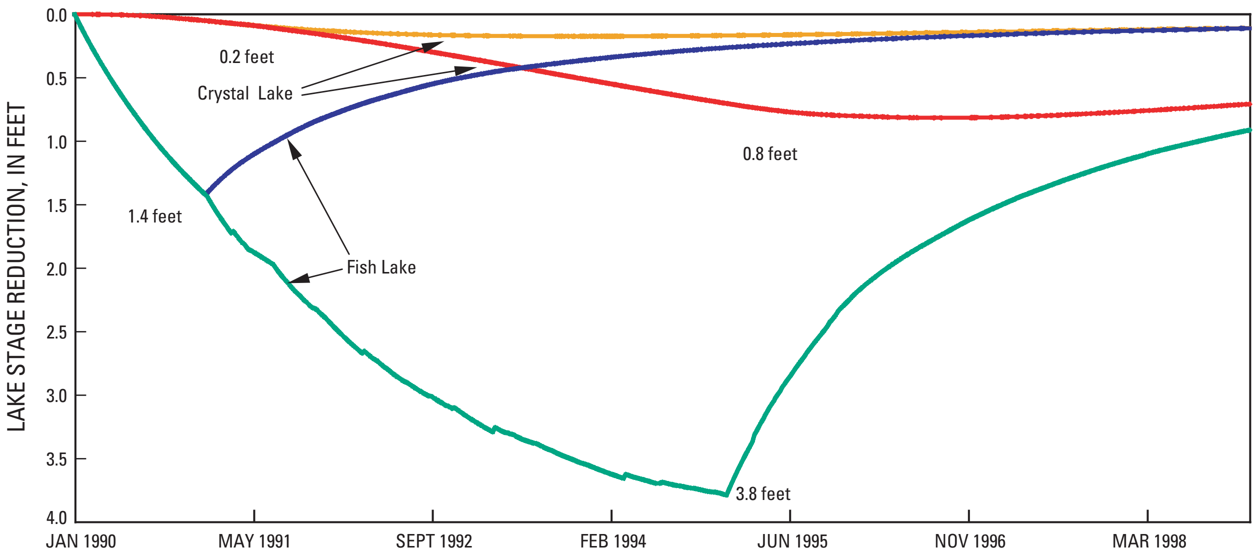


Figure 11. Simulated lake-stage reduction by withdrawing 500 gallons per minute from Fish Lake, Dane County, Wisconsin, 1990–98.

Two simulations using the transient-model input were performed. In both, water was withdrawn at 500 gpm from Fish Lake starting January 1, 1990 (fig. 11, table 2). Both simulations end on December 31, 1998. The simulations were started in 1990 because the stage during this period was high enough to cause concern over flooding of roads and some near-shore residences. In the first simulation, water was withdrawn for one year followed by 8 years of recovery. In the second simulation water was withdrawn for 5 years followed by 4 years of recovery.

Table 2. Simulated Fish, Mud, and Crystal Lakes stage reduction, in feet, due to withdrawing Fish Lake water at 500 gallons per minute for 1 year (simulation 1) and 5 years (simulation 2) starting January 1, 1990. Total simulation time is 8 years.

	Simulation 1	**Simulation 2**
Simulation period	1/1/90 to 12/31/98	1/1/90 to 12/31/98
Fish and Mud Lakes		
Withdrawal period	1/1/90 to 12/31/91	1/1/90 to 12/31/94
Maximum reduction	1.4 (12/29/90)	3.8 (12/26/94)
Reduction at simulation end	0.1 (2/17/93)	0.9 (12/31/98)
Crystal Lake		
Maximum reduction	.2 (12/31/98)	.8 (6/20/96)
Reduction at simulation end	.1 (12/31/98)	.7 (12/31/98)

Simulation 1 (1 year pumping and 8 years recovery) results indicated that Fish Lake stage would be 1.4 ft lower after one year of pumping. Pumping from Fish Lake also lowered Crystal Lake stage. Crystal Lake had a maximum decline of about 0.2 ft, however, it occurred about 2 years after pumping from Fish Lake ceased (fig. 11). This results because it takes almost 5 months for any effect of pumping Fish Lake to be conveyed through the ground-water system to Crystal Lake. The water table in the vicinity of Crystal Lake must be lowered to reduce lake stage. After pumping ceased for 1 year Fish Lake stage recovered within 0.8 ft of the pre-pumping stage and within 0.5 ft after 2 years. At the end of simulation 1, both Fish and Crystal Lakes were within 0.1 ft of pre-pumping levels.

Simulation 2 (5 years pumping and 4 years recovery) results indicated that Fish Lake stage would be 3.8 ft lower after 5 years of pumping and Crystal Lake would be a maximum 0.8 ft lower two years after pumping ceased. At the end of simulation 2, Fish Lake would be 0.9 ft lower and Crystal Lake would be 0.7 ft lower than pre-pumping levels. Additional scenarios based on pumping or other management plans can be simulated with the model.

SUMMARY

The stage of Fish Lake located in northwestern Dane County, Wis., has risen about 9 ft since 1966 causing flooding of roads and some near-shore residences.

In 2001, the U.S. Geological Survey, in cooperation with the Dane County Lakes and Watershed Commission and the Wisconsin Department of Natural Resources, completed a 2-year study that described the hydrology of Fish, Mud and nearby Crystal Lakes, their watersheds, and their relation to the shallow groundwater system. As part of the study, a model was developed to simulate the effect of pumping water from Fish Lake on future lake stages.

MODFLOW and the new LAK3 package were used to develop steady-state and transient ground-water flow models to simulate the interaction of Fish, Mud, and Crystal Lakes with the shallow ground-water flow system. The steady-state model was based on the previously developed Dane County regional model, although simplifying assumptions were made to stabilize the model solution and allow underflow beneath the lakes. Optimal parameters of recharge and hydraulic conductivity were estimated using the steady-state model and a parameter-estimation model (UCODE). Calibration targets for the steady-state model consisted of groundwater levels, streamflow and lake stages at these lakes. The steady-state model was calibrated satisfactorily using average climate conditions for the period 1966–98. The transient model was calibrated satisfactorily using an annual recharge rate equal to 80 percent of baseflow of Black Earth Creek, measured runoff coefficients and climate data (precipitation and evaporation) from nearby weather stations. The transient model was calibrated to Fish Lake stage for the period 1966–98.

After the models were calibrated, the transient model was used to simulate the hydrologic effects of withdrawing Fish Lake water over time. Simulation results indicate that withdrawing Fish Lake water would lower the stage of the lakes; however, without near-continuous withdrawal the lake stages should recover in a few years.

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