SIMULATION OF STAGE AND THE HYDROLOGIC BUDGET OF DEVILS LAKE, SAUK COUNTY, WISCONSIN

By J.T. Krohelski and W.G. Batten

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To Obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square foot (ft^2)	0.09290	square meter
cubic foot (ft^3)	0.02832	cubic meter
square mile (mi^2)	2.590	square kilometer
acre	4.047×10^{-3}	square kilometer
acre-foot (acre-ft)	1,233	cubic meter
foot per day (ft/d)	731.52	centimeter per second
gallon per minute	5.4505	cubic meter per day
gallon per minute	192.5	cubic foot per day
cubic foot per month (ft^3/mo)	0.02832	cubic meter per month

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.

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Abstract

Water clarity of Devils Lake, in the Driftless Area of southwestern Wisconsin, has been decreasing because of blue-green algal blooms. An understanding of the hydrology of Devils Lake is needed to develop a mitigation plan to reduce phosphorus input. A model was developed to test the current understanding of the hydrology of the lake including stage and hydrologic budget and to estimate the effects of proposed mitigation plans on lake stage.

Daily lake stage was simulated in the model by summing estimates of hydrologic-budget components. The Devils Lake hydrologic-budget components are precipitation on the lake surface, evaporation from the lake surface, runoff (consisting of overland flow to the lake and an intermittent stream flowing into the lake), and ground-water flow into and out of the lake.

The model was calibrated to measured lake stage for the period 1980-92. Simulated stage compares reasonably well with historical stage data for Devils Lake. The root mean square of the differences of simulated and measured daily lake stages for the period 1980-92 is 0.83 foot. Simulated lake stage is very sensitive to small changes in runoff and evaporation coefficients, and ground-water-flow rates used in the model.

The average model-calculated annual amounts of each hydrologic-budget component for the 1980-92 simulation period, in order of increasing volume, are evaporation (791 acre-feet), precipitation (973 acre-feet), runoff (1,107 acre-feet), and net ground-water flow, which is out of the lake (1,323 acre-feet).

Three mitigation plans were simulated. Mitigation plan 3, which includes the addition of water from a basin adjacent to the northeastern side of the Devils Lake Basin, allows for withdrawals of hypolimnetic water and maintaining lake stage closer to optimal levels than would result without mitigation.

INTRODUCTION

Devils Lake State Park is one of the most heavily used State parks in Wisconsin. Water clarity of Devils Lake has been decreasing because of blue-green algal blooms that develop during late summer and early fall. Phosphorus released from anoxic hypolimnetic sediments fuels these blooms as the enriched bottom water mixes with surface waters during destratification. An understanding of the hydrology of Devils Lake is needed to develop a mitigation plan to reduce this internal cycling of phosphorus. One approach being evaluated by the Wisconsin Department of Natural Resources (WDNR) is late-summer withdrawal of phosphorus-rich water from the bottom of the lake (hypolimnion) over a multiyear period (Wisconsin Department of Natural Resources, 1988).

In addition to an understanding of the hydrology, an analysis is needed to estimate changes in lake stage caused by proposed withdrawals of water from the lake and variations in hydrologic-budget components. A model can be used to test the current understanding of the hydrology and may be useful in assessing the effect of future-proposed mitigation plans on long-term lake stage.

A study to address the above needs began in October 1991. The study was conducted by the U.S. Geological Survey (USGS) in cooperation with the WDNR and the town of Baraboo.

Two previous studies (Wisconsin Department of Natural Resources, 1988; Dickrell, 1991) have addressed the hydrology of Devils Lake. During 1986-87, seepage meters were used to estimate nutrient loading from ground-water flow into the lake. The seepage-meter data indicated that the amount of ground-water inflow and the location of ground-water-inflow areas are highly variable (Wisconsin Department of Natural Resources, 1988). Dickrell (1991) estimated net ground-water flow by use of a hydrologic-budget approach. Hydrologic-budget components were estimated or measured, and net ground-water flow was calculated as a residual. Dickrell estimated net ground-water flow to be -5.1×10^6 and -4.4×10^6 ft^3/month (approximately 0.01 ft/d net ground-water flow from the lake), respectively, for spring and fall 1988.

Purpose and Scope

This report presents the results of the study of the hydrology of Devils Lake. Specifically, the report describes the development and application of a computer model to estimate changes in lake stage due to variations in hydrologic-budget components. Although the report is not meant to be a rigorous presentation of a hydrologic budget, a hydrologic-budget modeling approach was used because the long record of lake-stage data provides an opportunity for calibration of a model. The calibrated model was then used to simulate long-term lake-stage variations caused by withdrawal or addition of water.

Location and Physical Setting

Devils Lake is in the Driftless Area of southwestern Wisconsin, about 3 mi south of the city of Baraboo (fig. 1). The lake has an area of approximately 365 acres, a maximum depth of about 50 ft, and a drainage area of 3.24 mi^2. An intermittent stream flows into the lake from the southwest. No streams flow from the lake. The lake is bounded on the eastern and western shores by steep talus slopes of boulder-sized Precambrian quartzite, and on the northern and southeastern shores by gently sloping beach areas underlain by glacial, fluvial, and lacustrine sediment (Attig and others, 1990).

HYDROLOGIC-BUDGET COMPONENTS OF DEVILS LAKE

The hydrologic budget of Devils Lake can be described by the following components:

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

where

ΔS is change in lake storage,
P is precipitation falling directly on the lake,
RO is stream inflow and overland runoff into the lake,
E is water evaporated from the lake surface, and
$GW_{out\text{-}in}$ is net ground-water flow.

The sum of the hydrologic-budget components determines the change in lake storage (ΔS). If the sum is positive there will be a corresponding increase in lake storage which results in an increase in lake stage, area, and volume. The opposite results if the sum is negative. Regression equations, based on the relationship between lake stage, area, and volume (table 1), were developed from a bathymetric map. The equations were used to calculate lake stage from a calculated lake area or volume and to calculate lake area from a calculated lake stage (Appendix 1).

Historical climate data were obtained from nearby weather stations (Arlington and Baraboo, Wis.). Additional lake-stage, precipitation, and ground-water-level data from a gaging station installed during this study on the northeast shore of Devils Lake also were obtained. Historic measurements of lake stage (January 1980-July 16, 1991) were made by employees of Devils Lake State Park. In addition, eight piezometers were installed around the perimeter of the lake to determine the

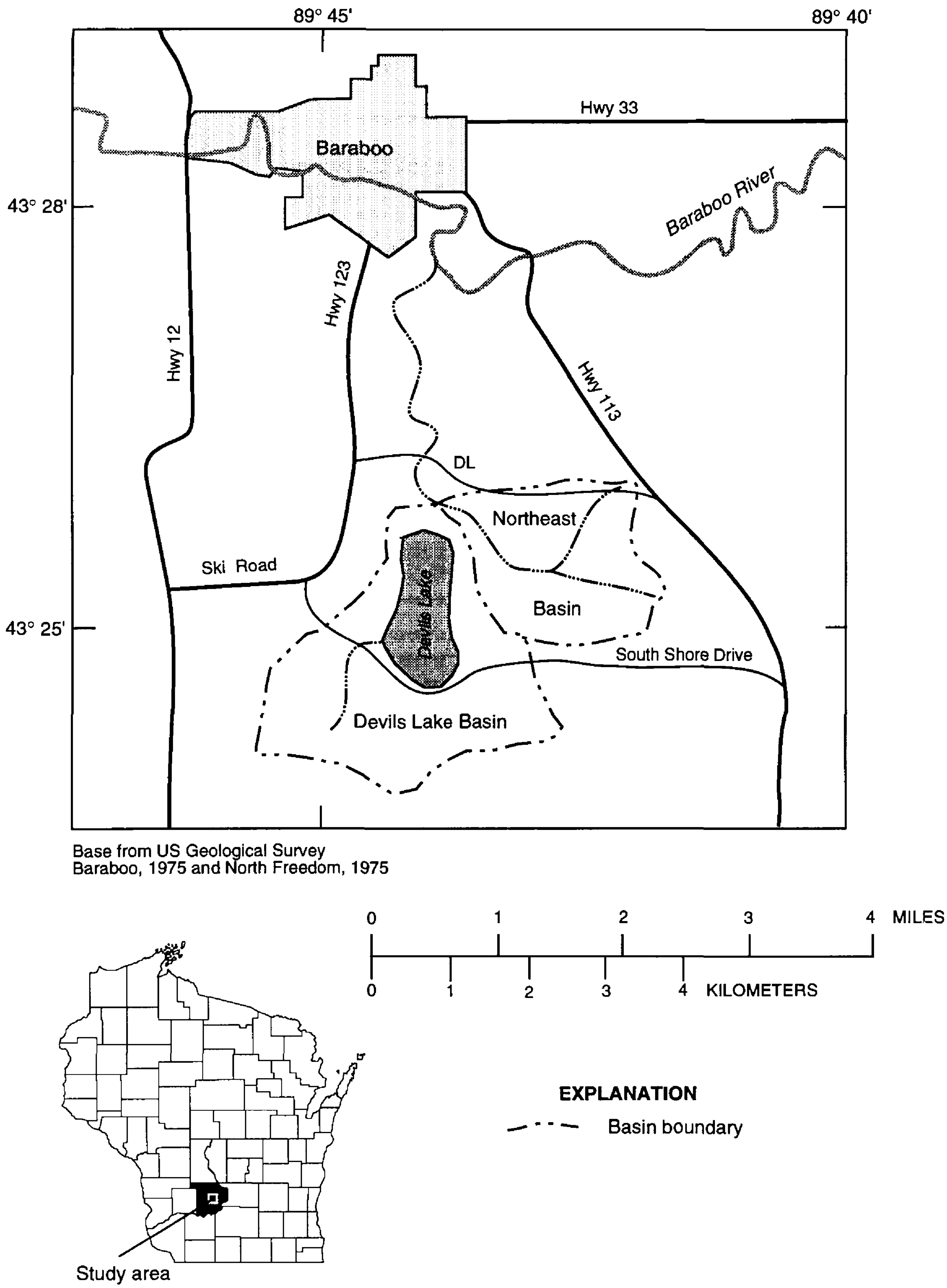

Figure 1. Location of Devils Lake and surrounding area, Wisconsin.

distribution of ground-water inflow and outflow areas.

Precipitation (P) data were obtained from the Baraboo weather station (January 1, 1980-July 16, 1991) and from the Devils Lake gaging station (July 17, 1991-September 30, 1992). The Baraboo weather station is approximately 3.25 mi north of Devils Lake.

Table 1. Stage, area, and volume, Devils Lake, Wis.

Stage (feet above sea level)	Area (square feet)	Volume (cubic feet)
963	15,920,000	484,890,000
960	15,270,000	438,110,000
958	14,480,000	408,360,000
953	13,220,000	339,130,000
948	12,730,000	274,260,000
943	12,280,000	211,740,000
938	11,640,000	151,950,000
933	10,680,000	96,170,000
928	7,500,000	50,950,000
923	5,330,000	19,030,000
918	2,010,000	1,340,000
916	0	0

Stream inflow and overland runoff and interflow into the lake were estimated by multiplying the lake-drainage area by precipitation and multiplying that product by a runoff coefficient (C_{RO}). Calculation of runoff coefficient for a single storm was as follows:

$$C_{RO} = (\Delta S - P \times A + E + GW_{net})/(P \times DA),$$

where ΔS is change in lake storage, P is precipitation, A is lake area, E is evaporation, GW_{net} is net ground-water flow, and DA is the lake drainage area. From these calculations (table 2), a single average runoff coefficient of 0.21 was estimated. The increase in lake volume resulting from a single storm was then calculated by relating the change in lake stage to lake volume.

Evaporation (E) from the lake surface was estimated by use of pan-evaporation data obtained from the Arlington weather station (not shown), approximately 20 mi southeast of Devils Lake. The pan-evaporation data for January 1, 1980 through September 30, 1992, were multiplied by a typical lake/pan coefficient for Wisconsin, to estimate evaporation from the lake surface (Chow, 1964, p. 11-9).

Table 2. Net change in lake volume due to runoff, precipitation, and runoff coefficients for selected periods, Devils Lake, Wis.

Period (year/month/day)	Net change in lake volume due to runoff (cubic feet)	Precipitation (inches)	Runoff coefficient
92/05/11-92/05/12	770,000	0.81	0.12
92/04/08-92/04/11	1,690,000	.82	.27
92/04/15-92/04/16	1,070,000	.97	.15
91/11/16-91/11/17	1,380,000	.85	.54
91/11/22-91/11/23	1,230,000	1.09	.22
91/11/27-91/11/29	460,000	.72	.08
91/12/08-91/12/12	1,380,000	1.90	.10
		Average	.21

Ground-water inflow and outflow areas were determined from eight piezometers installed around the northern and southern edges of the lake (fig. 2). Large pieces of quartzite covering the lake bottom along the eastern and western edges of the lake prevented installation of piezometers in these areas. Measured ground-water gradients indicate that Devils Lake is losing water to the ground-water system at five piezometer sites (fig. 2). A sixth piezometer was dry, possibly because an unsaturated zone was present beneath the lake at this site (the large negative gradient, -0.76, at an adjacent piezometer indicates this possibility). Some ground-water inflow occurs at the southwestern part of the lake. Similar results were also obtained from a piezometer survey by Dickrell (1991). Net ground-water flow, $GW_{(out-in)}$, is the sum of ground water flowing into the lake and lake water flowing into the ground. The piezometer survey indicates that the amount of lake water flowing into the ground is greater than the amount of ground water entering the lake.

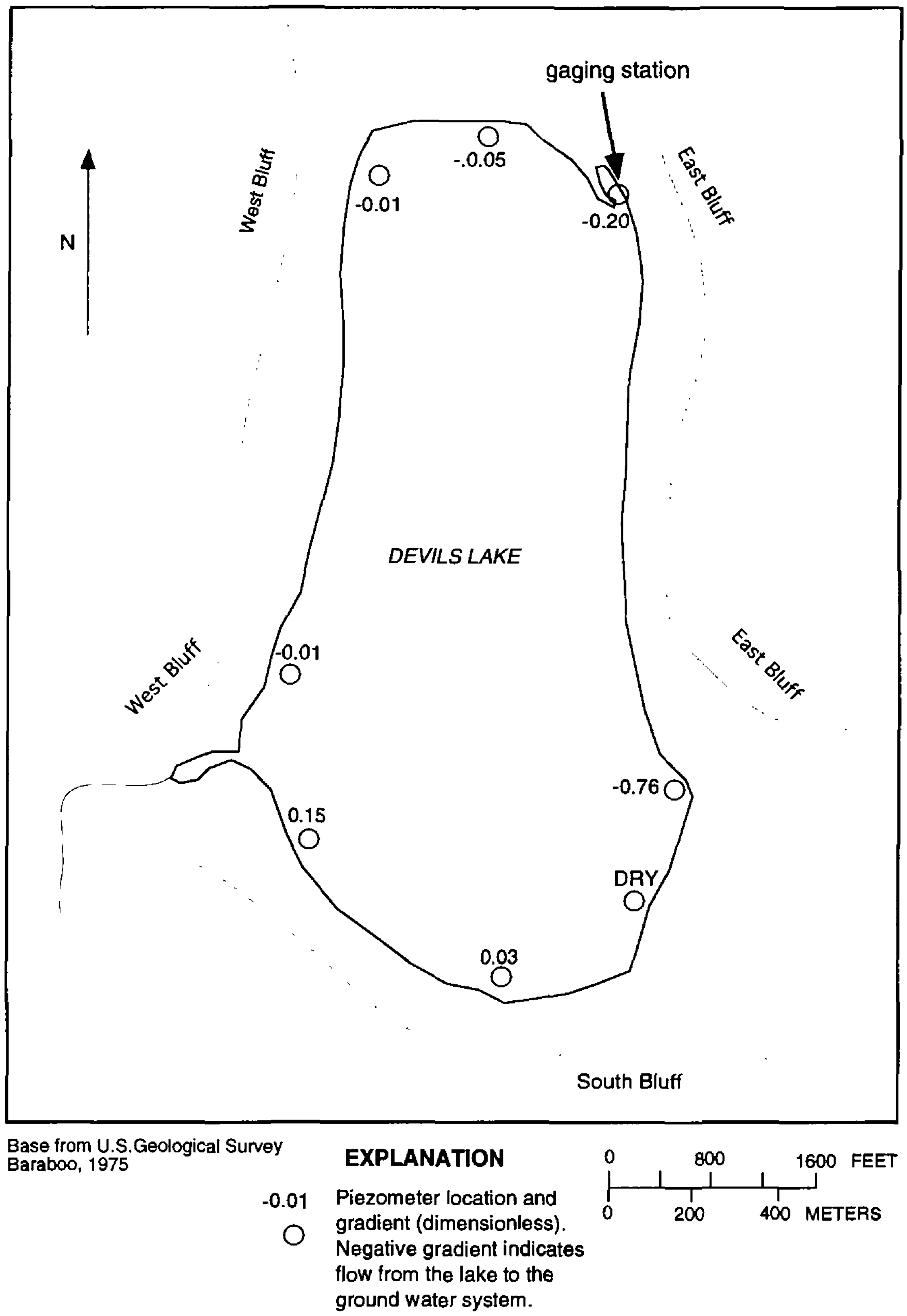

Figure 2. Location and measured ground-water gradients at piezometers in Devils Lake, Wisconsin, March 5, 1992.

Net ground-water-flow rate was estimated by plotting evaporation and lake-stage recession rate during periods of no precipitation (fig. 3). The Y-axis intercept (zero evaporation) of the regression line is equal to net ground-water flow. The net ground-water-flow rate, equivalent to 0.007 ft of lake surface per day, was assumed to be the average net ground-water-flow rate (fig. 3). The standard error of the intercept is 0.003 ft/d and the range of the intercept value for the 95-percent confidence interval is from 0.0002 to 0.01 ft/d. The significance level of the regression line is 0.01.

SIMULATION OF LAKE STAGE AND HYDROLOGIC BUDGET

A computer model program to simulate changes in lake stage caused by the variation in hydrologic-budget components was written in Fortran (Appendix 1). The program was used to simulate lake stage for the period January 1, 1980 through September 30, 1992.

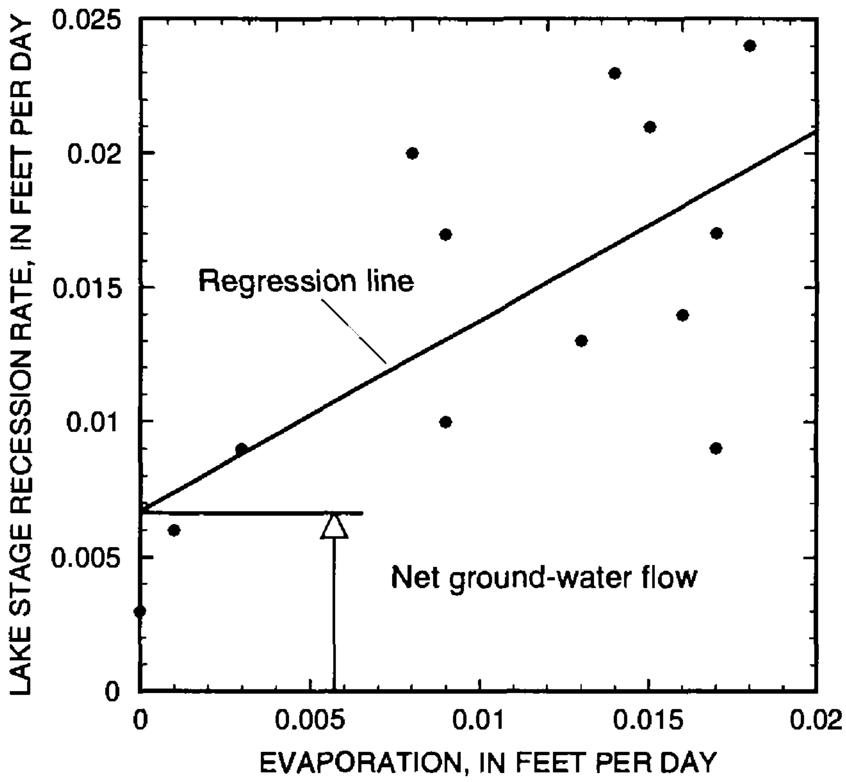

Figure 3. Relation of lake-stage recession rate to lake evaporation rate for selected periods of no precipitation or runoff at Devils Lake, Wis., July 1991-September 1992.

Assumptions and Model Program

The following assumptions were made to allow the use of available climatological data and to simplify the model:

1. Precipitation and evaporation amounts recorded at nearby weather stations were representative of the amounts at Devils Lake.

2. Inflow from the stream at the southwest corner of Devils Lake was assumed negligible during periods of little or no precipitation. This assumption is based on three measurements made during periods of little or no precipitation. Measurements of 0.17 and 0.10 ft^3/s were made on August 18, 1992 and October 15, 1992, respectively, by the USGS, and a measurement of 0.26 ft^3/s was made on June 6, 1988, by Dickrell (1991). During periods of precipitation, the inflow from the stream is included in the estimates of runoff coefficient.

3. Runoff estimated by use of an average coefficient of 0.21 was representative of the entire period of record. In addition, runoff from snowmelt was assumed over a two-day period, February 15 and March 15. The water equivalent of total snowfall from December through February 14 was summed and stored, and the total sum was added to the lake on February 15. Similarly, the water equivalent of snowfall from February 15 to March 14 was summed and stored and was added to the lake on March 15. Runoff to the lake during June, July, and August does not occur if precipitation during the day of interest was less than 0.5 in. and if precipitation did not fall during the previous day. These conditions must be exceeded to overcome the effects of evapotranspiration and dry soil conditions and produce runoff.

4. Hydraulic gradient was constant for the active simulation period. Hence, the volume of net ground-water flow was proportional to lake area.

The model program calculates daily lake stage. The major program steps are shown in figure 4. The program first reads precipitation and pan-evaporation data for the entire simulated period. Pan evaporation is multiplied by a coefficient to approximate lake-surface evaporation. Values for runoff and evaporation coefficients, ground-water-flow rate, drainage area, and an initial lake stage are set in the program. Then, from current or initial daily lake stage, lake volume and lake area are calculated.

A series of "if statements" are executed in the program to determine the volume of runoff that occurred during the current day. Runoff for three periods, winter (December, January, and February), spring and fall (March, April, May, September, October, and November) and summer (June, July, and August) are treated differently. For winter, runoff volume is summed and added to the lake in two increments; one on February 15 and one on March 15. The volume of runoff on a daily basis is calculated by multiplying the daily water equivalent of snow or rainfall by lake-drainage area and then multiplying that product by the runoff coefficient. For spring and fall months, the volume of runoff for the current day is calculated by multiplying the current daily precipitation by lake-drainage area by the coefficient. Runoff for summer is calculated the

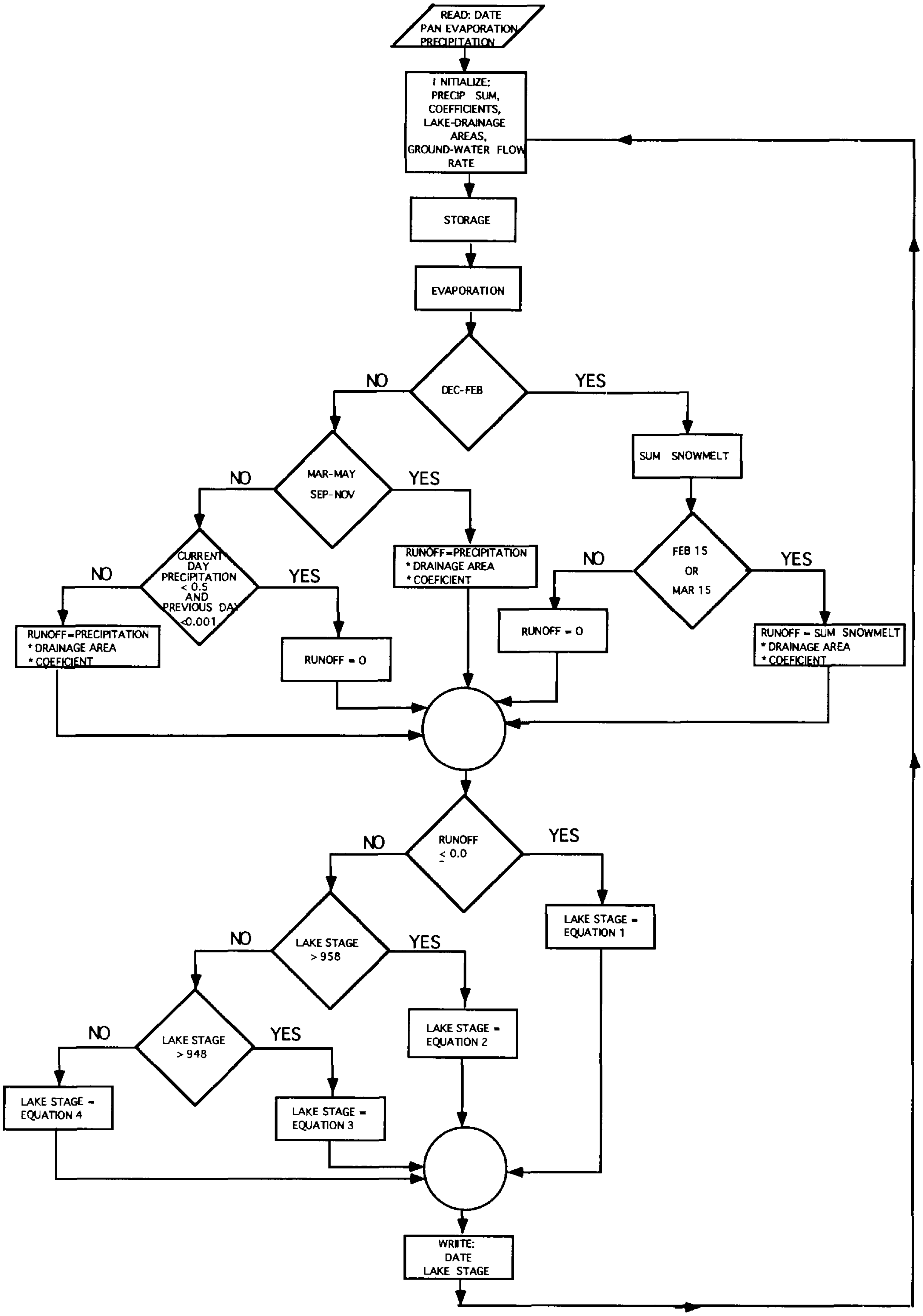

Figure 4. Program steps in hydrologic-budget model of Devils Lake, Wis. (Fortran code and equations are listed in Appendix 1).

same way as for spring and fall unless the current daily precipitation is less than 0.5 in. and there was no precipitation during the previous day. In this case, runoff is not calculated and is assumed to be zero for that day.

Finally, the lake stage for the start of the next day is calculated by adding precipitation and watershed runoff to, and subtracting evaporation and net ground-water flow from, the current daily lake stage. The next daily lake stage is then calculated in the model, starting with the calculation of a new lake storage volume.

Model Calibration and Sensitivity

Runoff and evaporation coefficients and ground-water-flow rate were varied over a reasonable range until the root mean square (rms) of the differences between measured lake stage and model-calculated lake stage were minimized. The lowest rms was 0.83 ft and resulted when the runoff coefficient was 0.21, the average calculated value (table 2), the pan-evaporation coefficient was 0.69, and the ground-water-flow rate was increased from 0.007 ft/d, the calculated coefficient based on lake stage recession periods, to 0.01 ft/d. The value of ground-water-flow rate is approximately the value estimated by Dickrell (1991).

Simulated stage compares reasonably well with historical stage data for Devils Lake (fig. 5). Long-term trends in the measured stage of Devils Lake indicate a gradual increase from 1980 to the end of 1986, a decrease to about 1988 and, then a fairly constant stage through 1992. These trends are also apparent in the simulated lake stage. The measured daily lake stage, however, does not always compare well with the simulated daily lake stage. Reasons for this are in all of the assumptions and necessary simplifications discussed in the previous section. The two most critical assumptions seem to be that precipitation measured at the Baraboo weather station is representative of precipitation measured at Devils Lake and that a single runoff coefficient of 0.21 can be used to calculate runoff to the lake.

An average runoff coefficient cannot be used to accurately calculate daily runoff because runoff is affected by antecedent moisture conditions and evapotranspiration, both of which can vary daily. Estimates of a runoff coefficient, calculated from data collected during this study, varied from 0.08 to 0.54. Furthermore, the ground-water-flow rate used is constant throughout model simulation. Figure 6 shows that the head difference between lake stage and the water table varies throughout the period of record, indicating that a variable ground-water-flow rate is probably necessary for accurate simulation of short-term net ground-water flow.

Sensitivity of the model was tested by changing values for runoff and evaporation coefficients, and ground-water-flow rate individually while keeping the other two values constant. It was found that the simulated lake stage is very sensitive even to small changes in all three of these values (fig. 7). A 10-percent change in any of these values causes a change of greater than 1 ft in the rms of the differences of simulated and measured lake stage.

A simulation was done in which precipitation data were restricted to data collected at Devils Lake (fig. 8), to further test the model calibration. The simulation covered the period July 17, 1991 through September 30, 1992.Trends in the simulated stage again compare well with the measured lake stage; however, discrepancies in daily fluctuations are large. These discrepancies cannot be attributed to errors in precipitation measurement because precipitation, except for the winter months, was recorded at the lake. Moreover, at least for the summer months, the discrepancies are probably not caused by model-simulation errors in evaporation or net ground-water flow from the lake. This is shown by comparison of the slopes of the simulated and measured lake-stage hydrographs, which are almost identical during extended recessions in July and August 1991 and May-August 1992. These nearly identical slopes indicate that the combined simulated rates of evaporation and net ground-water flow for this period are accurate. Comparison of the hydrograph slopes for the winter of 1991-92, however, indicates that the rate of simulated ground-water

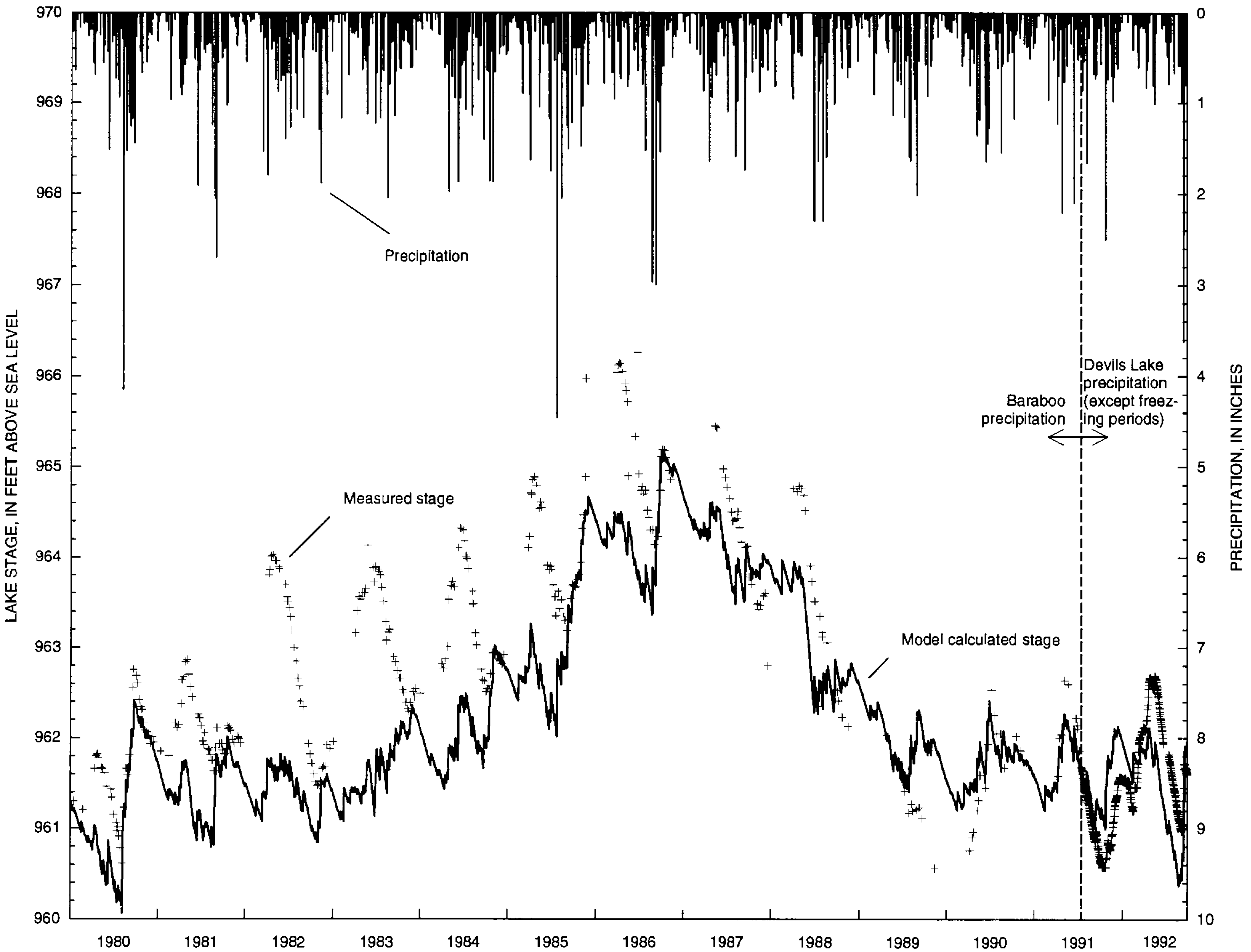

Figure 5. Model-calculated and measured lake stage and precipitation, Devils Lake, Wis., 1980-92.

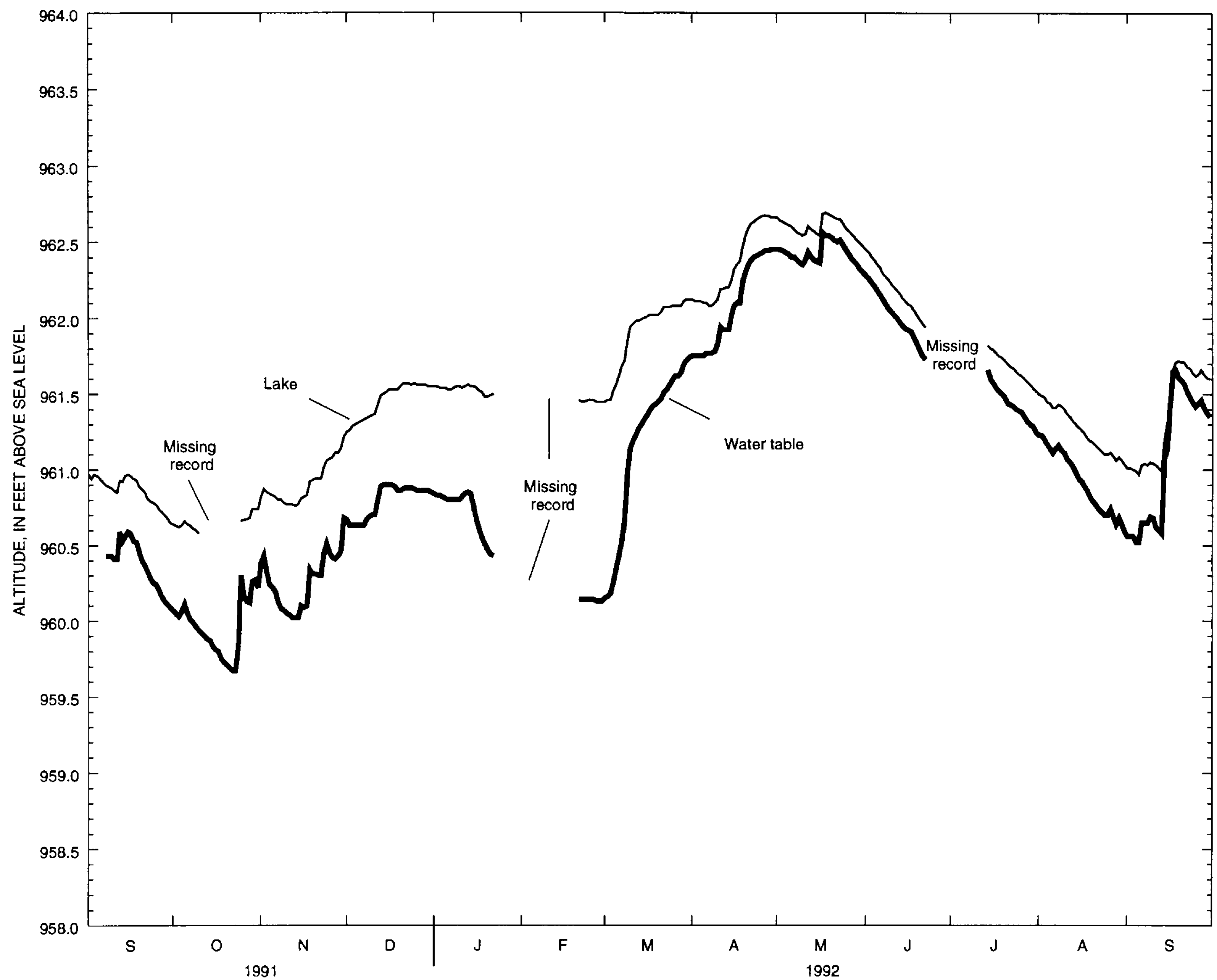

Figure 6. Lake and water-table altitude at the gaging station, Devils Lake, Wis.

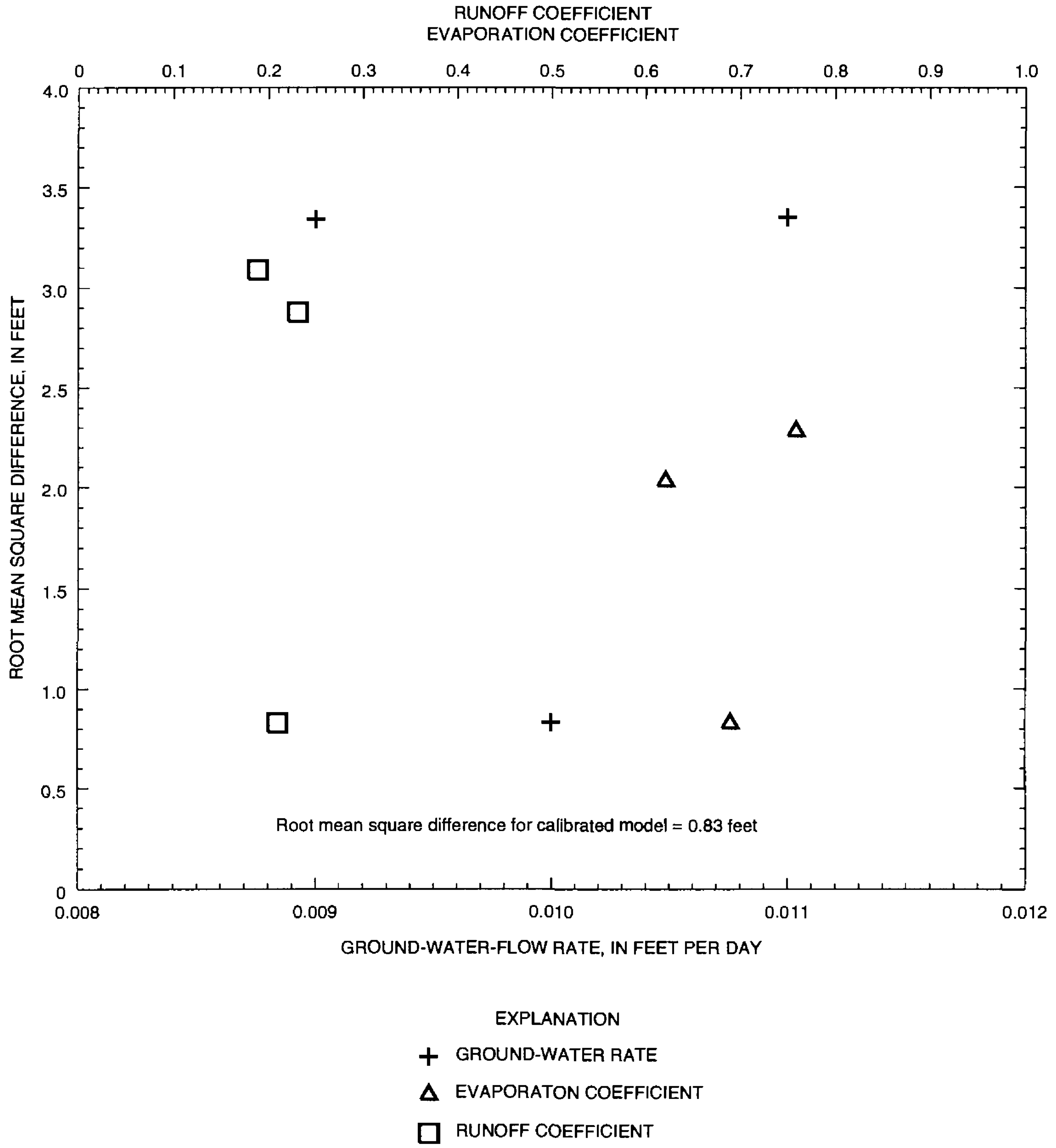

Figure 7. Relationship between root mean square difference of measured and model-calculated lake stage and evaporation and runoff coefficients and ground-water-flow rates in the hydrologic-budget model of Devils Lake, Wis.

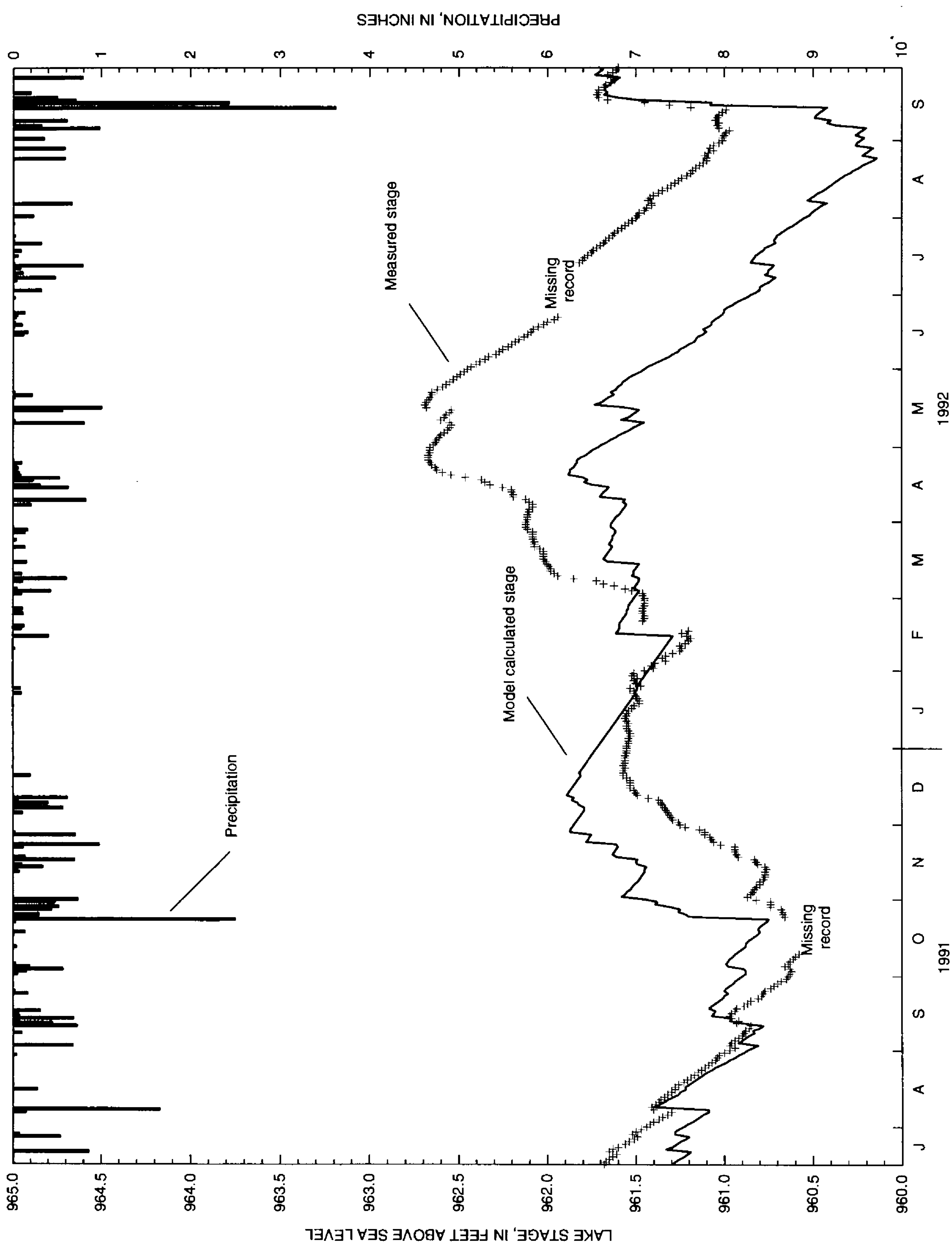

Figure 8. Model-calculated and measured lake stage and precipitation, Devils Lake, Wis., 1991-92.

flow from the lake is greater than the measured rate. In addition, at times the average runoff coefficient of 0.21 is probably too high to simulate accurately storm events. For example, the major storm in September 1992 produced runoff too low to cause the simulated increase in stage (fig. 8).

The annual change in model-calculated lake volume compares well to the annual change in measured-lake volume for most years (table 3). The annual residual, defined as the yearly difference between the model-calculated and measured change in lake storage ranges from -389 to 250 acre-ft, and the mean is -13 acre-ft. The measured change in lake volume was calculated by relating the change in lake stage (the difference in lake stage at the beginning of the year and the end of the year) to lake volume.

The relative amounts of each hydrologic-budget component are also shown in table 3. The average model-calculated yearly amounts for the simulation period, 1980-92, in order of increasing volume are evaporation (791 acre-ft), precipitation (973 acre-ft), runoff (1,107 acre-ft), and ground-water flow out of the lake (1,323 acre-ft).

Simulations of the Effects of Possible Mitigation Plans on Lake Stage

The model was used to simulate three possible mitigation plans to reduce the cycling of phosphorus in the lake. The plans involved withdrawing from, or adding water to, the lake. The purpose of the withdrawals or additions is to remove phosphorus-rich hypolimnetic water while maintaining lake stage at an optimum level for recreational use. For each mitigation plan, the Fortran program code (Appendix 1) was modified.

Mitigation plan 1 is to withdraw phosphorus-rich water from near the lake bottom (hypolimnetic water) during late summer (Richard Lathrop, Wisconsin Department of Natural Resources, Bureau of Research, oral commun., 1991). Figure 9 shows the effects of removing water from the lake at two different rates during the months of September for 1980-92 and compares the results to the calibration stage for the same period. The hydrographs of simulated lake stage are shown as a result of withdrawing the volume of water occupied by the lowermost 3.28 and 6.56 ft of lake depth every September. The volumes of the lowermost 3.28

Table 3. Model-calculated hydrologic-budget components and measured change in lake volume, Devils Lake, Wis.
[all values are in acre-feet]

		Model calculated					
Water year[1]	Precipitation	Evaporation	Net ground-water flow	Surface runoff	Change in volume	Measured change in volume	Residual
1980	864	720	1,307	929	-233	-292	59
1981	816	689	1,307	917	-263	0	-263
1982	1,053	687	1,306	1,261	322	359	-37
1983	938	707	1,319	1,075	-14	-11	-3
1984	1,290	836	1,328	1,468	594	415	179
1985	1,229	772	1,355	1,355	457	373	84
1986	837	858	1,359	941	-438	-348	-90
1987	912	1,071	1,345	1,027	-476	-440	-36
1988	817	781	1,319	965	-318	-493	175
1989	956	784	1,310	1,071	-69	320	-389
1990	875	797	1,309	998	-233	-483	250
1991	1,083	787	1,311	1,273	258	338	-80
Average	973	791	1,323	1,107	-34	-22	-13

[1] October 1 through September 30.

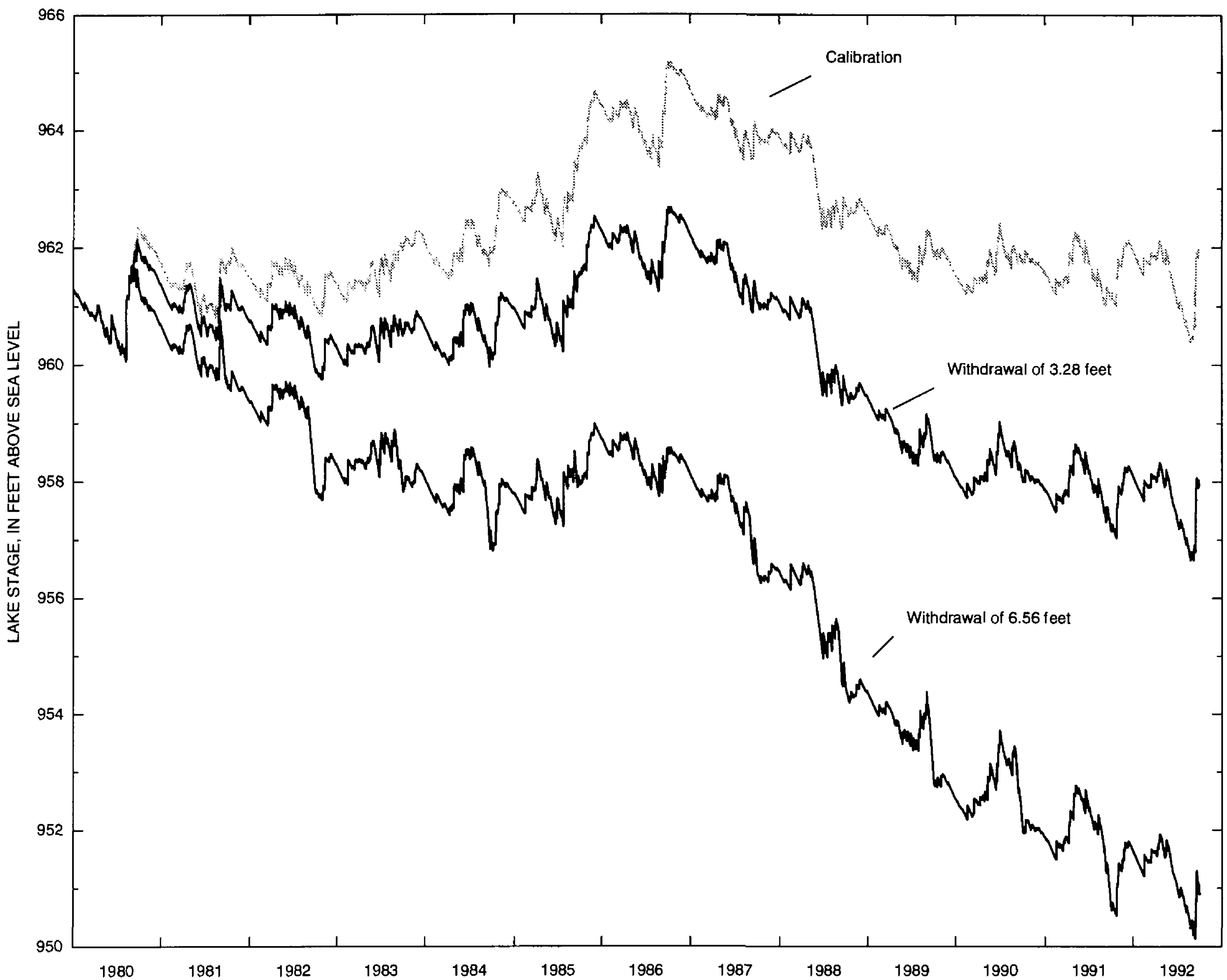

Figure 9. Model-calculated lake stage for calibration and withdrawal of 3.28 and 6.56 feet of hypolimnetic water from Devils Lake, Wis., during the months of September, 1980-92 (mitigation plan 1).

and 6.56 depths are 5,600,000 and 16,300,000 ft^3, respectively. For withdrawal of the 3.28 ft and 6.56 ft volumes during September, water must be pumped continuously at rates of 972 and 2,800 gallons per minute, respectively. The lake stage is approximately 3.98 and 11.03 ft lower, respectively, than the simulated lake stage with no withdrawals (calibration stage) at the end of this period. If 95 percent of the 6.56 ft volume were returned, the simulated lake stage at the end of the 1980-92 period is approximately 0.5 ft lower than the simulated lake stage with no withdrawals.

Mitigation plan 2 is to withdraw water in September but only during years of high stages. The effects of removing the 6.56 ft volume during September 1986, a high-stage period, in relation to the calibration stage are shown in figure 10. The results indicate that even in 1992 (6 years after the 1986 withdrawal) lake stage is more than 1.0 ft lower than it would be had the withdrawal not occurred.

Both of these simulated mitigation plans would lower the lake stage to levels unacceptable for optimal recreation use. An optimal lake stage for recreation is assumed to be 963.75 ft above sea level, which is the approximate elevation of the end of asphalt closest to the lake at the boat landing.

A third mitigation plan is to maintain an optimal lake stage while withdrawing hypolimnetic water in August and September. Water withdrawn would be replaced with water from the intermittent stream in the watershed northeast of the Devils Lake watershed (fig. 1) by means of a control structure. The intermittent stream flows from east to west until it turns north, where it comes within about 200 ft of the northern side of Devils Lake. The drainage area of this watershed upstream of the proposed diversion point is 1.65 mi^2. The Fortran program code was modified to account for available runoff that could be diverted from this basin to Devils Lake.

Mitigation plan 3 is simulated as follows: (1) Withdraw the 6.56 ft volume during August and September; (2) whenever lake stage is below a stage of 962.00, water is not withdrawn but is added from the northeastern basin; (3) add water from the northeastern basin equal to the amount withdrawn during August and September, if the lake stage is greater than 963.00; and (4) no water will be added if the stage is greater than 963.75 (the optimal lake stage) from the northeastern basin, but will still be withdrawn during August and September. In figure 11, the results of this simulation are shown for the period 1980-92, along with the calibration stage for the same period. In general, the effect of mitigation plan 3 is to increase lake stage during periods when lake stage would normally be low (that is, without the addition of water from the northeastern basin) and to decrease lake stage when lake stage would normally be high (that is, without the withdrawal of hypolimnetic water). Mitigation plan 3 increases or decreases lake stage to maintain the optimal stage of 963.75.

SUMMARY

An understanding of the hydrology of Devils Lake is needed to develop a mitigation plan to reduce phosphorus input. A model that can be used to estimate changes in lake stage resulting from variation in hydrologic-budget components and withdrawals of water from the lake was developed to test current understanding of lake hydrology and was used to simulate three possible mitigation plans.

Daily lake stage is simulated in the model by summing estimates of hydrologic-budget components. The Devils Lake hydrologic-budget components are precipitation on the lake surface, evaporation from the lake surface, runoff (consisting of overland flow to the lake and an intermittent stream flowing into the lake), and ground-water flow into and out of the lake. Amounts of precipitation and pan evaporation (multiplied by a coefficient) recorded at the nearby weather stations in Baraboo and Arlington, respectively, were used to estimate these components. A gaging station installed at the lake measured precipitation for July 1991 through September 30, 1992. A runoff coefficient was multiplied by daily precipitation and drainage area to estimate the runoff component. The method of calculating runoff volume was varied seasonally: the water equivalent of daily snowfall during the winter was summed and released to the lake on February 15 and March 15,

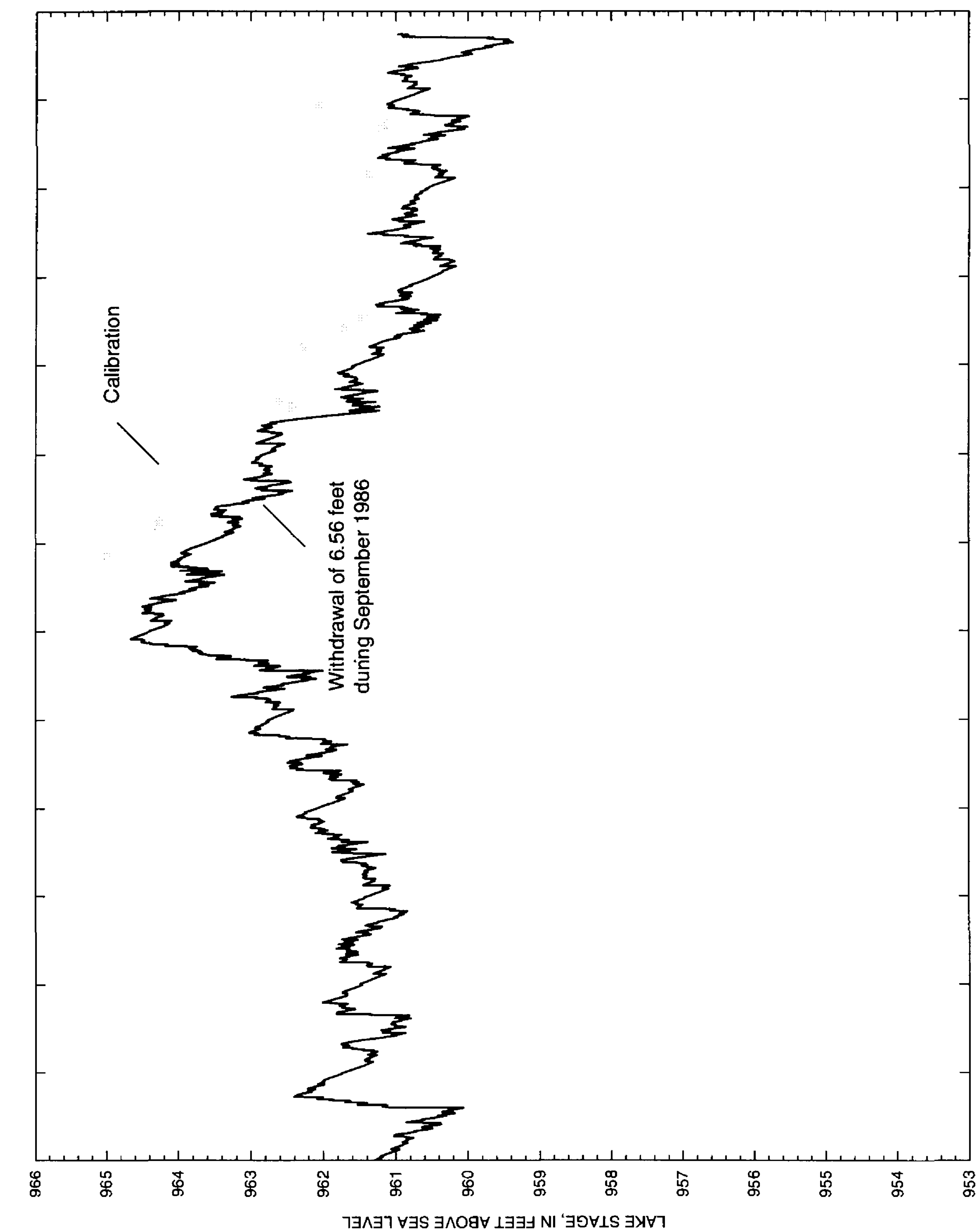

Figure 10. Model-calculated lake stage for calibration and withdrawal of 6.56 feet of hypolimnetic water from Devils Lake, Wis., during September 1986 (mitigation plan 2).

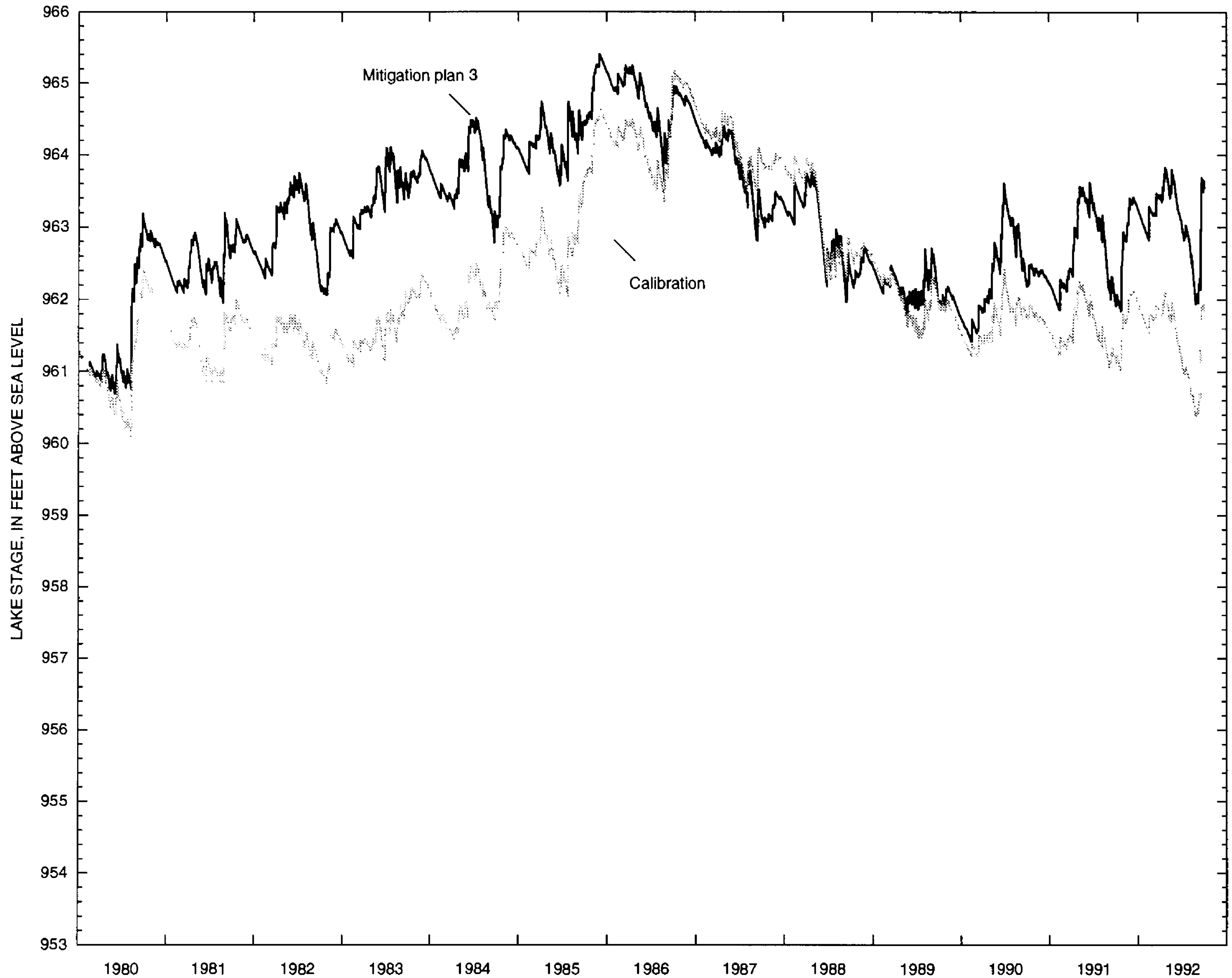

Figure 11. Model-calculated lake stage for calibration and withdrawal of 6.56 feet of hypolimnetic water from Devils Lake, Wis., during August and September and addition of water from the northeast basin during periods of low lake stage (mitigation plan 3).

and runoff was calculated for the summer months when precipitation exceeded 0.5 in. on the day of interest or when precipitation had fallen on the previous day. Net ground-water flow leaving the lake was calculated by multiplying the current lake area by a coefficient.

The model was calibrated by comparing model-calculated and measured lakes stages for the period 1980-92. The root mean square of the differences of simulated and measured daily lake stage for the period 1980-92 is 0.83 ft. Simulated lake stage is very sensitive to small changes in the evaporation and runoff coefficients and the ground-water-flow rate. A 10-percent change in the values of the coefficients or ground-water-flow rate causes the root mean square of the differences of simulated and measured lake stage to be greater than 1 ft.

The average model-calculated yearly volume for the simulation period 1980-92, in order of increasing volume, is evaporation (791 acre-ft), precipitation (973 acre-ft), runoff (1,107 acre-ft), and net ground-water flow which is out of the lake (1,323 acre-ft).

The model was used to simulate three possible mitigation plans to reduce the cycling of phosphorus in the lake. Mitigation plans 1 and 2 would lower lake stage to levels unacceptable for optimal recreation use. Mitigation plan 3, which includes the diversion of water from a nearby watershed to Devils Lake, allows for withdrawing hypolimnetic water and maintaining lake stage closer to optimal levels than would be possible without mitigation.

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APPENDIX

APPENDIX 1. FORTRAN PROGRAM CODE TO SIMULATE CHANGES IN LAKE STAGE DUE TO VARIATIONS IN HYDROLOGIC-BUDGET COMPONENTS

```
C
C DECLARE AND DIMENSION VARIBLES
C
      PARAMETER ND=4657,MD=740
      COMMON PI(ND),RO(ND),EO(ND),PRECIP(ND),EVAP(ND),
     &LL(ND),PUMP(ND),AREA(ND),STOR(ND),YEAR(ND),
     &MONTH(ND),DAY(ND)
      REAL PI,RO,EO,PRECIP,EVAP,LL,AREA,STOR,GW,SUM
      INTEGER YEAR,MONTH,DAY,MYEAR,MMONTH,MDAY
C
C
C PRECIP IS PRECIPITATION FROM BARABOO OR GAGE (INCHES)
C PI IS DIRECT PRECIPITATION ON LAKE (FEET)
C RO IS RUNOFF FROM DRAINAGE AREA (CUBIC FEET)
C EVAP IS PAN EVAPORATION FROM ARLINGTON (INCHES)
C EO IS EVAPORATION FROM LAKE SURFACE (FEET)
C GW IS NET GROUND-WATER FLOW (FEET PER DAY)
C SUM IS THE TOTAL PRECIPITATION USED TO CALCULATE RUNOFF
C   FROM SNOWMELT (FEET)
C AREA IS TOTAL LAKE AREA (SQUARE FEET)
C STOR IS LAKE STORAGE (CUBIC FEET)
C PUMP IS AMOUNT PUMPED FROM LAKE (FEET)
C LL IS DAILY LAKE LEVEL (FEET ABOVE MEAN SEA LEVEL)
C
C READ IN DATE AND PRECIP AND EVAP IN INCHES
C
      DO 3 I=1,ND
    3 READ(11,20)YEAR(I),MONTH(I),DAY(I),PRECIP(I),EVAP(I)
   20 FORMAT(3I2,2F10.2)
C
C INITIALIZE SUM OF SNOWMELT, RUNOFF AND GROUND-WATER
C AND EVAPORATION COEFFICIENTS AND, DRAINAGE AREA
C
      SUM=0.0
      ROCOEF=0.21
      EVCOEF=0.69
      GW=0.01
      DA=90480000.00
C
C INITIALIZE LAKE LEVEL
C
      LL(1)=961.30
C
      DO 9 I=1,ND
C
C CALCULATE LAKE STORAGE IN CUBIC FEET
C
       IF (LL(I).GT.958.00) THEN
        STOR(I)=-1.427657E10+(1.532838E7*LL(I))
```

```
ELSE
    STOR(I)=-1.243888E10+(1.340973E7*LL(I))
    END IF
C
C CALCULATE PI (PRECIP IN FEET)
C
    PI(I)= PRECIP(I)/12
C
C SUM PRECIP FOR SNOWMELT
C
    SUM=SUM+PI(I)
C
C CALCULATE EO (EVAP IN FEET)
C
    EO(I)=(EVAP(I)/12)*EVCOEF
C
C CALCULATE RO (RUNOFF IN CUBIC FEET)
C
C
C RUNOFF FOR DECEMBER, JANUARY AND, FEBRUARY
C
    IF (MONTH(I).GT.11.OR.MONTH(I).LT.3) THEN
     RO(I)=0.0
C
C RUNOFF FOR MARCH, APRIL, MAY, SEPTEMBER, OCTOBER AND, NOVEMBER
C
    ELSE IF (MONTH(I).LT.6.OR.MONTH(I).GT.8) THEN
      RO(I)=PI(I)*DA*ROCOEF
C
C RUNOFF FOR MARCH 1-15 IS ZERO
C
     IF (MONTH(I).EQ.3.AND.DAY(I).LT.16) THEN
      RO(I)=0.0
     END IF
C
C RUNOFF FOR JUNE, JULY AND AUGUST
C
    ELSE IF (MONTH(I).GT.5.AND.MONTH(I).LT.9) THEN
     IF (PRECIP(I-1).LT.0.001.AND.PRECIP(I).LT.0.5) THEN
      RO(I)=0.0
     ELSE
      RO(I)=PI(I)*DA*ROCOEF
     END IF
    END IF
C
C RUNOFF FROM SNOWMELT (FEBRUARY 15 AND MARCH 15)
C
     IF (MONTH(I).EQ.2.AND.DAY(I).EQ.15) THEN
      RO(I)=SUM*DA*ROCOEF
```

```
      SUM=0.0
      END IF
C
      IF (MONTH(I).EQ.3.AND.DAY(I).EQ.15) THEN
       RO(I)=SUM*DA*ROCOEF
      END IF
C
      IF (MONTH(I).EQ.11.AND.DAY(I).EQ.30) THEN
       SUM=0.0
      END IF
C
C CALCULATE NEW LAKE STAGE IN FEET ABOVE MSL AND RUNOFF IN INCHES
C
C EQUATION 1
      IF (RO(I).LE.0.0) THEN
       LL(I+1)=LL(I)+PI(I)-EO(I)-GW
C EQUATION 2
      ELSE IF (LL(I).GT.958.) THEN
       LL(I+1)=PI(I)-EO(I)-GW+9.313862E2+(6.522769E-8*
     &(RO(I)+STOR(I)))
C EQUATION 3
      ELSE IF (LL(I).GT.948.) THEN
       LL(I+1)=PI(I)-EO(I)-GW+9.276105E2+(7.454654E-8*
     &(RO(I)+STOR(I)))
C EQUATION 4
      ELSE
       LL(I+1)=PI(I)-EO(I)-GW+9.244415E2+(8.570591E-8*
     &(RO(I)+STOR(I)))
      END IF
C
C WRITE DATE AND LAKE LEVEL
C
      WRITE(13,21)YEAR(I),MONTH(I),DAY(I),LL(I)
   21 FORMAT (I2,'/',I2,'/',I2,2X,F8.2)
C
    9 CONTINUE
C
      STOP
      END
```