Simulation of the Effects of Operating Lakes Mendota, Monona, and Waubesa, South-Central Wisconsin, as Multipurpose Reservoirs to Maintain Dry-Weather Flow

By William R. Krug

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To Obtain
foot (ft)	0.3048	meter
square mile (mi^2)	2.590	square kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

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.

Simulation of the Effects of Operating Lakes Mendota, Monona, and Waubesa, South-Central Wisconsin, as Multipurpose Reservoirs to Maintain Dry-Weather Flow

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Abstract

A digital reservoir routing model was used to simulate the operation of Lakes Mendota, Monona, and Waubesa, south-central Wisconsin for various levels of minimum release. Twenty-five years of record (1970–94) were used in model simulation. The amount of water available to maintain streamflow and lake levels during dry periods has declined because of extensive pumping of ground water for municipal use and diversion of the effluent around the lakes. The goal of the simulation was to determine whether using the lakes as multipurpose reservoirs to maintain flow during periods of low flow would appreciably lower the lake levels.

The model results indicated that it would be possible to maintain a minimum flow of 36 cubic feet per second in all but the driest years simulated (1970, 1976, 1977, 1981, 1989, and 1991) without lowering the lake levels more than they have been lowered from 1970 to 1994 under current operating conditions. Maintaining minimum flow would require detailed computations to guide the operation of the dams during the year.

INTRODUCTION

The Madison metropolitan area in central Dane County, Wis. (fig. 1), surrounds a chain of large lakes. The municipalities of the Madison metropolitan area obtain their water supply from wells surrounding the lakes. Since 1959, the sewage effluent from the area has been diverted around the lakes to Badfish Creek, which joins the Yahara River far downstream. This diversion was intended to reduce the load of nutrients entering the lakes. Since 1959, other communities in the headwaters of the Yahara River and in adjacent river basins have been connected to the Madison Metropolitan Sewerage District. Effluent from most of these communities formerly flowed into streams upstream from the lakes but now is part of the diversion around the lakes. The total effluent diverted from the metropolitan area averaged 68 ft^3/s in 1993. The removal of 68 ft^3/s of water from the hydrologic system of the lakes by the wells, and diversion of this water to a point downstream from the lakes, has resulted in a substantial reduction in the streamflow leaving the lakes.

Water use, distribution, and the diversion of effluent by the metropolitan area has had an appreciable effect on the hydrology of the area. The Dane County Regional Planning Commission, in cooperation with the Wisconsin Geological and Natural History Survey and the U.S. Geological Survey, conducted a multiyear study to better understand the hydrology of the area and the effects of ground-water pumpage and effluent diversion. The main part of the study focused on understanding the occurrence and movement of ground water and is the subject of separate reports (Krohelski and others, in press). The surface-water part of the study was directed to determine whether it would be possible to adjust the management of the dams controlling the lakes to mitigate some of the effects of the diversion of water away from the lakes.

Regulatory limits on allowable variation in lake levels are included in orders issued by the Wisconsin Department of Natural Resources on January 18, 1979 (Douglas Morrissette, Wisconsin Department of Natural Resources, written commun., 1979). These orders established maximum levels for the lakes for the entire year and two minimum lake levels: a higher minimum lake level "between the first spring runoff occurring after March 1, and October 30," and the lower minimum lake level "between November 1 and the first spring runoff occurring after March 1." These orders limit the allowable fluctuations in lake levels to 0.5 ft during the summer and fall and to 1.9 ft on Lake Mendota and 3.0 ft on Lakes Monona and Waubesa during the rest of the year. The elevations are summarized in the following table:

Lake	Maximum	March–Oct.	Nov.–February
Mendota	10.1 ft	9.6 ft	8.2 ft
Monona	5.2 ft	4.7 ft	2.2 ft
Waubesa	5.0 ft	4.5 ft	2.0 ft

The water levels given here, and in the rest of this report, are referenced to the datum of the USGS gaging stations (840.00 ft above sea level).

The orders also establish minimum outflows from the dams: 4 ft^3/s from Lake Mendota and 10 ft^3/s from Lake Waubesa. In addition, from April 1 through May 15, one tainter gate at the outlet of Lake Mendota must be open at least 0.3 ft, and the outflow from Lake Waubesa must be at least 50 ft^3/s. A final constraint is that "During normal flow and low flow conditions, the level of Lake Mendota shall be held within 4.9 feet of the level of Lake Monona."

At times the physical limits of the dams and outlet channels make it impossible to keep lake levels within these limits. The channel downstream from the outlet of Lake Waubesa limits the possible outflow from the lake. This limitation varies seasonally because weed growth in the channel impedes streamflow to varying degrees. Periodically, this limitation is partially offset by mechanical harvesting of the weeds.

Purpose and Scope

The purpose of this report is to describe effects on lake levels that would result from managing the storage in Lakes Mendota, Monona, and Waubesa to maintain low flows in the Yahara River. The management options considered were constrained by the present channels and dams and by the existing regulations regarding allowable lake levels.

The simulation of the operation of two dams was used to determine whether the dams controlling lakes (Mendota, Monona, and Waubesa) could be operated to sustain various minimum low flows without lowering the lake levels below the established legal limits. Twenty-five years of record (1970–94) were used in model simulations, including a range of wet, normal, and dry years. Nearly all of the diversion of effluent was in effect for this period.

Physical Setting

Lakes Mendota, Monona, and Waubesa are on the Yahara River in the city of Madison in Dane County in south-central Wisconsin (fig. 1). The drainage area at the outlet of the most downstream lake (Lake Waubesa) is 327 mi^2. The lakes have surface areas of 15.2, 5.3, and 3.3 mi^2, respectively. The metropolitan area of Madison, Wis., is a substantial part of the drainage area of the lakes.

Water levels in the lakes are regulated by two dams. One dam controls the outlet of Lake Mendota. A short channel leads from this dam to Lake Monona. Lake Monona is connected to Lake Waubesa by a slightly longer channel, and except for short periods of high and low flow, the water level of Lake Monona is usually 0.2 ft higher than that of Lake Waubesa. The second dam controls the outlet from Lake Waubesa. The dam at Lake Mendota has radial gates that are fairly easy to operate. The dam at Lake Waubesa consists of stoplogs, which are slightly more difficult to operate than radial gates.

LAKE-LEVEL AND STREAMFLOW DATA

Lake-stage data have been collected by the USGS on Lake Mendota since January 1916 and on Lake Monona since September 1915. Much of the early data is fragmentary, especially during winter.

Streamflow data have been collected on the Yahara River at McFarland, Wis., since September 1930. This station is just downstream from the outlet of Lake Waubesa.

Missing daily lake levels were estimated by linear interpolation between recorded lake levels. The daily change in lake level was multiplied by the surface area of the lakes and added algebraically to the daily outflow to compute the net inflow. Constant surface areas were used in these computations because the change in surface area over the range of lake levels considered is a negligible fraction of the total surface area. Lakes Monona and Waubesa were combined and treated as a single reservoir because their changes in lake level are nearly identical. This net inflow is the sum of streamflow entering the lakes, direct precipitation on the lakes, and inflow from ground water, minus outflow to ground water and evaporation. At times, in the summer and fall, evaporation can exceed all inflows, and the net inflow is negative.

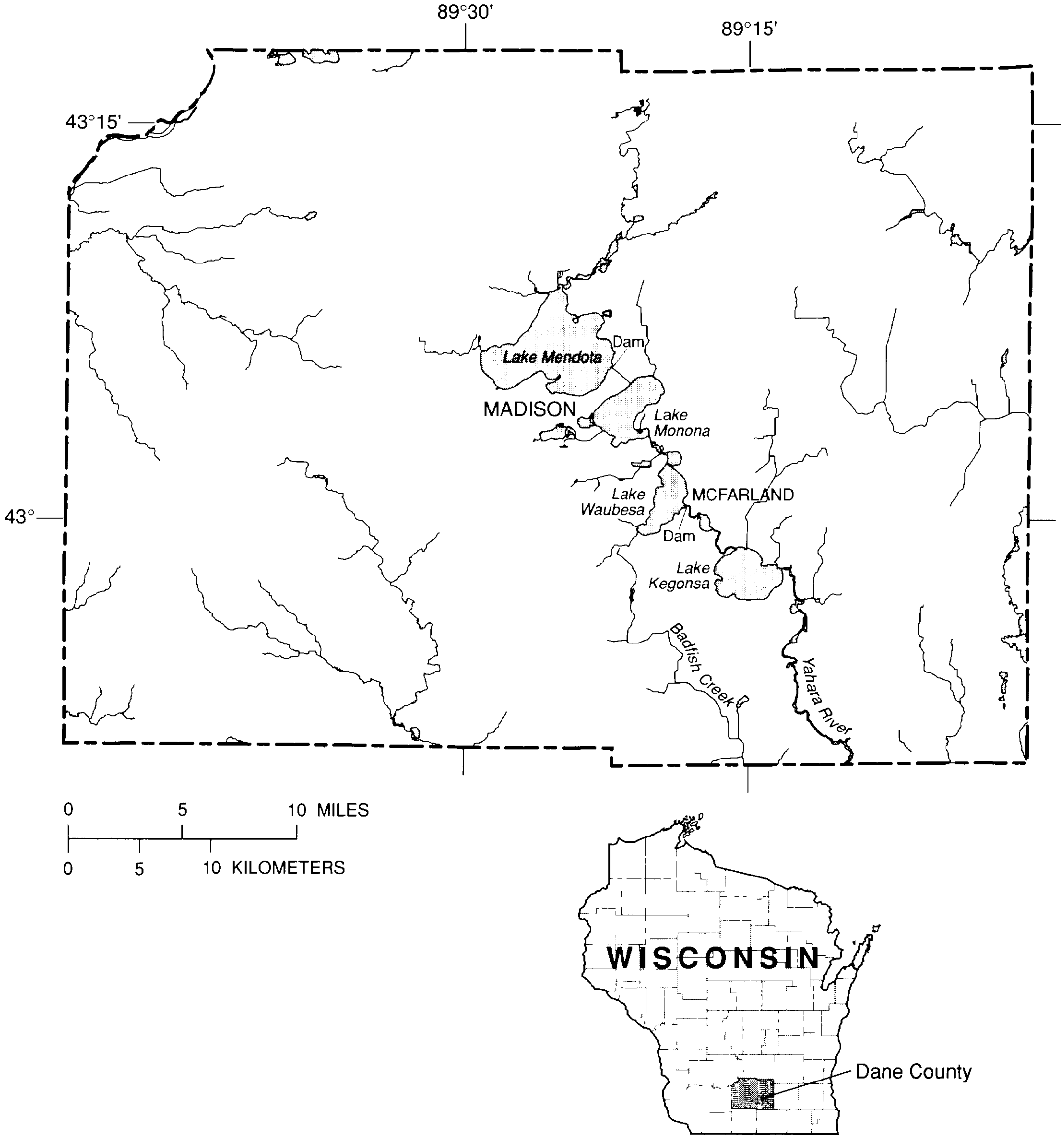

Figure 1. Location of study area in Wisconsin.

SIMULATION OF RESERVOIR OPERATION

Model Description

The model applied in this study was adapted for this study from a reservoir operation model originally developed for a simulation of Lake Winnebago (Krug, 1981). The model was extensively modified to include specific operation limits and criteria for the Madison lakes.

Regulatory and Physical Limits

All of the regulatory and physical limiting factors were included in the model. It was assumed in the model that the minimum outflow specified for the simulation, or required by law, would be maintained at all times even when this outflow resulted in lake levels below the minimum allowable lake level. The historical records of levels of Lake Monona were analyzed along with the historical outflow from Lake Waubesa to determine the maximum and minimum discharges that were released from the lakes at all stages of Lake Monona. These discharges were then used as the limits of practical operation in the model. The model would never simulate more or less outflow than has been observed at the gaging station for the same level of Lake Monona.

The effect of variable weed growth in the channel downstream from Lake Waubesa was simulated with an average backwater effect that varied seasonally. Concurrent measurements of discharge and water levels over a number of years showed a backwater effect of as much as 2 ft. Almost 200 of these measurements were averaged seasonally to determine the backwater effect to be used in the model. This seasonal average ranged from 0.31 ft, from mid-February to mid-April, to about 1 ft, from mid-July to mid-September.

Operating Procedures

Each day the operation of the dam controlling Lake Mendota was simulated first with the model. The general model outline was to adjust the outflow to counteract the effects of varying inflow and to try to bring the level of Lake Mendota to 4.9 ft higher than the level of Lake Monona within approximately 5–7 days. The minimum regulatory outflow of 4 ft^3/s or 35 ft^3/s, depending on the season, was always released from Lake Mendota. Simulation of the operation of the dam controlling Lakes Monona and Waubesa was complex. During each day, it was assumed that no stoplog changes were made until noon. At noon, the changes in lake level were evaluated, and a change to the number of stoplogs in place was computed to try to bring the lake level to the target level for the season of the year, within a limited period of time. The target level was always within the regulatory limits, rising from a low in late winter to the maximum regulatory limit in late spring and early summer. The target level then fell gradually to the lower regulatory limit at the end of the summer/fall season. A detailed explanation of the operating rules is included in the appendix.

The objective of the operating procedures is to achieve a winter minimum level of 4.0 ft on Lake Monona and 8.9 ft on Lake Mendota by the end of February. These levels were selected after analysis of the total volume of spring runoff during the period of record. With the lakes at these levels, there would be a sufficient volume of water in the spring runoff to fill the lakes to their maximum summer operating levels by the beginning of May in all of the years. A lower minimum winter drawdown would risk not filling the lakes to their minimum summer level during the driest springs.

The operating procedures were developed through repeated simulations of various wet, normal, and dry years. The goal of the procedures was to attempt to maintain low flows through dry periods without allowing lake levels to go below the regulatory minimum. In order to meet this goal (whenever possible), it was necessary to reduce the flow to near the minimum value during dry summer periods. If flow was not reduced early enough, the lake system would run out of water above the minimum level in the driest years, and simulated lake levels would be below the regulatory minimum level. The observed and simulated lake levels for both Lakes Mendota and Monona, as well as the observed and simulated outflow are illustrated: maintaining a minimum flow of 10 ft^3/s (fig. 2a) and 36 ft^3/s (fig. 2b), for 1988, one of the driest years in the period simulated. Similar comparisons for a year of normal flow (1989) is illustrated in figure 3.

Operating Alternatives Simulated

Four operating alternatives were evaluated in the model. Each alternative involved imposing a different level of minimum release from the outlet of Lake Waubesa: 8.5 ft^3/s, 10 ft^3/s, 30 ft^3/s, and 36 ft^3/s. The required minimum flow is 10 ft^3/s. Each of these alternatives was simulated for the period 1970–94 because most of the effluent diversion around the lakes was included by 1970.

RESULTS OF SIMULATION

In each operating alternative, the release of the minimum flow was simulated at all times during the year. In the driest years, this required that the lake levels be drawn down below the regulatory minimum level; however, the lake levels were not drawn down more than has been observed during the same period. Maintaining a minimum flow of 8.5 ft^3/s resulted in minimum lake levels higher than observed minimum lake levels, and maintaining a minimum flow of 36 ft^3/s resulted in lake levels that were very similar to the observed minimum lake levels (fig. 4). The highest lake levels simulated in the model were never higher than the lake levels that have been observed over the same period (fig. 5).

During the driest year simulated, with a minimum outflow of 36 ft^3/s, the simulated minimum lake level was low enough that flow was limited by the outflow channel. It was impossible to maintain a flow of 36 ft^3/s under these conditions.

Table 1 shows a comparison of the minimum levels of Lake Monona during May–October of each year sim-

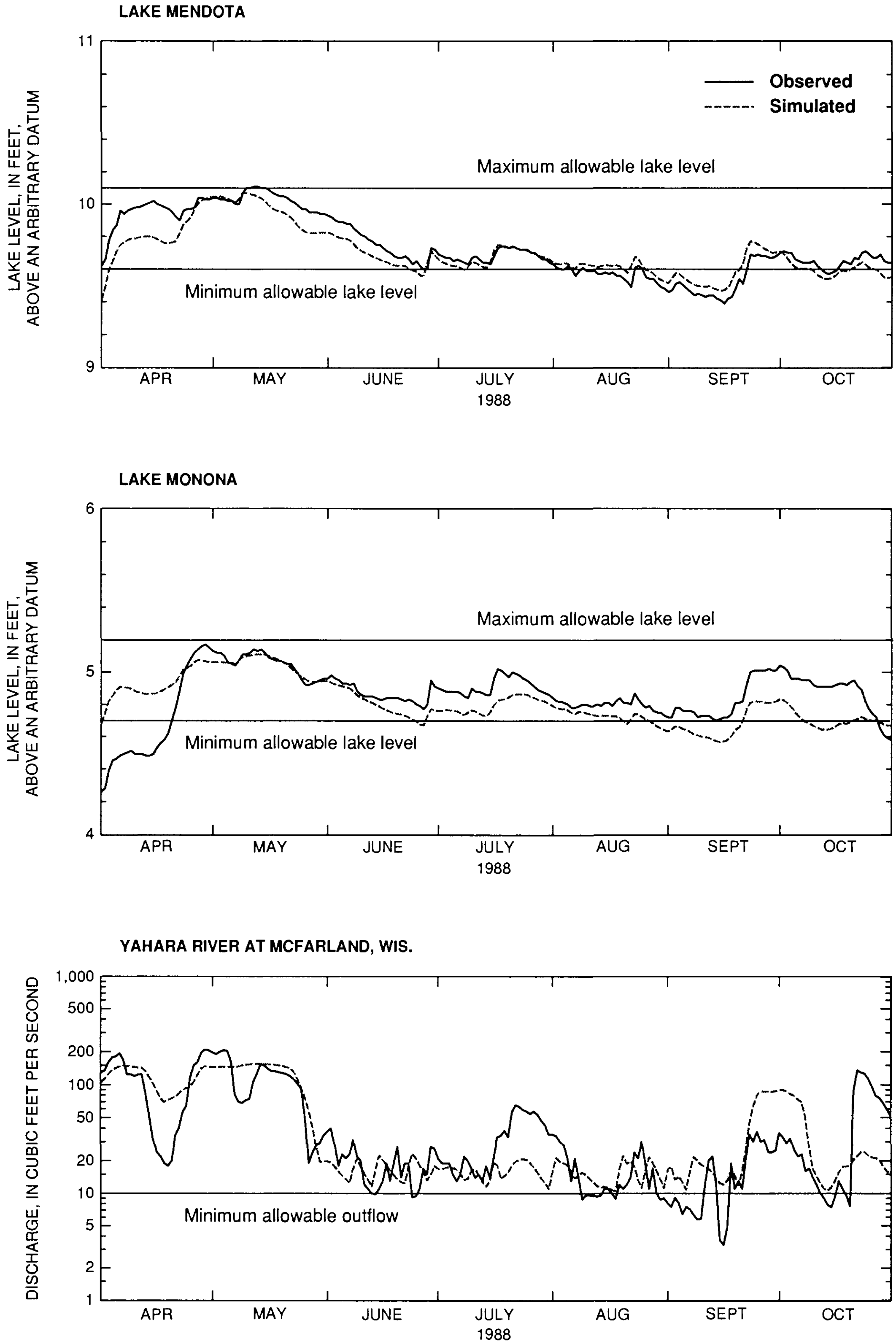

Figure 2a. Graphs showing observed and simulated daily levels of Lakes Mendota and Monona and daily streamflow for the Yahara River at McFarland for 1988, with a minimum outflow of 10 ft^3/s.

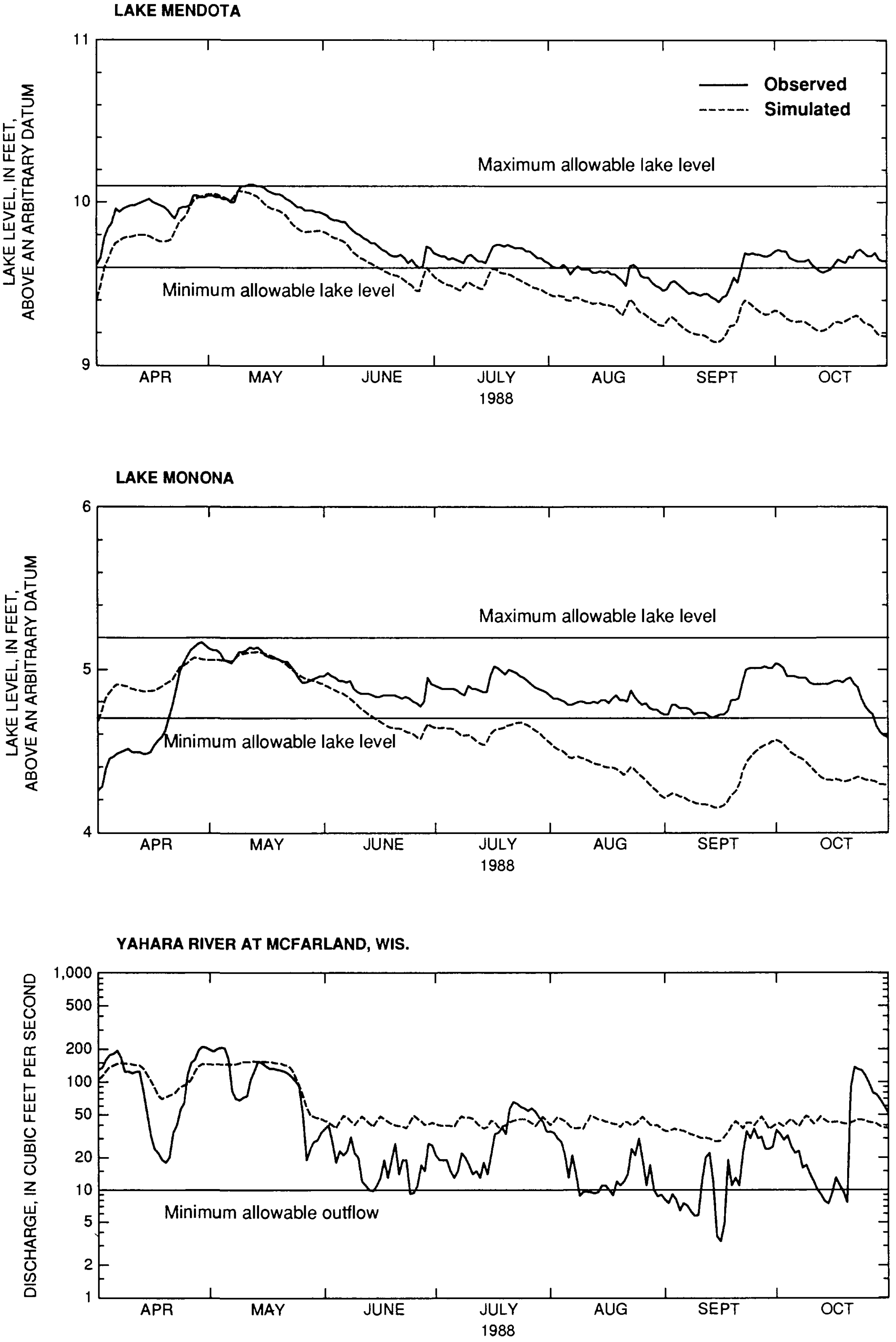

Figure 2b. Graphs showing observed and simulated daily levels of Lakes Mendota and Monona and daily streamflow for the Yahara River at McFarland for 1988, with a minimum outflow of 36 ft^3/s.

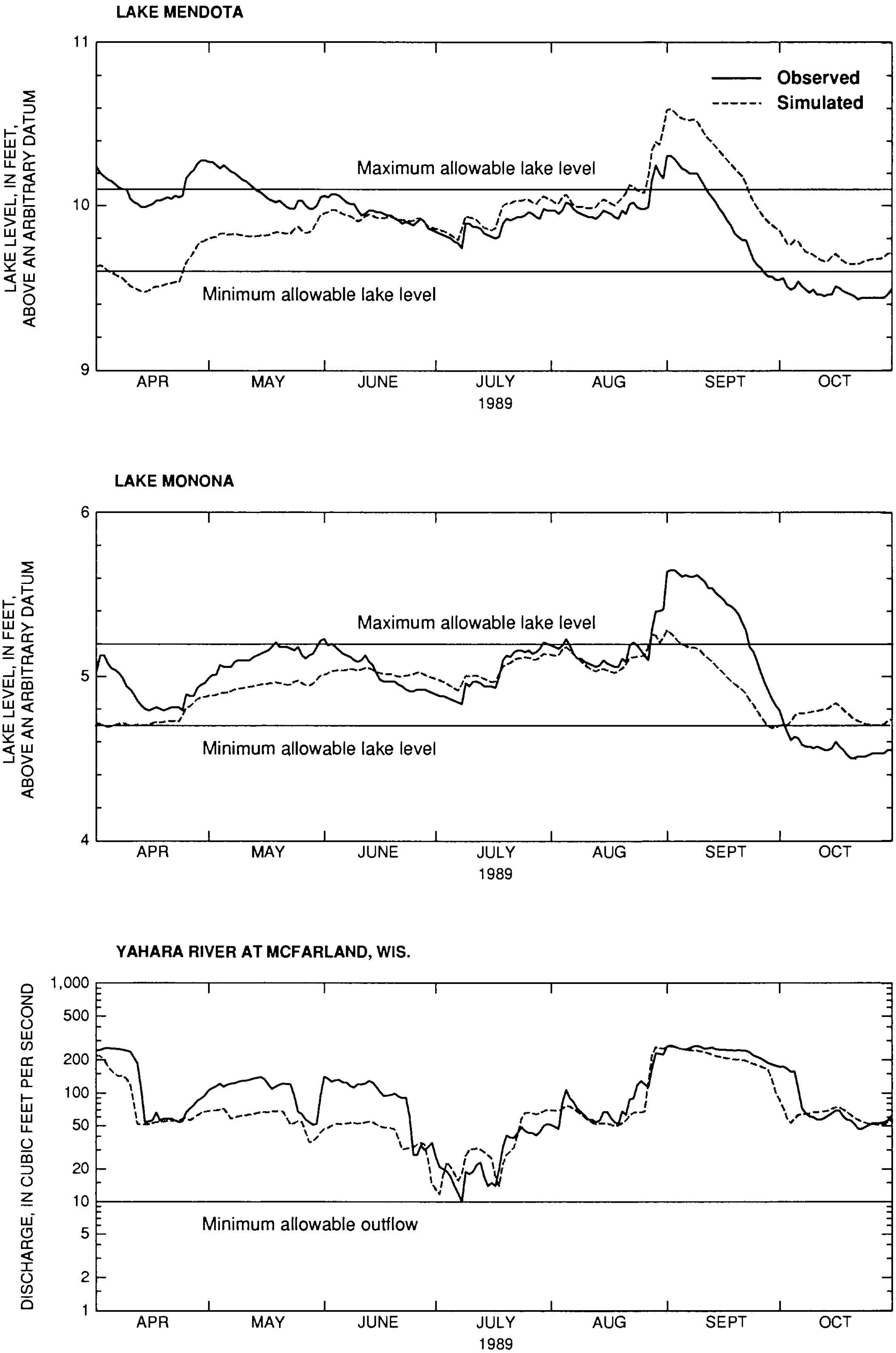

Figure 3a. Graphs showing observed and simulated daily levels of Lakes Mendota and Monona and daily streamflow for the Yahara River at McFarland for 1989, with a minimum outflow of 10 ft^3/s.

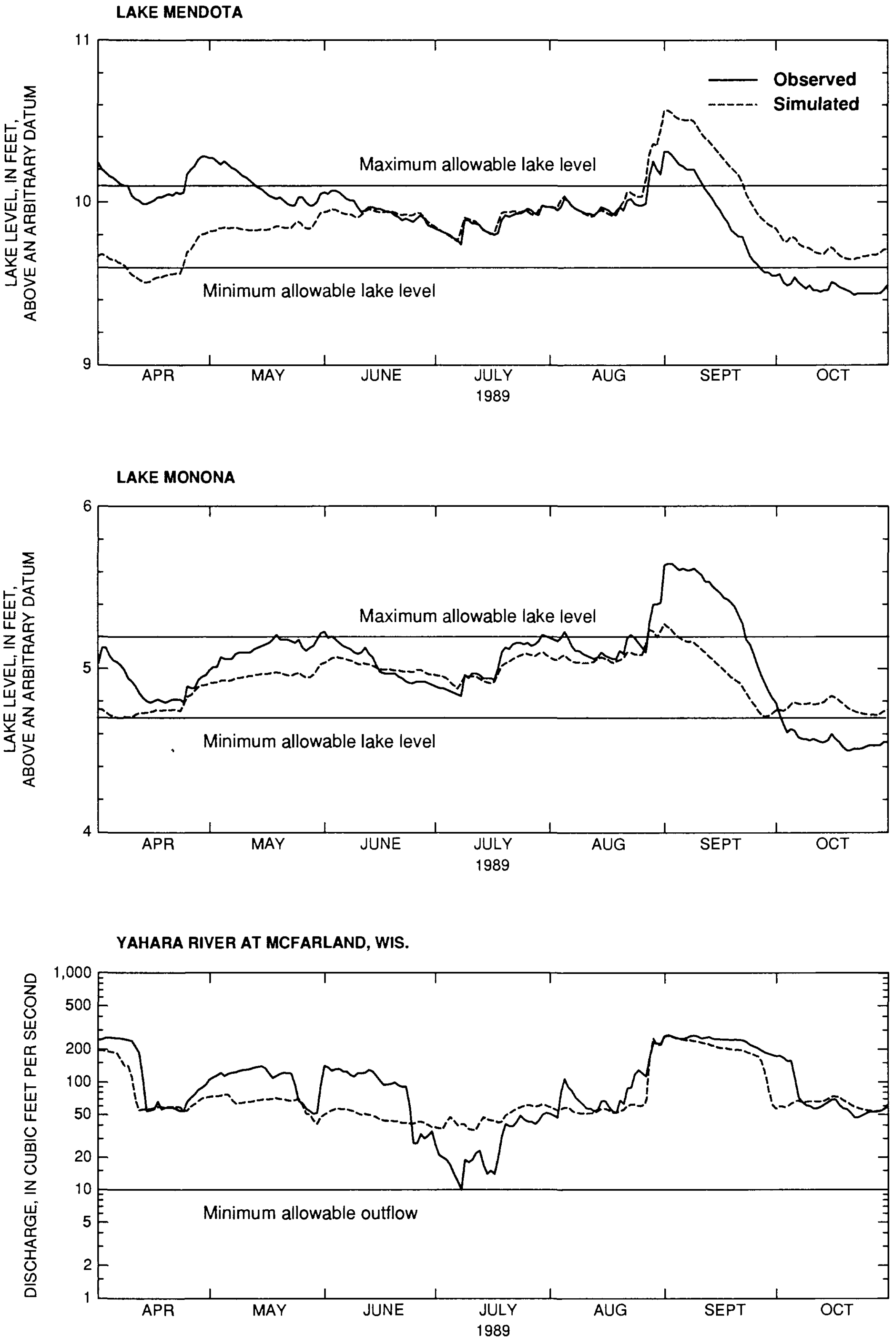

Figure 3b. Graphs showing observed and simulated daily levels of Lakes Mendota and Monona and daily streamflow for the Yahara River at McFarland for 1989, with a minimum outflow of 36 ft^3/s.

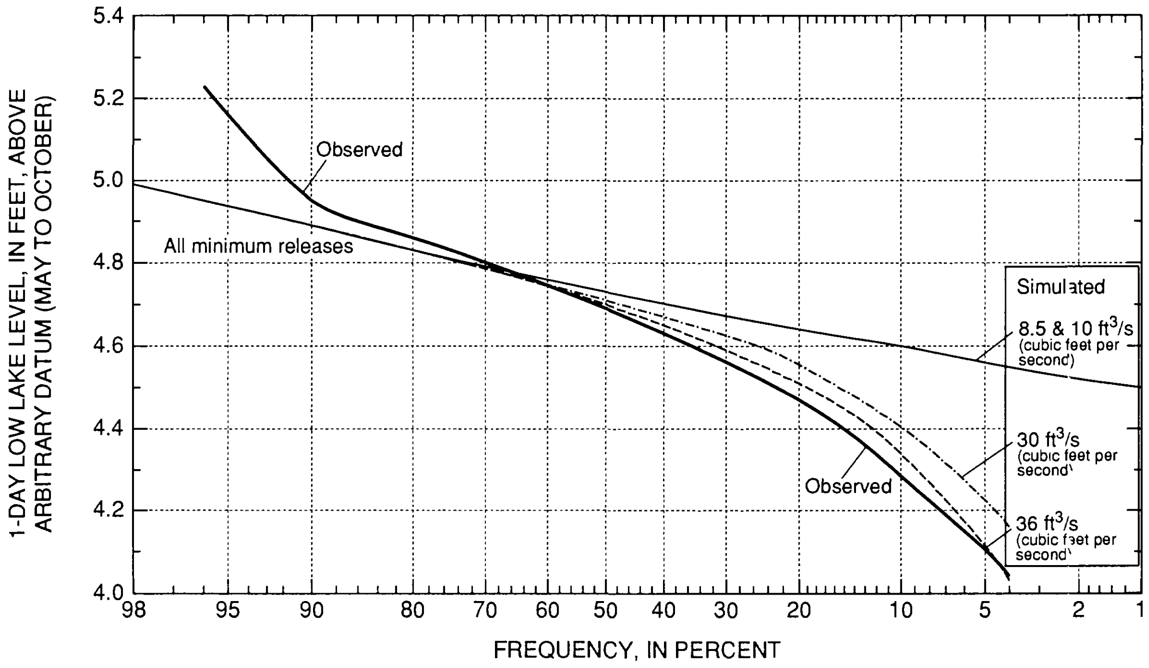

Figure 4. Frequency curve of May–October minimum level of Lake Monona for observed and simulated conditions, 1970–93.

Table 1. Annual minimum levels of Lake Monona, Wis., during May–October for simulated minimum flows of 8.5, 10, 30, and 36 ft^3/s, compared to observed minimum levels

Year	Observed level (feet)	Minimum flow maintained, in cubic feet per second			
		8.5	10	30	36
		Simulated level			
1970	4.53	4.64	4.64	4.58	4.51
1971	4.60	4.67	4.67	4.65	4.64
1972	4.80	4.84	4.84	4.76	4.74
1973	5.22	4.87	4.87	4.91	4.91
1974	4.82	4.85	4.84	4.84	4.84
1975	4.04	4.55	4.53	4.16	4.04
1976	4.22	4.57	4.57	4.30	4.15
1977	4.71	4.71	4.71	4.69	4.67
1978	4.58	4.65	4.65	4.61	4.62
1979	4.60	4.67	4.67	4.65	4.64
1980	4.74	4.79	4.79	4.72	4.71
1981	4.80	4.85	4.84	4.80	4.79
1982	4.71	4.76	4.73	4.70	4.69
1983	4.63	4.68	4.68	4.67	4.64
1984	4.82	4.85	4.85	4.84	4.84
1985	4.84	4.86	4.86	4.84	4.85
1986	4.89	4.87	4.87	4.85	4.89
1987	4.65	4.70	4.69	4.68	4.66
1988	4.58	4.66	4.66	4.64	4.63
1989	4.50	4.63	4.63	4.54	4.47
1990	4.73	4.76	4.76	4.71	4.71
1991	4.69	4.70	4.69	4.68	4.67
1992	4.24	4.63	4.61	4.43	4.40
1993	5.24	4.99	4.99	4.99	4.99

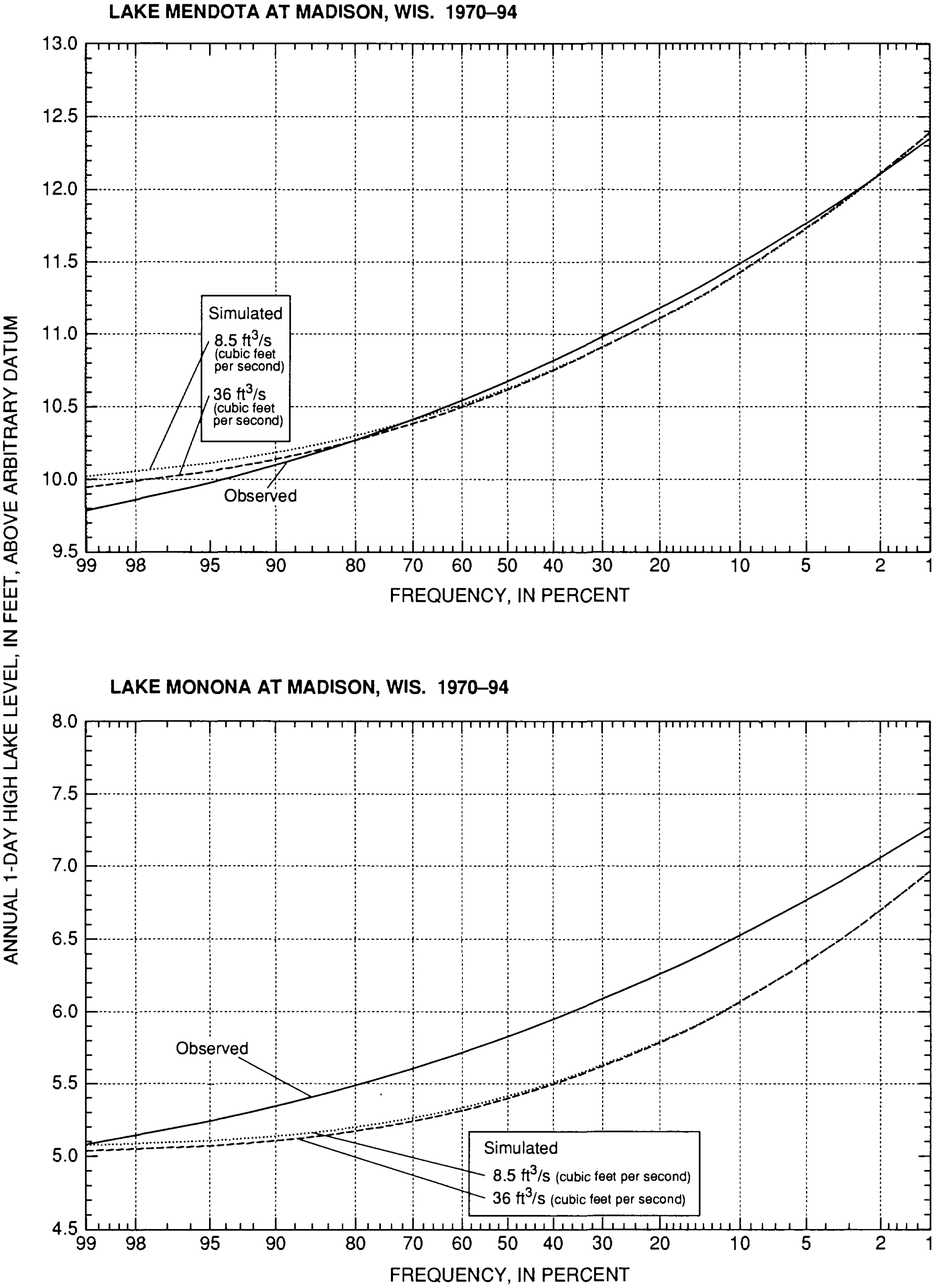

Figure 5. Frequency curves of annual maximum level of Lakes Mendota and Monona for observed and simulated conditions, 1970–94.

Table 2. Frequency of annual May–October low level of Lake Monona, Wis., for various minimum releases for the period 1970–94

Non-exceedance probability	Recurrence interval (in years)	Observed level (feet)	Simulated level for minimum flow maintained, in cubic feet per second			
			8.5	10	30	36
			Simulated level			
0.96	1.04	5.23	4.95	4.95	4.95	4.95
.9	1.11	4.95	4.89	4.89	4.89	4.89
.8	1.25	4.86	4.83	4.83	4.83	4.83
.5	2	4.69	4.73	4.73	4.71	4.70
.2	5	4.47	4.64	4.64	4.56	4.51
.1	10	4.28	4.60	4.60	4.40	4.34
.05	20	4.10	4.56	4.56	4.22	4.12
.04	25	4.04	4.55	4.55	4.16	4.03

ulated. Table 2 shows the frequency table of the same data.

SUMMARY AND CONCLUSIONS

A digital reservoir routing model was used to simulate the operation of Lakes Mendota, Monona, and Waubesa for various levels of minimum release. Twenty-five years of record (1970–94) were used in the simulation. The results of simulation demonstrate that it would be possible to maintain a minimum streamflow in the Yahara River greater than the 10 ft^3/s currently maintained without causing the water levels in the lakes to substantially exceed the range that has been observed from 1970 through 1994. Achieving this result in practice would require detailed computations to reach decisions on lake levels and dam operations.

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APPENDIX

APPENDIX: OPERATING RULES USED IN LAKE MODEL

The lake levels are in feet above 840.00 ft above sea level. Inflows and outflows are in cubic feet per second. The model changes Lake Mendota outflow at midnight and Lake Waubesa outflow (by changes in stoplogs) at noon.

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LAKE MENDOTA

I. Compute target lake level for Lake Mendota. Normally, this is the Lake Monona level plus 4.9 ft.

If the outflow at McFarland is greater than 200 ft^3/s and the Lake Monona level is higher than 4.9 ft, calculate the target level for Lake Mendota as two times the Lake Monona level (but not more than 5.2 ft above the Lake Monona level).

II. Compute the change in the outflow from Lake Mendota as the sum of components (A) and (B) as calculated below. (The outflow is never to be less than 4 ft^3/s at any time, and it must be at least 35 ft^3/s from April 1 to May 15.)

....

(A): 1. Compute the amount that the level of Lake Mendota is above the target level.

2. Add the 24-hour decrease of the Lake Monona level to the result of (A1).

3. Multiply the sum (A2) by 60.0.

(Note that either (1) or (2) or both can be negative.) If the result of this calculation (A) is a positive number, the outflow from Lake Mendota increases. If the result is negative, outflow decreases.

....

(B): Use this component only if any ONE of the following three conditions is met:

1. Lake Mendota level is above the target AND is rising.

2. Lake Mendota level is below the target AND is falling.

3. The rate of change in the Lake Mendota level in the past 24 hours would cause it to pass the target level by more than 0.03 ft if it continues to change at the same rate for another 24 hours.

If the Lake Mendota level is rising, increase the outflow: multiply the 24-hour rise in Lake Mendota level by 245.

If the Lake Mendota level is falling, decrease the outflow: multiply the 24-hour rise in Lake Mendota level by 700.

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LAKES MONONA AND WAUBESA

I. Compute target lake level for Lake Monona:

Dates	Target Lake Level
January and February	4.0 ft
March through April 10	Rises linearly from 4.0 to 5.0 ft*
April 11 through June	Rises linearly from 5.0 to 5.2 ft*
July through October	Falls linearly from 5.2 to 4.7 ft*
November and December	Falls linearly to 4.0 ft

*Possible variations explained in the following sections.

1. March through April 10: If lake level rises above the target, the target level is reset to the actual lake level (but no more than 5.0 ft). Once actual lake level reaches 5.0 ft, the target level is fixed at 5.0 ft until April 10. If the target level is raised but is still less than 5.0 ft, it continues to rise linearly to 5.0 ft on April 10.

2. April 11 through June: Similar to March through April 10. If actual lake level is above the target, the target level is reset to actual lake level (but no more than 5.2 ft). Whenever the target level is below 5.2 ft, it continues to rise linearly to 5.2 ft on June 30.

3. July through October: If actual lake level is above the target, reset the target level to the actual lake level (but no more than 5.2 ft). The target level will then fall by 0.004 ft per day, as long as the lake level is below the target level.

....

II. At noon, each day, compute the number of stoplogs to add (or remove). In the following calculations, a positive number is the number of stoplogs to add, and a negative number is the number of stoplogs to remove. Use one of two basic rules depending on the date and on the lake level relative to the upper and lower limits.

Use Method A (below) if ANY of the following conditions are met:

1. Date is from November 1 to April 10.

2. Lake Monona level is outside of the allowable summer range (4.7 to 5.2 ft).

3. Lake Monona level is rising at a rate that would put it over 5.2 ft by tomorrow noon.

Use Method B (below) at all other times. (That is, date is from April 11 to October 31, AND Lake Monona level is within the allowable range, AND Lake Monona is NOT rising fast enough to put it over 5.2 ft by tomorrow noon.)

....

Method A:

The number of stoplogs to add to the dam is computed by the following three components:

(1) Multiply (Target level minus Lake Monona level) by 12.

If Lake Monona level is less than 5.2, AND is rising, AND will not exceed 5.2 by tomorrow noon at the current rate, add the result of the following calculation to the preceding:

(2) Multiply (Rise in Lake Monona in the past 12 hours) by 175.

Finally, if Lake Monona Level is between 4.7 and 5.2, AND will not exceed 5.2 by tomorrow noon at the current rate, AND the outflow is less than 1000 cubic feet per second, THEN multiply the sum of the previous two components by:

(3) Divide (Square root of outflow) by 31.62.

....

Method B:

Compute "net inflow" as the sum of the following three components:

(Note that "net inflow" may be negative, if lake levels are falling)

(1) Multiply (7-day rise in Lake Monona/Waubesa level) by 421.3

(2) Multiply (7-day rise in Lake Mendota level) by 700.8

(3) 7-day average outflow at McFarland.

Net inflow = (1) + (2) + (3).

B1: If net inflow is greater than 100 cubic feet per second, the number of stoplogs to add to the dam is computed by the sum of the following two components:

(1) Multiply (Target level minus Lake Monona level) by 12.

(2) Divide (Current outflow minus (0.92 times net inflow)) by 90.0

Stoplogs to add to the dam = (1) + (2).

B2: If "net inflow" is less than 100 cubic feet per second, make a preliminary adjustment based on Lake Monona level (interpolating between the entries in the following table):

Lake Monona level (feet above arbitrary datum)	Adjustment (cubic feet per second)
4.7	80
Target level	130
5.2	220

If "net inflow" is between 0 and 100, multiply the adjustment by the following factor:

Divide (100 minus "net inflow") by 100.

Compute "adjusted net inflow" as "net inflow" plus the adjustment

If "adjusted net inflow" is greater than 100, the adjusted net inflow equals 100.

Finally, compute the number of stoplogs to add to the dam as the sum of the following two components:

(1) Multiply (Target minus Lake Monona Level) by 12.

(2) Divide (Current outflow minus "adjusted net inflow") by 90.0.

Stoplogs to add to the dam = (1) + (2).

....

For both Methods A & B: If the number of stoplogs to add (or to remove, if the number calculated is negative) is 4 or fewer, further reduce the stoplog adjustment by the following formula:

Adjusted number = $(\text{Calculated number})^2 / 4$.

....

Round off the number of stoplogs to add (or remove) to the nearest whole number.

Estimate what the outflow would be after the stoplogs are added or removed. If the outflow will be less than the minimum outflow, readjust the number of stoplogs until the minimum outflow will be released at the current lake level.

Various numerical constants are used in these operating rules. The values of these constants were derived by trial and error with the model simulations. The initial values of the constants were derived from the area of the lakes and the changes in outflow required to bring the lake levels to the target level within a small number of days, assuming constant inflow. The initial values were adjusted to prevent simulated outflow from changing too abruptly with small changes in inflow, but still to respond quickly to large changes in inflow.

The different choices in operating rules were necessary to respond aggressively to changes whenever lake levels were outside of the regulatory limits, but to respond more slowly when lake levels were within the regulatory limits. When only small changes were indicated, the operating rules reduce the amount of adjustment to be made to avoid frequent small adjustments to the gates.