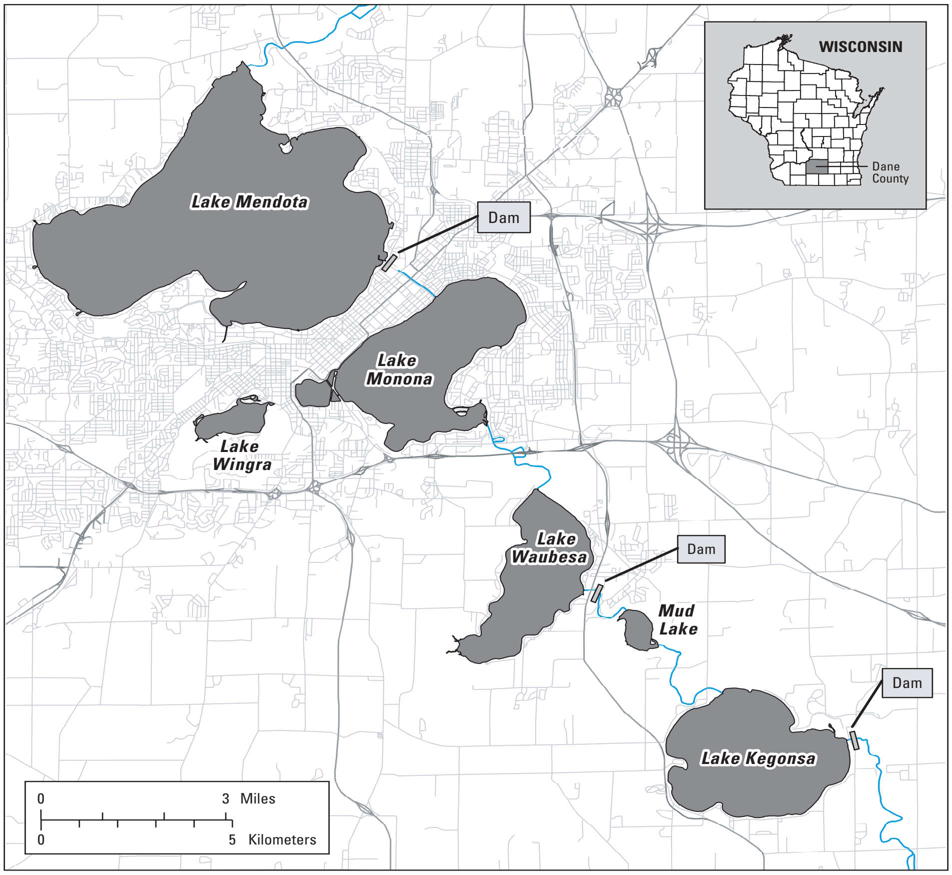
science for a changing world

In cooperation with the Dane County Regional Planning Commission, Dane County, and the Wisconsin Department of Natural Resources

Simulation of the Effects of Operating Lakes Mendota, Monona, and Waubesa, South-Central Wisconsin, as Multipurpose Reservoirs to Reduce Water Levels During Floods



Open-File Report 2004-XXXX

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

Simulation of the Effects of Operating Lakes Mendota, Monona, and Waubesa, South-Central Wisconsin, as Multipurpose Reservoirs to Reduce Water Levels During Floods

By W.R. Krug and P.E. Hughes

In cooperation with the Dane County Regional Planning Commission , Dane County, and the
Wisconsin Department of Natural Resources

Open-File Report 2004–______

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

U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

U.S. Geological Survey, Reston, Virginia: 2004
For sale by U.S. Geological Survey, Information Services
Box 25286, Denver Federal Center
Denver, CO 80225

For more information about the USGS and its products:
Telephone: 1-888-ASK-USGS
World Wide Web: http://www.usgs.gov/

Contents

Figures

Tables

Conversion Factors and Datum

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Simulation of the Effects of Operating Lakes Mendota, Monona, and Waubesa, South-Central Wisconsin, as Multipurpose Reservoirs to Reduce Water Levels During Floods

By W.R. Krug and P.E. Hughes

Abstract

A digital reservoir routing model that was used in a previous study of low flows was modified to simulate the operation of Lakes Mendota, Monona, and Waubesa, south-central Wisconsin for various operation rules to attempt to limit high water levels on the lakes. Seventy-one years of record (1931–2001) were used in model simulation. The goal of the simulation was to determine the degree to which modifications in the operation of the dams controlling the outlets could affect high lake levels.

Introduction

The Madison metropolitan area in central Dane County, Wis. (fig. 1), surrounds a chain of large lakes. Twice in recent years (1993 and 2000), the shorelands surrounding these lakes have been damaged and threatened by record high water levels.

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:

Table 1. Regulatory levels for Lakes Mendota, Monona, and Waubesa

Lake	Maximum	March–Oct.	Nov.–Feb.
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 reduce maximum lake levels during floods. 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 reduce maximum flood levels without adversely affecting low flows in the Yahara river. Seventy-one years of record (1931–2001) were used in model simulations, including a range of wet, normal, and dry years. Diversion of wastewater effluent was begun in 1959, and increased in stages with most of the current diversion in effect by 1970.

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. This metropolitan area is one of the most rapidly developing urban areas within Wisconsin and as a result the lakes are receiving more direct surface water runoff from the ever increasing impervious areas.

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.

Simulation of Reservoir Operation

Model Description

The model applied in this study was adapted from a reservoir operation model originally developed for a simulation of Lake Winnebago (Krug, 1981), and previously adapted for a low-flow study of these lakes (Krug, 1999). The model was extensively modified for the 1999 study to include specific operation limits and criteria for the Madison lakes, and was further modified for this study to include specific operation rules for reducing high stages. The earlier model was modified for additional lake level and outflow data obtained since the previous study. The relation between the water level and discharge in the channel downstream from Lake Waubesa was changed in the model to agree with the present rating curve for the gaging station. The seasonal average backwater effect was adjusted for this change as well. In addition, an equation relating the difference in elevation between Lakes Monona and Waubesa as a function of outflow from Lake Waubesa was used to simulate the relation of Lake Monona water levels with the outflow from Lake Waubesa.

Regulatory and Physical Limits

All of the regulatory and physical limiting factors were included in this 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 less than 0.10 ft, from mid-February to mid-April, to more than 1 ft, from mid-July to mid-September.

The seasonal average backwater effect used in the model limited the ability to compare the model results with actual lake

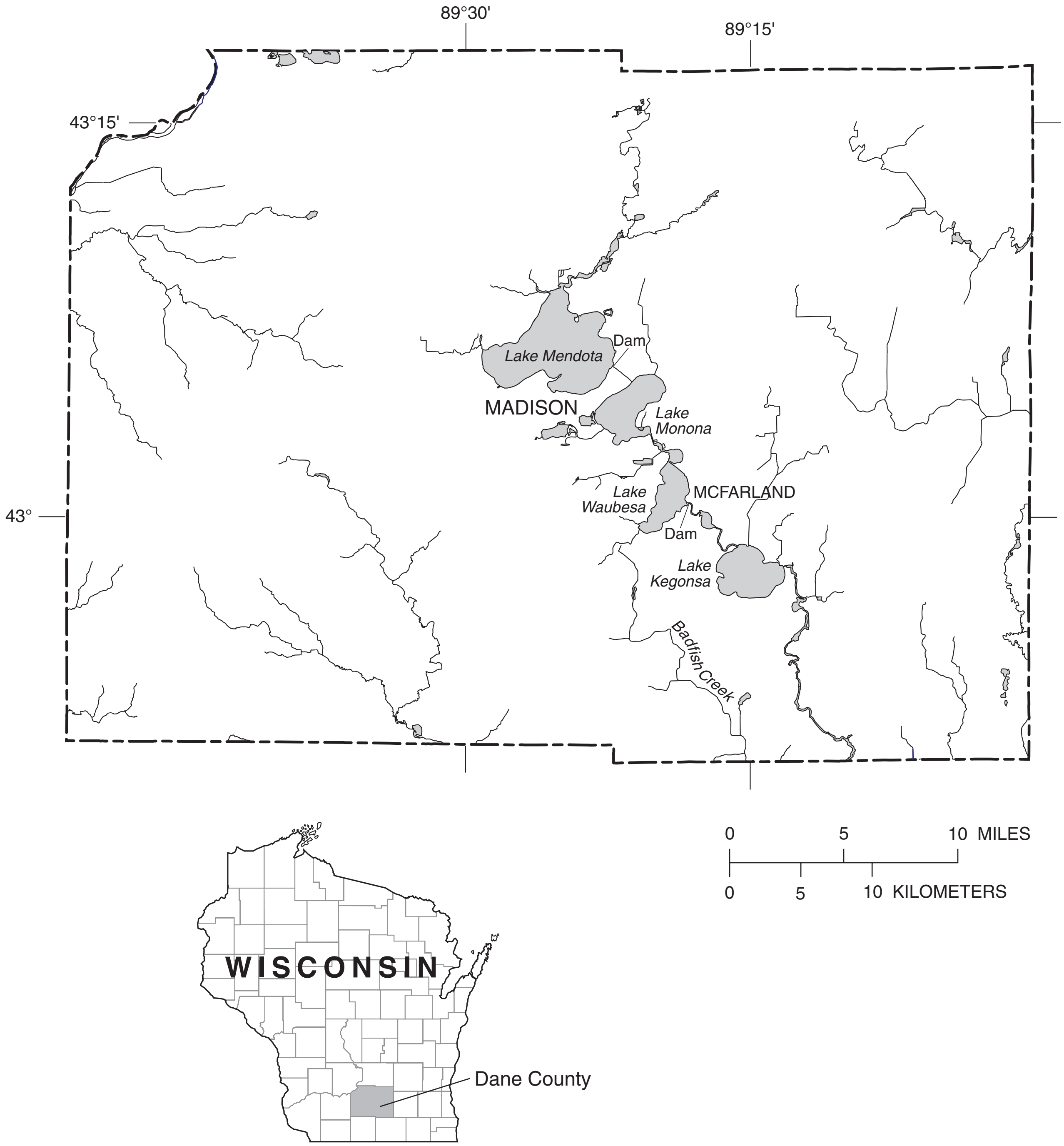


Figure 1. Location of study area.

levels. In any particular year, the actual backwater could be as much as a foot different from the average used by the model.

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 a maximum level 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.

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. Limitations of the outflow capacity of the dams and channels make it impossible to actually reach these minimum drawdown levels in many years. The practical result of this winter operating procedure is to lower the lake levels as much as possible, given the physical constrains on the outflow.

The operating procedures in the low-flow model 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.

Operating Alternatives Simulated

Three operating alternatives were evaluated in the model. For each alternative, a minimum release from the outlet of Lake Waubesa of 30 ft^3/s was required. The three alternatives were: (1) an extreme simulation; essentially keeping lake levels as low as possible at all times, (2) a high-stage reduction simulation with early summer target elevations closer to the middle of the regulatory lake level range, rather than at the upper limit (originally proposed by John Dunn from the Dane County Public Works Department), and (3) the low-flow simulation used in the previous study. A fourth alternative, that included modified operations at the LaFollete Park dam on Lake Kegonsa and the downstream Stoughton dam, could not be included in the analyses due to incomplete data records for the Stoughton dam. For the first alternative, the model simulated free outflow from Lake Waubesa, with no stoplogs in place, and the lock gate open at all times. The lake level and outflow were governed by the seasonal average relation between water level and discharge at the gaging station at the lake outlet.

For the second alternative, the target stages in the model were changed from those used in the low-flow model.The second alternative was identical to the low-flow model for the period from November 1 to April 10. After April 10, the target stage in the low-flow model rose from 5.00 ft to 5.20 ft on July 1, then declined to 4.70 ft on November 1. The target stage for the second alternative rose more quickly, from 5.00 ft on April 10 to 5.20 ft on May 15, then declined to 4.95 ft on June 1. The target stage then remained at 4.95 ft until September 15. After September 15 the target stage declined again to 4.70 ft on November 1. The second alternative had a higher target stage from April 10 to May 20, then a lower target stage from May 20 to September 1. After September 1 there was little difference in the target stage.

Results of Simulation

In each operating alternative, the release of the minimum flow of 30 ft^3/s 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. In general, the second alternative resulted in lower lake levels than the earlier simulation. This was true for both wet and dry periods.

Figures 2–4 demonstrate the effects of the model simulation during notable dry and wet periods. The discharge of the Yahara River at McFarland is plotted on the secondary Y axis of each figure. Figure 2 shows the simulated stage of Lake Monona during the dry summer of 1988. The simulated lake levels of alternative 1 are very low, as expected. The simulated lake levels for alternatives 2 and 3 are very similar, and both are lower than the actual lake level for this period. The simulations for alternatives 2 and 3 included maintaining at least 30 ft^3/s of outflow, while the actual outflow for the months of June–September was about 21 ft^3/s.

Figure 3 shows a similar comparison for the flood period of July and August 1993. In this year all three of the simulated alternative lake levels were virtually identical. The preceding several months were also very wet, and all of the simulations included water levels well above the maximum allowable lev-

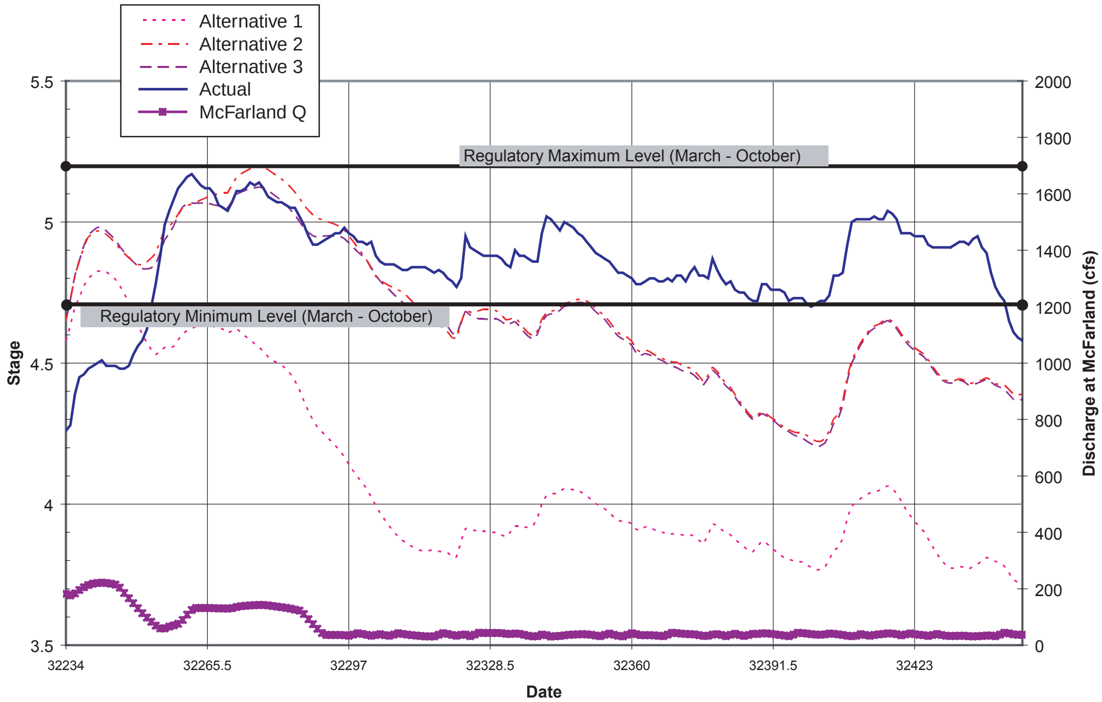


Figure 2. Lake Monona simulation during the dry period of summer 1988.

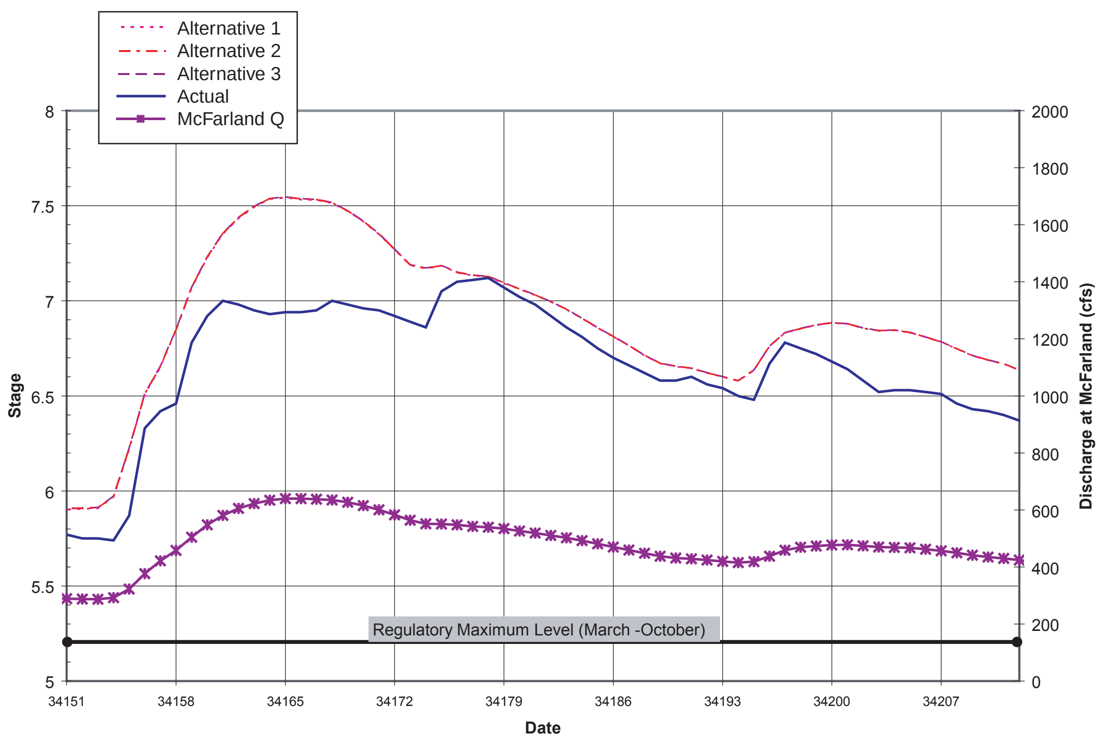


Figure 3. Lake Monona simulation during the flood period of July - August 1993.

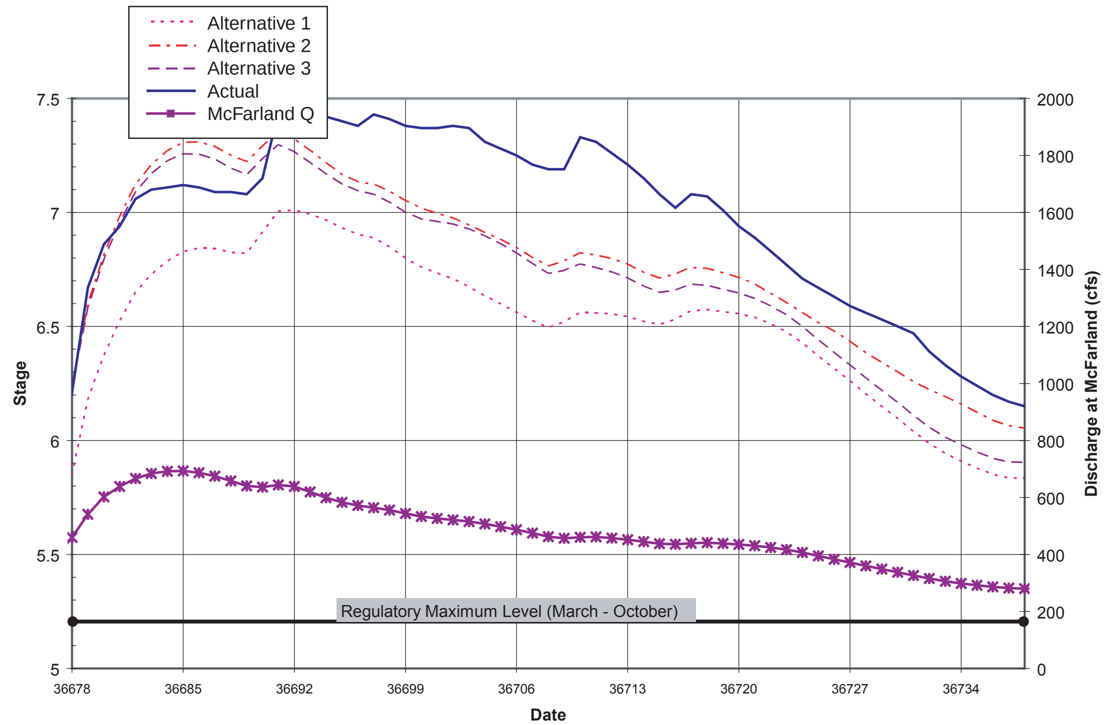


Figure 4. Lake Monona simulation during the flood period of July 2000.

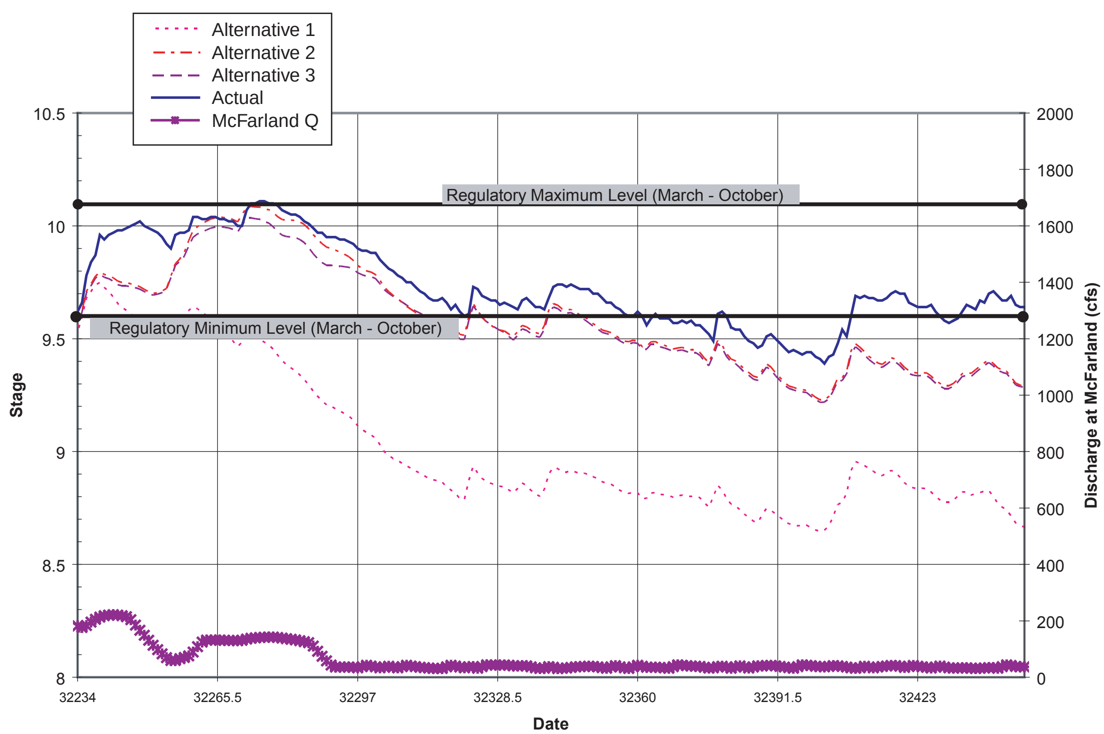


Figure 5. Lake Mendota simulation during the dry period of summer 1988.

els. Thus all of the simulations were identical—having all gates open to allow the maximum amount outflow. The actual water level was lower than all of the simulations because of differences between the actual backwater from the channel downstream and the average value used in the model.

Figure 4 shows a comparison for the flood period of June and July 2000. In this case there are differences among the alternative simulations. During the months preceding this flood period the water levels had been more normal, and the 3 alternatives simulated slightly different water levels because of the different target elevations used. In this case, the alternative 3 simulation started from a lower lake level than the alternative 2 simulation. This difference continued through the flood period. The actual water level was higher than any of the simulations because the backwater from the channel downstream was greater than the average backwater during this period.

Figures 5–7 show the simulated stage data for Lake Mendota for the same time periods as the Lake Monona data. These figures show that Lake Mendota had a similar response to Lake Monona except that the actual stage for Lake Mendota drops down below the simulated stage in July 2000; while at Lake Monona the actual stage was above the simulated stages throughout the June–July 2000 flood period.

Table 2 shows the average of the highest lake levels for Mendota and Monona for the 10 wettest years of the model simulation. The differences between alternatives 2 and 3 were very slight. And both of these alternatives had maximum water levels that were only 0.2 to 0.3 ft higher than the extreme alternative.

Table 2. Average of the highest level of Lakes Mendota and Monona for the 10 wettest years

Lake	Alternative 1	Alternative 2	Alternative 3	Observed
Mendota	11.65	11.96	11.97	11.55
Monona	6.50	6.71	6.73	6.85

Table 3 shows the average of the lowest summer lake levels for Mendota and Monona for the 10 driest years of the model simulation. Alternative 2 had slighlty lower summer minimum water levels than alternative 3. Alternative 1 was designed to have very low summer levels to test the lowest possible water levels that could be maintained.

Table 3. Average of the lowest summer level of Lakes Mendota and Monona for the 10 driest years

Lake	Alternative 1	Alternative 2	Alternative 3	Observed
Mendota	8.58	9.04	9.18	8.81
Monona	3.65	4.11	4.24	4.28

Another illustration of the differences between the alternatives is the number of days when the water levels are either above the maximum allowable stage or below the summer minimum stage. For the calculation of the number of days below the summer minimum stage, the days were counted starting with the day after March 1 each year when the stage first rose above the minimum stage. Only data from 1979–2001 was used for this evaluation to show the modeling results during the period with the current operating rules in effect. Table 4 shows the average number of summer days between 1979–2001 with water levels below the summer minimum for the three modeled alternatives and the observed data.

Table 4. Average number of summer days 1979–2001 with water levels below summer minimum stage

Lake	Alternative 1	Alternative 2	Alternative 3	Observed
Mendota	66	14	13	12
Monona	73	18	14	9

Table 5 shows the average number of summer days between 1979–2001 with water levels above the summer maximum for the three modeled alternatives and the observed data.

Table 5. Average number of summer days 1979–2001 with water levels above the maximum stage

Lake	Alternative 1	Alternative 2	Alternative 3	Observed
Mendota	77	110	119	94
Monona	53	70	76	108

Alternative 2 had slightly fewer days above the maximum stage than alternative 3, but it had slightly more days below the minimum stage. Even alternative 1, trying to keep the lake levels as low as possible, had a significant number of days with water levels above the maximum.

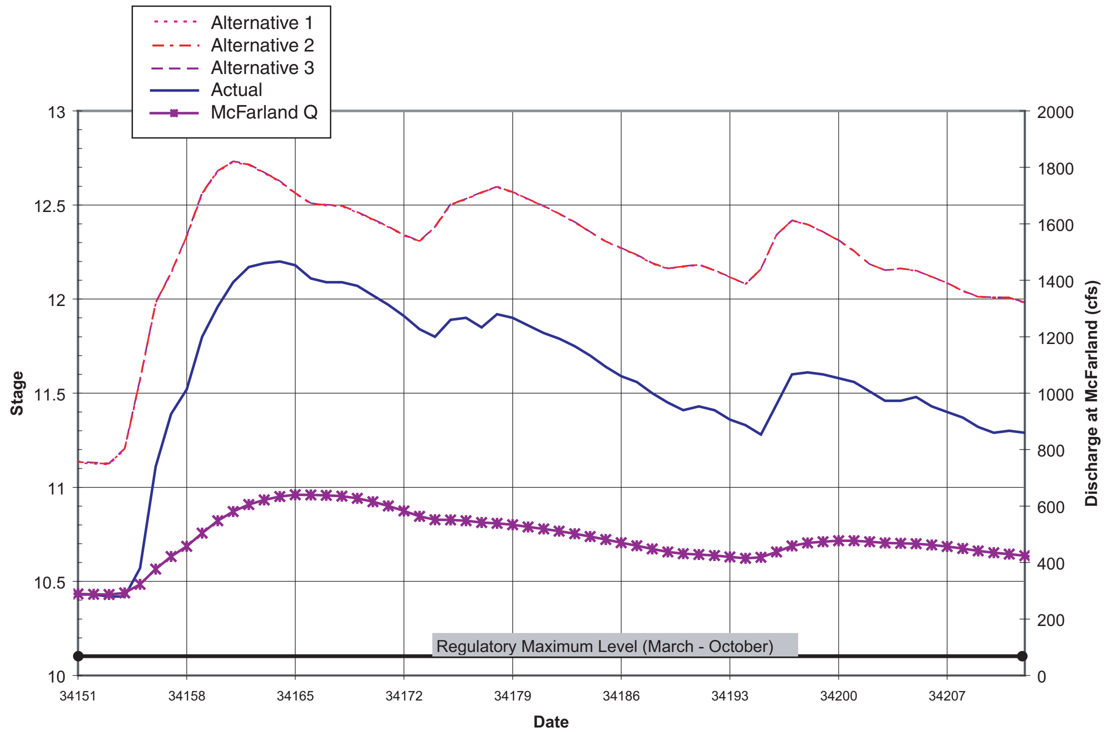


Figure 6. Lake Mendota simulation during the flood period of July - August 1993.

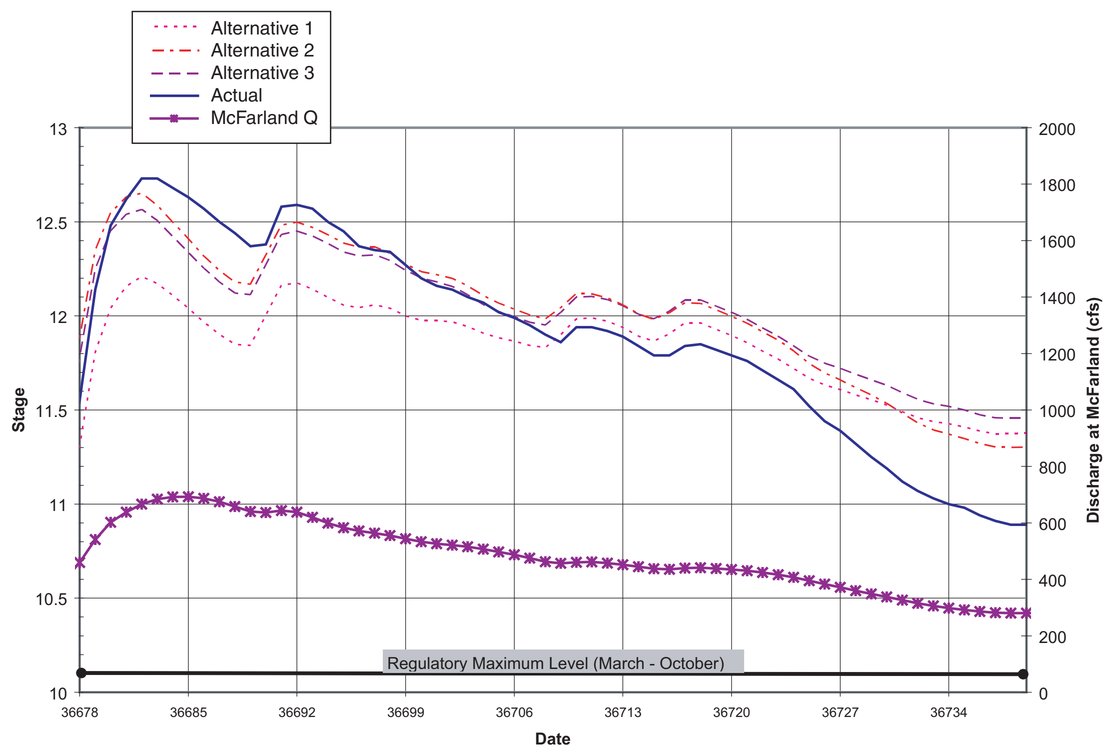


Figure 7. Lake Mendota simulation during the flood period of June - July 2000.

Limitations of Model

The model has several limitations in simulating the actual conditions. Input data is based on observed historical conditions, and the current hydrologic conditions have probably been modified by land use modifications from increasing urbanization. The outflow limitations are based on seasonal average backwater conditions affecting the channel downstream from Lake Waubesa. These backwater conditions are primarily due to weed growth and decay in the channel, but other factors may also affect the backwater, possibly including the variable lake level of Lake Kegonsa farther downstream.

The first limitation might be overcome by an accurate simulation of rainfall-runoff conditions in the watershed with a computer model. Such simulation was beyond the scope of this study, and would require a significant expansion of the rainfall-runoff modeling which has been done on small parts of the basin.

Overcoming the second limitation would require more research into the exact conditions limiting the outflow in the channel downstream from Lake Waubesa. Many factors could be involved, beyond those already observed.

Summary and Conclusions

A digital reservoir routing model that was used in a previous study of low flows was modified to simulate the operation of Lakes Mendota, Monona, and Waubesa, south-central Wisconsin for various operation rules to attempt to limit high water levels on the lakes. Seventy-one years of record (1931–2001) were used in model simulation. The goal of the simulation was to determine the degree to which modifications in the operation of the dams controlling the outlets could affect high lake levels.

The results of the simulation for alternative 2 demonstrates that it is possible to lower the maximum water levels slightly but that minimum water levels would also be lowered. This alternative would reduce the number of days that water levels were above the maximum allowable stage, but would also increase the number of days that the water levels were below the minimum allowable stage during the summer season. However, these changes were small, when compared to alternative 3, which was intended to augment low flows as much as possible.

Simulation of alternative 1—intended to keep the lake levels as low as possible—demonstrates that the limitations of the outflow channels make it impossible to keep the lake levels below the regulatory limits during wet years. Even this alternative has maximum stages significantly above the maximum allowable stage, and a significant number of days when water levels are above the maximum allowable stage.

References Cited

Krug, W.R., l98l, Hydrologic effects of proposed changes in management practices, Winnebago pool, Wisconsin: U.S. Geological Survey Water-Resources Investigations 80–l07, 19 p.

Krug, W.R., l999, Simulation of the effects of operating Lakes Mendota, Monona, and Waubesa, south-central Wisconsin, as multipurpose reservoirs to maintain dry-weather flow: U.S. Geological Survey Open-File Report 99–67, 18 p.