OPEN-FILE REPORT 79-253

Simulation of Streamflow of Rock River at Lake Koshkonong, Wisconsin, to Determine Effects of Withdrawal of Powerplant-Cooling Water

PREPARED BY
UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

IN COOPERATION WITH
WISCONSIN DEPARTMENT OF NATURAL RESOURCES

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By William R. Krug

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William R. Krug

ABSTRACT

A flow-routing model was used to simulate 44 years of stage data from Lake Koshkonong and streamflow data from the Rock River downstream from the lake. The simulation was repeated for five possible rates of consumptive use, ranging from zero to an annual average of 40 cubic feet per second. A minimum release rule was applied to the simulated operation of the dam at Indianford to guarantee at least the 7-day, 10-year low-flow discharge in the Rock River downstream from Lake Koshkonong.

The simulated stage of Lake Koshkonong with consumptive use at 40 cubic feet per second was as much as 0.42 feet lower than the simulated stage with zero consumptive use for the same period. Duration of drawdown below the regulatory minimum stage of 11.8 feet, occurring once in 10 years, increased from 83 to 132 days as consumptive use increased from 0 to 40 cubic feet per second.

INTRODUCTION

In 1974 the Wisconsin Electric Power Co. proposed to build a nuclear powerplant near Lake Koshkonong, Wis. The proposed plant would use lake water for cooling. As much as 50 ft^3/s would be lost to evaporation and drift from the cooling towers (Nuclear Regulatory Commission, 1976). The Wisconsin Department of Natural Resources (DNR) was concerned about a number of possible adverse effects. Consumptive use of water from Lake Koshkonong could conflict with other water use in the lake and in the river downstream at low flows. Reduction of low flows downstream could decrease the waste-assimilation capacity of the river, reducing water quality. Reduction of lake stage could hinder recreational use of the lake in summer and could increase the probability of fish kills in winter due to reduced water volume in the lake (DNR, oral commun., 1977). The proposal for a nuclear powerplant at the Lake Koshkonong site has been dropped, but a similar nuclear plant or a smaller fossil-fuel plant may be proposed in the future.

The purpose of this project was to evaluate the potential impact of consumptive use of cooling water by a powerplant on the flow of the Rock River and on the stage of Lake Koshkonong. The study was conducted in cooperation with the DNR. At the request of DNR, the study included several possible levels of consumptive use, and a requirement for a minimum release of 69 ft^3/s from Lake Koshkonong.

For the use of readers who prefer the International System of Units (SI) rather than inch-pound units, the conversion factors for the terms used in this report are listed below.

Multiply inch-pound unit	By	To obtain SI unit
acre	$4.047X10^{-3}$	square kilometer (km^2)
cubic foot per second (ft^3/s)	$2.832X10^{-2}$	cubic meter per second (m^3/s)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.59	square kilometer (km^2)

The Rock River basin is in southern Wisconsin. This study deals with the Rock River between Watertown, Wis., and the Illinois State line (fig. 1). Lake Koshkonong is roughly midway between Watertown and the State line.

Lake Koshkonong was largely a marsh along the Rock River before construction of a low dam about 1850 at Indianford. The dam was rebuilt and raised nearly to its present height in 1917 (Poff and others, 1968). The current dam maintains a lake of about 11,000 acres, with an average depth of less than 5 ft (Nuclear Regulatory Commission, 1976).

The narrow valley near Indianford prevented a lake from forming just upstream from the dam. Lake Koshkonong is 6 mi upstream from the dam at Indianford. The channel between Lake Koshkonong and the dam is generally less than 1,000 ft wide and is similar to the channel downstream from the dam.

DATA USED FOR DIGITAL MODELING

Streamflow records for five regular gaging stations were used to model the study reach of the Rock River. The stations used, with their period of record and drainage area, are listed in table 1. Locations of the stations are shown on figure 1. Sufficient information was available for adequate modeling for water years 1932 through 1975.

The Watertown gage was discontinued at the end of the 1970 water year, and the Indianford gage was not begun until May 1975. The Watertown records were, therefore, extended, based on correlation with records from the Milford gage to obtain a complete period of record for modeling.

The complete period of record at Watertown, 1932-75, was simulated from the Milford record and compared with the actual record at Watertown for 1932-70. Day-to-day differences were large in some cases, but the generalized flow characteristics (flow duration, low-flow and high-flow

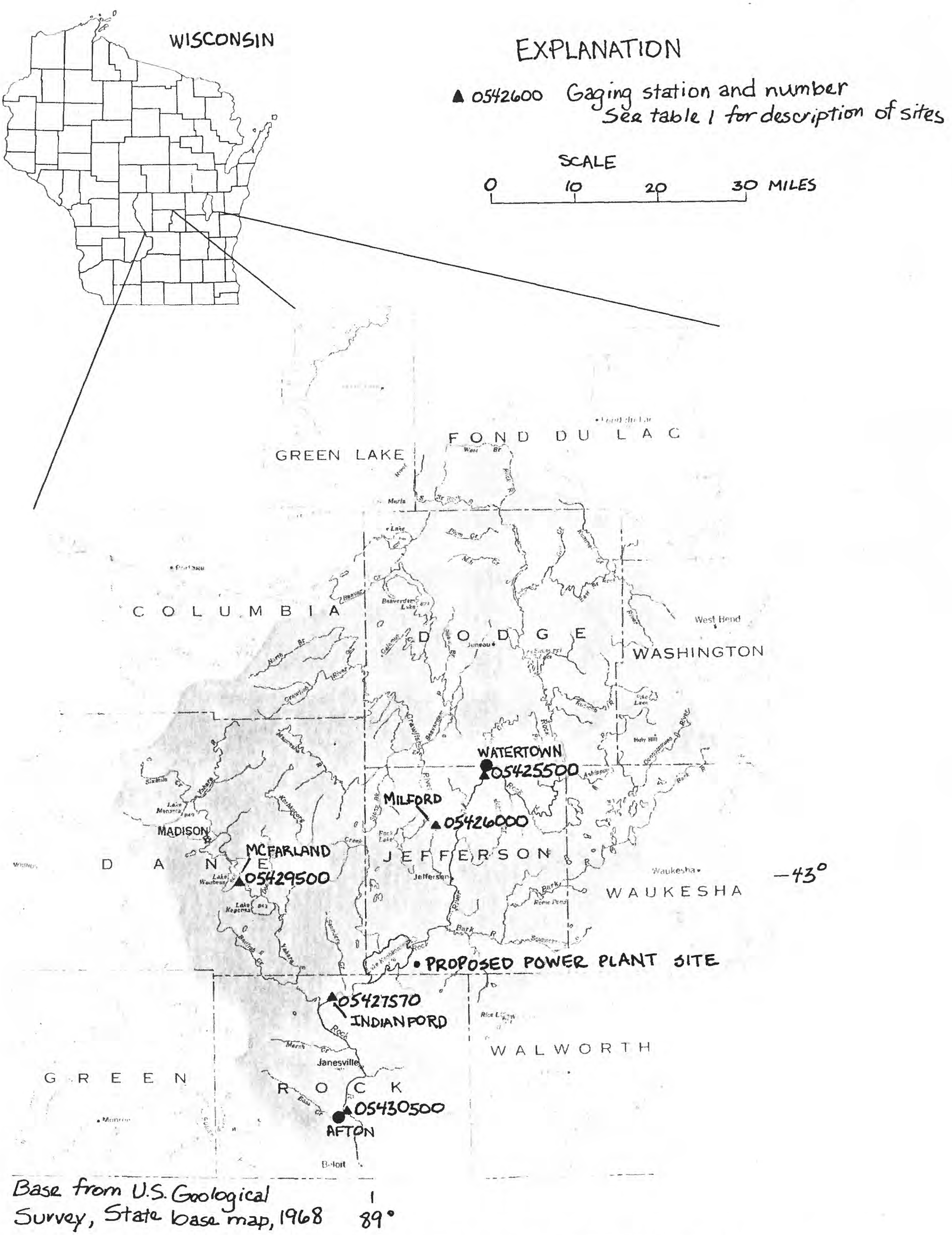

Figure 1. Location of study area and gaging stations used in the model.

Table 1.--Gaging stations used in the study and their drainage areas and period of record

Station number and name		Drainage area (mi2)	Water years of record[1]
05425500	Rock River at Watertown	971	1931-70
05426000	Crawfish River at Milford	732	1931-76
05427570	Rock River at Indianford	2,573	1975-76
05429500	Yahara River near McFarland	327	1930-76
05430500	Rock River at Afton	3,338	1914-76

[1]Beginning water year of record is incomplete at all stations.

frequency) agreed except at very low flows. During the years 1971-75, the streams in the basin all had relatively high base flows.

The final verification of the simulated streamflow at Watertown was the accuracy of the simulated streamflow at Indianford. Streamflow at Indianford was simulated twice, first for 1932-75 using the simulated streamflow at Watertown, and second for 1932-70 using the recorded streamflow at Watertown. Eight years were selected from 1932-70 when the minimum 7-day mean flows were closest to the minimum, 7-day mean flows for the years 1971-75. In these 8 years, the difference between the minimum 7-day mean flows averaged 7 percent. Similarly, the maximum 7-day mean flows were compared for 10 years and the differences averaged 1 percent.

Additional data for modeling were obtained from the Madison Metropolitan Sewerage District (MMSD). Effluent from their treatment plant (averaging 35 ft3/s in 1975) is discharged to Badfish Creek, which flows into the Yahara River downstream from the McFarland gage. Before 1958 the effluent was discharged to the Yahara River upstream from the gage. The MMSD effluent discharges (using monthly averages) were added to the record for 1958-76 at the McFarland gage to obtain a consistent record at McFarland.

DESCRIPTION OF CHANNEL-ROUTING MODELS

Channel-Routing Submodel

The streamflow-routing model used in this study is based on the unit-response concept and convolution technique described by Sauer (1973), with the unit-response functions computed by the diffusion-analogy method (Keefer, 1974). A unit-response function, as determined by the diffusion-analogy method, depends upon:

1. Length of the reach, and
2. the coefficients,

   C_o, for wave celerity, and

   K, for wave-dispersion.

C_o and K are determined for a selected representative discharge Q_o and are functions of the channel width, water-surface slope, slope of stage-discharge relation, and Froude number; all at discharge Q_o.

The channel characteristics used to determine C_o and K should represent the entire reach. In practice, they can be measured only at selected points. Thus, the computed C_o and K values are estimates and must be tested on a reach where simulated discharges can be compared with observed discharges. Usually these estimated C_o and K values are adjusted during model calibration to obtain the best possible agreement between simulated and recorded discharges.

The unit-response function defines the discharge at the downstream end of a modeling reach as a function of the discharge at the upstream end. Although the unit-response function is continuous, for daily routing, daily unit-response coefficients are computed by averaging the ordinates of the function for each day. For a daily discharge at the upstream end, the unit-response coefficients specify the percentage of that discharge that arrives at the downstream end on the same day and on each successive day. Daily discharge at the downstream end for a given day is the summation of the contribution of discharge at the upstream end from that day and each preceding day.

If the unit-response function has zero values for more than a day before nonzero values start, a traveltime is used instead of routing coefficients equal to zero.

Reservoir-Routing Submodel

The reservoir-routing model simulates operation of the dam at Indianford and its effects on the stage of Lake Koshkonong and flow in the Rock River downstream from the dam. The model computes daily outflow at the dam based on the mean gage height upstream from the dam. Differences in water-surface elevation between the dam and the lake due to friction loss in the channel between them are computed as a function of discharge. Changes in gage height are computed from the differences in inflow and outflow and a stage-storage function for the lake.

The dam at Indianford is a low, run-of-the-river structure. The dam includes an unused powerplant at its west end, six small lift gates at its east end, and an uncontrolled spillway between them. Gage height at the upstream side of the dam is referred to datum 763.74 ft above the National Vertical Geodetic Datum. Current regulations call for maintaining the gage height between 11.8 and 12.1 ft whenever possible. Maintaining gage height within this range is possible whenever discharge through the dam is between 120 and 1,340 ft^3/s. Outflows in this range are controlled by opening or closing gates as necessary. The powerplant is now being repaired for future power generation, but operation of this plant is not considered in this study.

The reservoir-routing model simulates the actual operating procedures, with several simplifications. The model does not simulate gate openings and closings when gage height is between 11.95 and 12.05 ft and discharge is between 210 and 1,280 ft^3/s. The model assumes that some unspecified gate openings will maintain discharge and stage within these limits whenever possible. If gage height and discharge are greater than these limits, the model uses the rating curve of the spillway and all gates open to relate gage height and discharge. If gage height and discharge are less than these limits, the model uses the rating curve of the spillway alone to relate gage height and discharge.

As requested by the DNR (written commun., 1977), the model simulates a release from storage in Lake Koshkonong, during low-flow periods, in the interest of maintaining minimum flow in the river downstream. The rules, requested by DNR, governing this release are different in winter and summer. During the entire year, the simulated discharge at Indianford is at least 69 ft^3/s, the annual minimum 7-day mean flow below which the flow will fall on the average of once in 10 years ($Q_{7,10}$). From April 1 to October 31, the model simulates a release from storage whenever the discharge is less than the 95 percent flow duration (117 ft^3/s). In this case the simulated discharge is the mean of 117 ft^3/s and the discharge that would flow over the spillway at the simulated stage, but no less than 69 ft^3/s. Part of this composite rating curve is shown in figure 2.

The reservoir-routing model computes daily outflow based on gage height using this rating curve. A trial-and-error method is used to balance inflow, outflow, and change in storage. A cubic equation, determined from the stage-storage curve for Lake Koshkonong, is used to relate surface area of the lake to gage height.

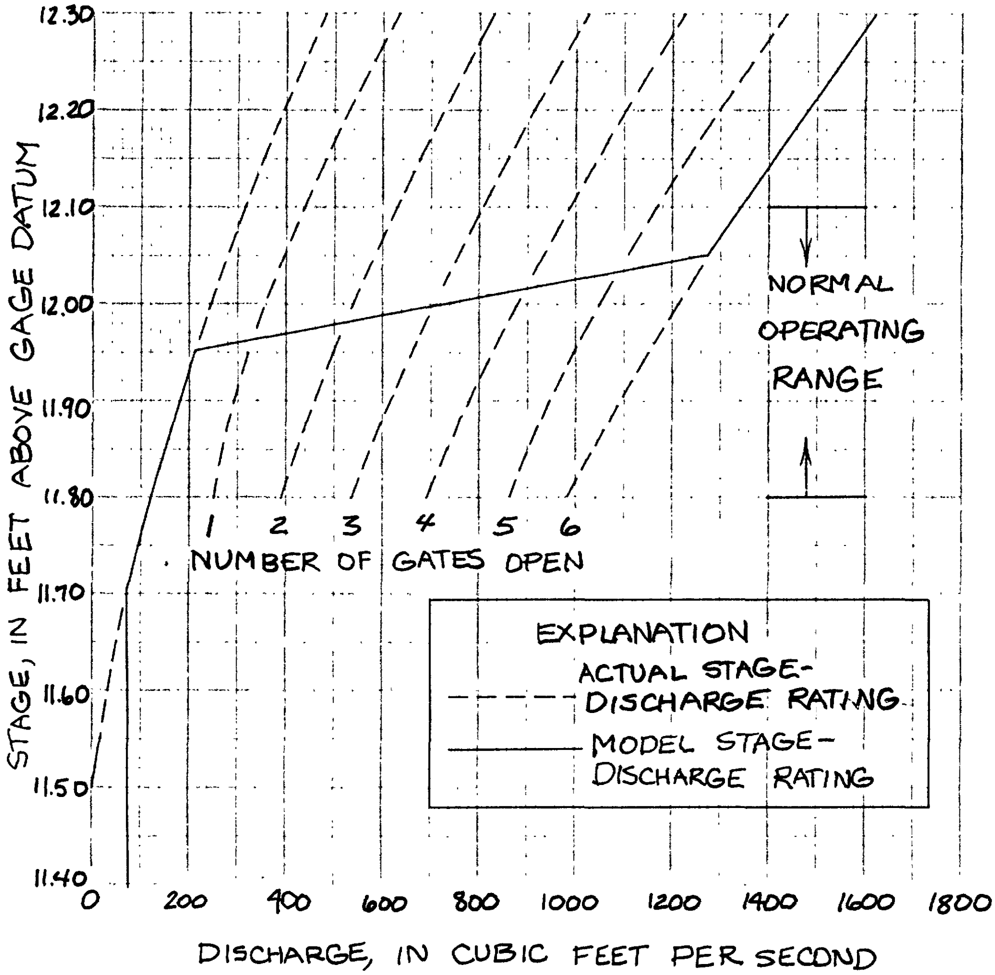

Figure 2. Comparison of stage-discharge rating used in reservoir submodel with actual stage-discharge rating at Indianford.

Modeling Reaches

Six channel-routing reaches were needed to model flow adequately in the part of the Rock River system studied. They are:

Routing reach	Channel-routing reach
1	Rock River from Watertown to confluence with Crawfish River
2	Crawfish River from Milford to mouth
3	Rock River from confluence with Crawfish River to Lake Koshkonong
4	Yahara River from McFarland to mouth
5	Rock River from Indianford to Afton
6	Rock River from Afton to Wisconsin-Illinois State line

The relation of these reaches is shown schematically in figure 3.

The model considers the confluence of the Yahara and Rock Rivers to be at Indianford, just downstream from the dam, although it is nearly 2 mi downstream. The errors introduced by assuming the confluence of these two rivers to be 2 mi upstream from the actual location is negligible.

MODEL CALIBRATION

To refine the modeling parameters C_0 and K computed from physical characteristics of the channel, simulated discharges computed by the model are compared to recorded discharges. C_0 and K are then adjusted to minimize the differences between recorded and simulated discharge. Only 17 months of observed record was available for calibration at Indianford, from May 7, 1975, to September 30, 1976.

The final unit-response coefficients determined by calibration with the available records are summarized in table 2. The traveltime of 6 days for reach 4 (Yahara River from McFarland to the mouth), indicates that it would take 6 days for a change in discharge at McFarland to influence the discharge at the mouth of the Yahara River. In all other reaches a change in discharge at the upstream end will begin to affect the discharge at the downstream end on the same day.

The large ground-water inflow to the Rock River between Indianford and Afton was considered in the model. Based on average aquifer transmissivity and water-table slope, ground-water discharge into this reach of the river was estimated to be 80 ft^3/s. However, during model calibrations the simulated ground-water inflow was adjusted to 100 ft^3/s to improve the accuracy of the simulation at Indianford. This adjustment was well within the range of possible values estimated from the data available.

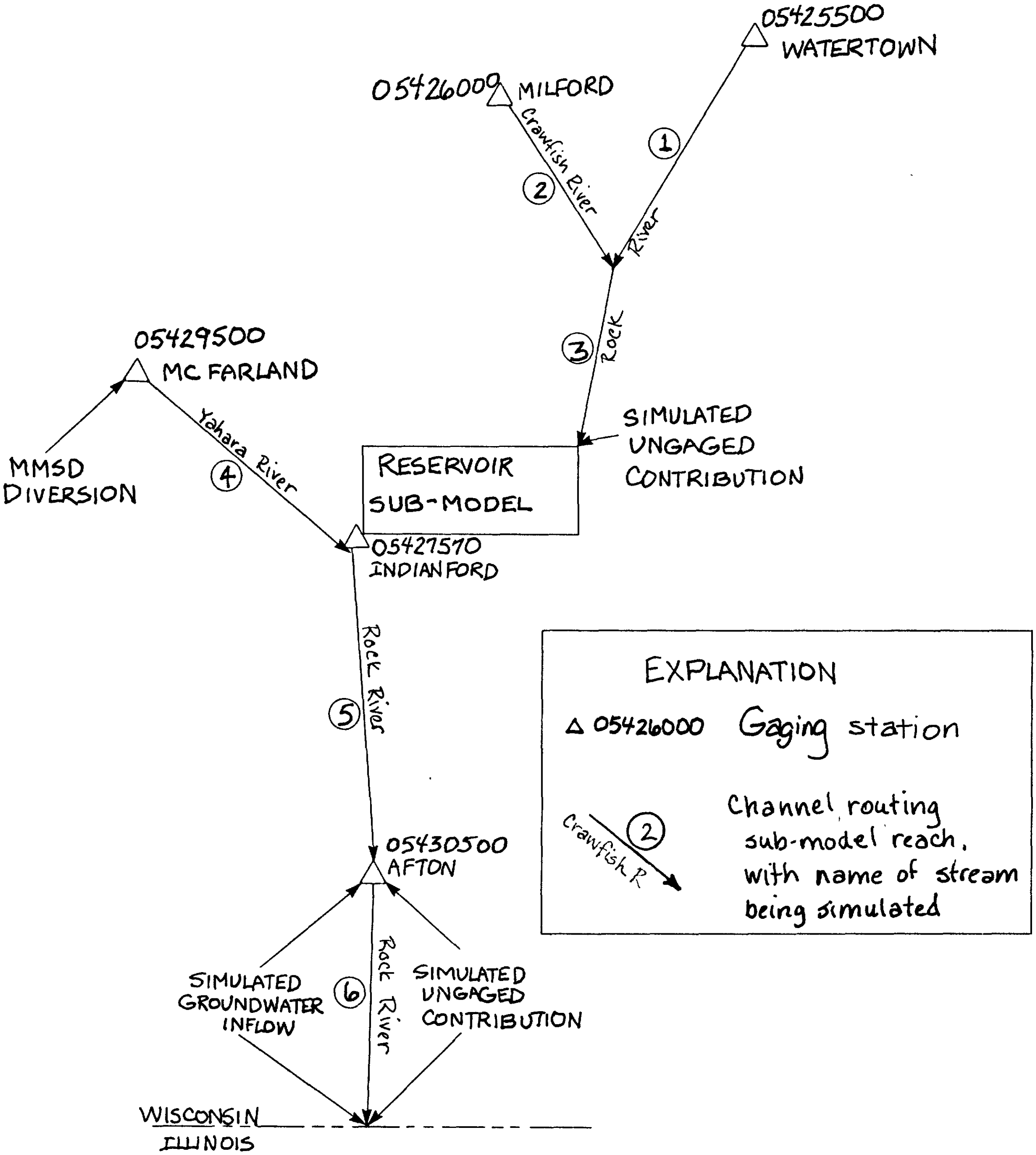

Figure 3. Diagram of gaging stations and reaches used in model.

Table 2.--Unit-response routing coefficients for reaches used in model

Reach number	Traveltime (days)	Unit-response coefficients				
		1	2	3	4	5
1	0	0.13	0.74	0.13		
2	0	.73	.27			
3	0	.62	.34	.03	0.01	
4	6	.06	.35	.41	.16	0.02
5	0	.54	.46			
6	0	.55	.39	.05	.01	

Inflow to Lake Koshkonong from ungaged drainage area was simulated by a "difference record". The difference record was computed by simulating the daily discharge at Afton for the period 1932-75 without considering any inflow from ungaged areas and subtracting these simulated discharges from the recorded discharges. The difference record was then divided between the reaches upstream and downstream from Indianford in proportion with the ungaged drainage areas.

Wind blowing along the axis of Lake Koshkonong can cause changes in stage at Indianford that do not represent the mean stage of the lake. Wind setup of 0.5 ft is common at Indianford, and setup of greater than 1 ft is possible. Such changes in stage can produce significant changes in discharge at Indianford. The changes are present at all stages but are most noticeable when discharge at Indianford averages less than 250 or 300 ft^3/s and all gates are closed. Simulation of these wind effects was not included in the model. The simulated stage approximates the mean lake stage, rather than the stage at any one point. The wind-caused fluctuations of stage and discharge at Indianford would be superimposed on any simulated conditions, and their net effect would be zero when averaged over several days.

A comparison of recorded and simulated discharge at Indianford is shown in figure 4, together with wind velocities recorded at Madison, Wis. The wind velocities plotted are the resultant velocities along the axis of the lake bearing N. 50° E. Wind blowing from the northeast increases stage and discharge at Indianford. On figure 4 winds from the northeast are plotted above the zero line. The simulated discharge follows an average of the recorded discharge. The gates were all closed for the 3 months plotted

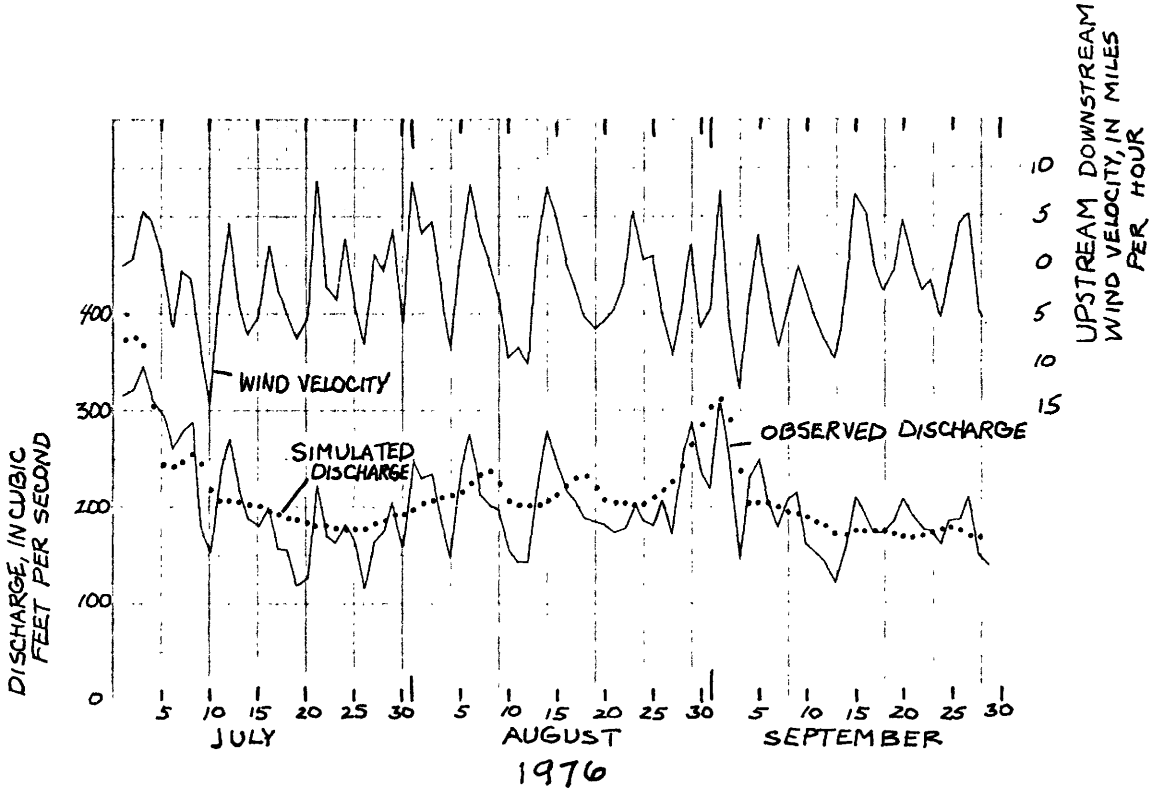

Figure 4. Comparison of recorded and simulated discharge at Indianford and component of wind velocity along axis of Lake Koshkonong measured at Madison.

on figure 4; however, when the simulated discharge is greater than 210 ft^3/s, the reservoir model assumes some gate opening. Therefore, during early July 1976, and again around September 1, 1976, the simulation is affected by errors in simulating gate manipulation. For example, on September 1, 1976, the model simulated a discharge of 312 ft^3/s (216 ft^3/s over the spillway and 96 ft^3/s through gates) at a stage of 11.96 ft. This is 96 ft^3/s more than would have occurred with the same stage and no gate opening.

MODEL VERIFICATION

Sufficient data are not available for the Rock River at Indianford to verify the model directly because the entire period of record was used to calibrate the model. Therefore, the model was verified by comparing low-flow characteristics at Indianford simulated by the model with those obtained by correlation with the gaging station at Afton (Grant, 1977). For this verification, the model was used without the minimum release rule at Indianford. The low-flow characteristics computed from the simulated record at Indianford agree closely with those computed by correlation, considering the differences in low-flow characteristics computed at Afton for the different periods of record. The comparison is summarized in table 3. Low-flow characteristics determined for Indianford from the simulated streamflow 1932-75 are lower than the same characteristics determined by correlation with 7-day mean discharge at Afton. However, the low-flow characteristics determined for Afton also would be lower if the same 1932-75 period were used instead of the entire period of record, 1914-75. This implicitly verifies that the models adequately predict low flows at Indianford.

The simulated discharges at Indianford were routed to Afton, with the constant ground-water contribution and the remainder of the "difference record" added to account for ground water and ungaged surface inflow. Because the recorded discharge at Afton was used to determine ungaged inflow, the simulated discharge at Afton is forced into close agreement with the recorded discharge. The only differences in the simulated record are those caused by the simplified operating rules for the Indianford dam and by neglecting wind effects. The simulated record at Afton does agree very closely with the recorded discharge. Volume errors over periods of several months are 2 percent or less. Large daily errors are common. They are caused by differences in the operation of the dam at Indianford and in a few cases to exceptional operations of the run-of-the-river dams at Janesville.

SIMULATED POWERPLANT USE

The proposal for a nuclear plant has been withdrawn by the power company, and it is uncertain what water demand, if any, may ultimately be imposed at the site. Construction of a smaller, fossil-fuel powerplant or a nuclear powerplant may be considered.

Table 3.--Comparison of low-flow characteristics estimated at Indianford and determined from streamflow records at Afton

Site	Method of determination	$Q_{7,10}$ (ft^3/s)	95 percent duration (ft^3/s)
Indianford	Correlation with concurrent 7-day mean discharge at Afton (using Afton low-flow characteristics determined from period of record 1914-1975)	69	117
Indianford	Simulated streamflow 1932-1975	52	108
Afton	Recorded streamflow 1914-1975	200	318
Afton	Recorded streamflow 1932-1975	175	288

Four levels of consumptive use were considered in the model, to include the range of possible use at the site. Mean consumptive uses of 10, 15, 20, and 40 ft^3/s were considered. For each level, the use was varied monthly to account for changes in evaporative losses due to changing climatic conditions. Consumptive use ranged from about 80 percent of the mean in winter to about 120 percent of the mean in summer. No adjustments were made for the possibility that the powerplant would be shut down periodically for maintenance or for a powerplant being operated at less than full capacity.

EFFECTS OF SIMULATED POWERPLANT USE

Simulated consumptive use had very little effect on simulated conditions during high-flow and normal-flow periods. Discharge downstream was decreased by the consumptive use, but the decrease was a small percentage of total flow. During prolonged low-flow periods, the simulated consumptive use decreased the simulated discharges, lowered the simulated lake stage, and increased the time when lake stage was below the desired minimum stage.

Simulated Discharge

The minimum-release rule in the reservoir model guarantees that simulated discharge will never be less than 69 ft^3/s. As a result, the simulated $Q_{7,10}$ at Indianford is 69 ft^3/s, regardless of consumptive use. The effect of consumptive use is more apparent at the annual minimum 7-day

Table 4.--Simulated $Q_{7,2}$ at Indianford at different rates of consumptive use

Consumptive use (ft^3/s)	$Q_{7,10}$ (ft^3/s)		
	Entire year	April-October	November-March
0	150	155	246
10	142	146	234
15	138	143	228
20	134	139	222
40	122	126	203

mean flow below which the flow will fall on the average once every 2 years ($Q_{7,2}$). The $Q_{7,2}$ values at Indianford are summarized in table 4. During the winter, the $Q_{7,2}$ is reduced by more than the consumptive use because many of the lowest winter flows occurred while lake storage was being managed to recover from drawdown caused by withdrawal during the summer. Discharge from the lake was thus decreased by more than the consumptive use because a part of the inflow went into storage in the lake. This was not a factor during the summer, when most of the minimum flows were concurrent with the minimum lake stage for the year.

Curves relating consumptive use to various low-flow characteristics of simulated streamflow at Afton and at the Illinois State line are shown in figures 5 and 6. Simulated low-flow characteristics at Afton for zero consumptive use are higher than those computed from observed flows because the model simulates a minimum release from the Indianford dam. In actual practice, flows less than 69 ft^3/s have been released because the minimum-release rule has not been enforced. Increasing consumptive use from 0 to 40 ft^3/s lowers the simulated $Q_{7,10}$ at Afton from 226 to 213 ft^3/s. Both of these are higher than the $Q_{7,10}$ of 200 ft^3/s determined from gaging-station records.

The accuracy of simulated streamflow at the State line is less certain than at Afton because there are no records of observed streamflow at the State line to compare with flows simulated by the model for this reach. Although the accuracy of the low-flow characteristics shown in figure 6 is uncertain, the changes in low-flow characteristics due to consumptive use should be as accurate at the State line as at Afton.

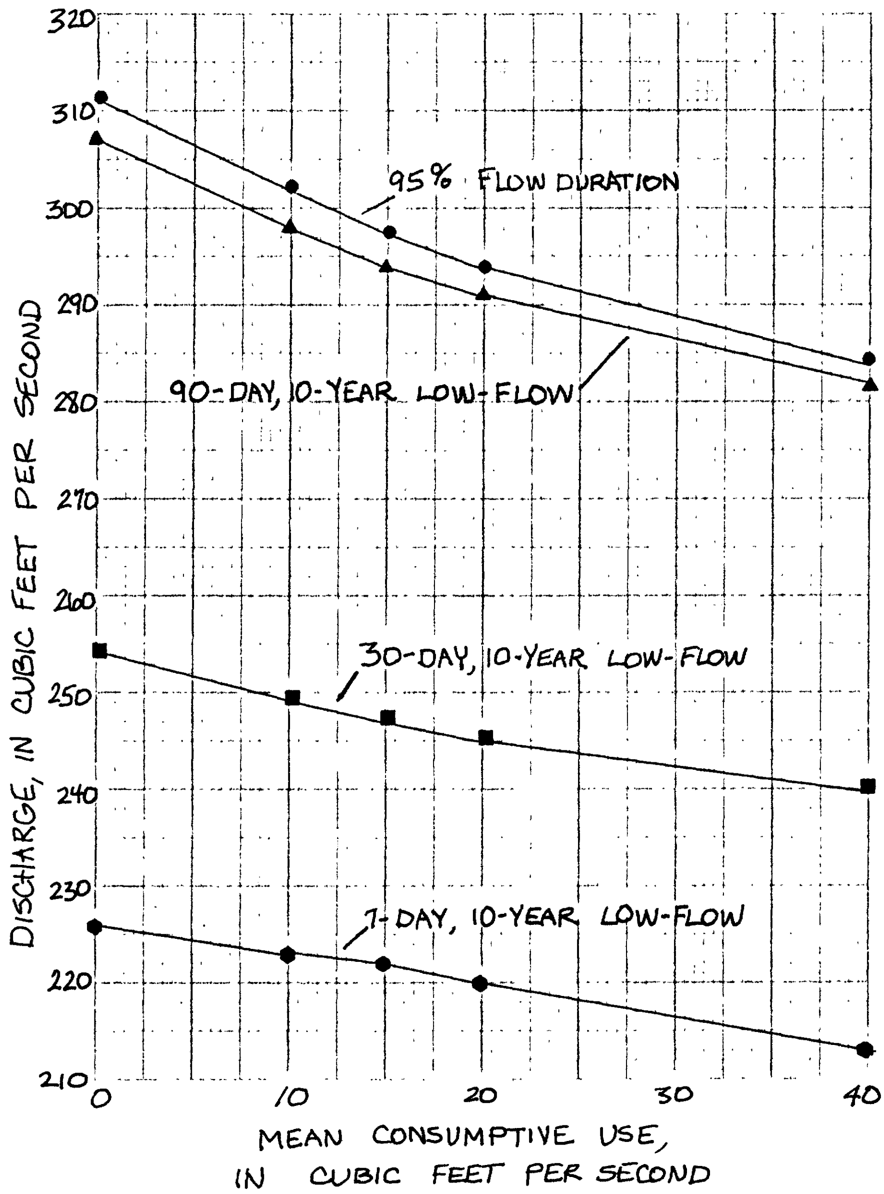

Figure 5. Simulated low-flow characteristics for the Rock River at Afton at various levels of simulated consumptive use at Lake Koshkonong.

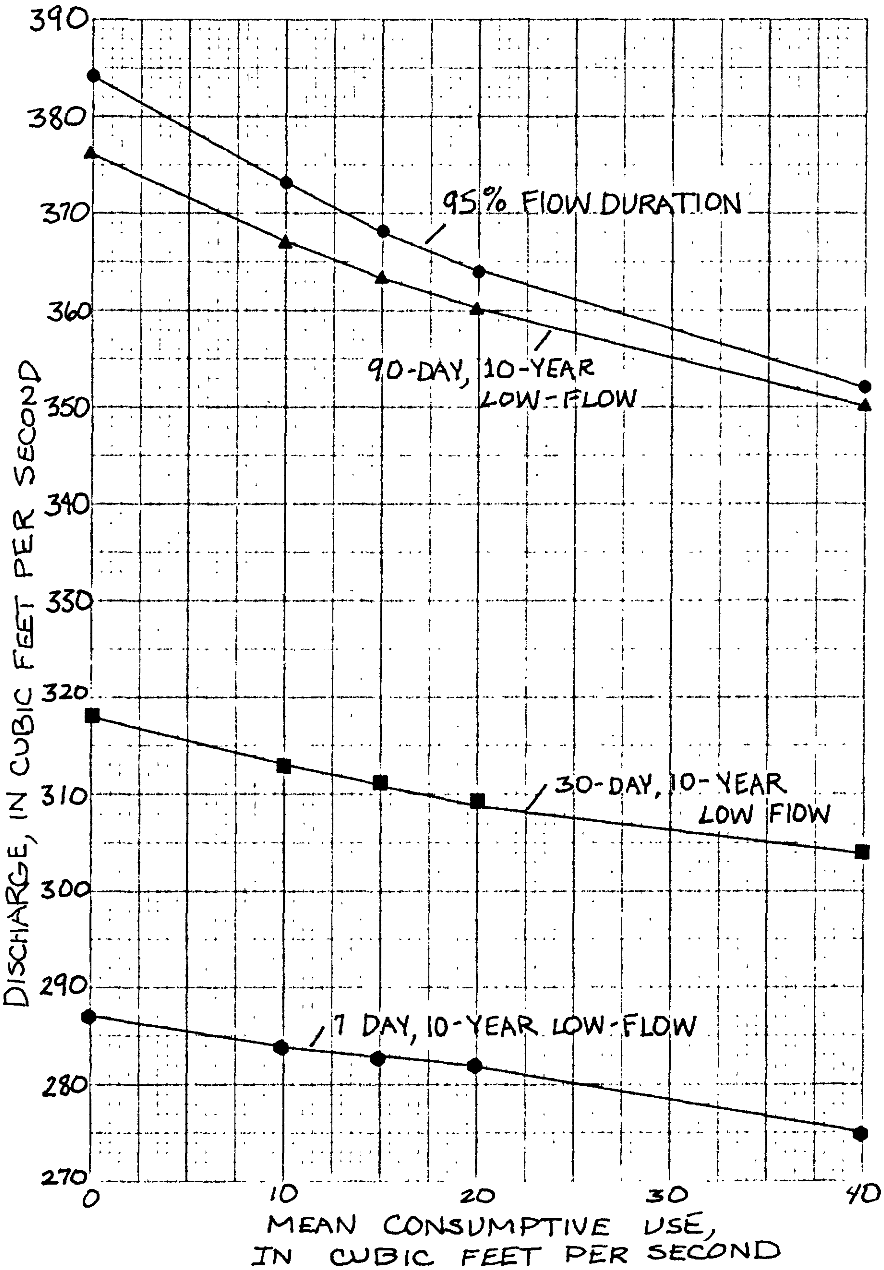

Figure 6. Simulated low-flow characteristics for the Rock River at the Wisconsin-Illinois State line at various levels of simulated consumptive use at Lake Koshkonong.

Simulated Stage--Entire Year

Under the operating rule of the reservoir-regulation model, the main consequence of consumptive use during dry periods is to increase drawdown of the lake. Comparisons of stage hydrographs simulated by the model for the four driest periods of record are shown on plate 1. The increases in maximum drawdown during the summer are summarized below.

Consumptive use (ft^3/s)	Increase in drawdown (ft)		
	1934	1964	1963
10	0.11	0.08	0.05
15	.13	.12	.08
20	.20	.18	.12
40	.42	.41	.42

Increased consumptive use also increases the duration of drawdown. Curves showing the duration of drawdown below various stages for the 10-year low flow are shown in figure 7. During the 10-year low flow, consumptive use of 40 ft3/s would increase the time when stage is below 11.80 ft (the regulatory lower limit and 0.2 ft below normal) from 83 to 132 days and would increase the time when stage is below 11.65 ft (0.35 ft below normal) from 21 to 104 days.

Simulated Stage--Winter

Between December 1 and March 31, drawdown of the lake is less frequent than during the summer. The DNR considers any drawdown below the 12.0-ft stage under ice cover to be undesirable because this will increase the probability of fish kills (oral commun., 1977). The probability that the stage will be below 12.0 ft for 60 consecutive days during any year is about 11 percent and for 30 days it is about 17 percent. These probabilities are not significantly affected by consumptive use because extended periods of drawdown begin soon after inflow falls below 244 ft^3/s and normally ends with the start of spring runoff--regardless of consumptive use. The probability of stage being below 12.0 ft for 14 consecutive days during the winter ranges from 22 percent for zero consumptive use to 33 percent for 40 ft^3/s consumptive use (fig. 8).

The magnitude of drawdown is affected by consumptive use, as shown below for the three driest winters of record. Stage hydrographs for these periods are shown on plate 1. Winter drawdown is insignificant except at a consumptive use of 40 ft^3/s.

Consumptive use (ft^3/s)	Increase in drawdown (ft) 1964	1965	1959
10	0.02	0.02	0.02
15	.03	.03	.04
20	.03	.03	.07
40	.35	.32	.21

CONCLUSIONS

A combination of channel-routing and reservoir-routing models has been used to simulate the long-term effects of consumptive use of cooling water from Lake Koshkonong. The reservoir-routing model includes a minimum-release rule for the dam at Indianford that guarantees that flow downstream from the dam will be at least the $Q_{7,10}$ (69 ft^3/s).

Maintaining streamflow in the Rock River during prolonged dry periods lowers the level of Lake Koshkonong. Consumptive use of 10 ft^3/s would increase drawdown by as much as 0.11 ft in summer and 0.02 ft in winter for the period of record studied. Consumptive use of 40 ft^3/s would increase drawdown by as much as 0.42 ft in summer and 0.35 ft in winter. With no consumptive use, the lake would be below the minimum regulatory gage height (11.8 ft) for more than 83 consecutive days once in 10 years. Consumptive use of 10 ft^3/s would increase this to 92 days and 40 ft^3/s would increase it to 132 days.

Increasing consumptive use at Lake Koshkonong from 0 to 40 ft^3/s would decrease the $Q_{7,10}$ at Afton from 226 to 213 ft^3/s. This is more than the $Q_{7,10}$ computed from recorded discharges at Afton because the model includes a minimum release at Indianford.

Although there are large errors in the simulated daily flows due to somewhat random gate manipulations and wind setup, the generalized streamflow characteristics and lake stage computed from the simulated streamflow are considered good. The estimated streamflow characteristics provide a good basis for evaluating some of the water-related environmental impacts of water use from Lake Koshkonong.

If the model is to be used to evaluate other combinations of operating rules and consumptive use, several additional years of observed streamflow data at Indianford would be very useful to verify the model directly and possibly to refine the calibration.

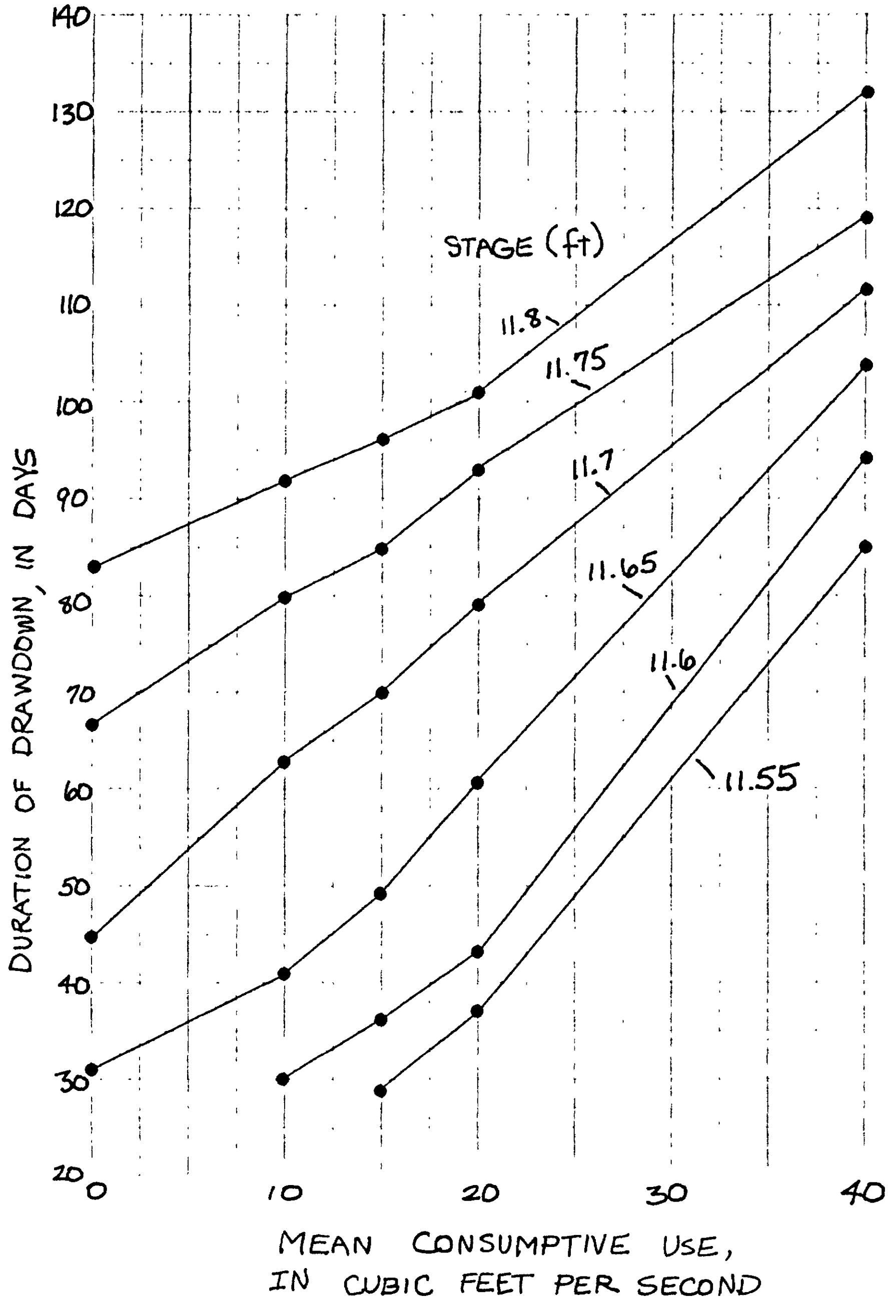

Figure 7. Number of consecutive days that simulated stage at Lake Koshkonong is below selected stage once in 10 years due to simulated consumptive use.

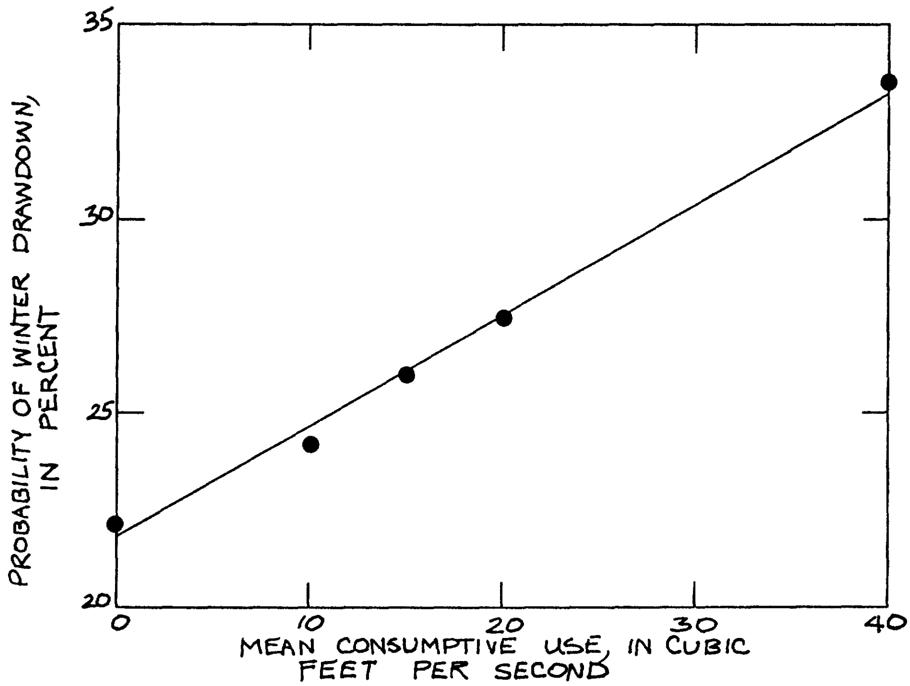

Figure 8. Increase in probability of 14-day, winter drawdown of Lake Koshkonong due to increased consumptive use.

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