WATER-RESOURCES INVESTIGATIONS
OPEN-FILE REPORT 80-1103

Streamflow Model of Wisconsin River for Estimating Flood Frequency and Volume

PREPARED BY
UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
IN COOPERATION WITH
WISCONSIN DEPARTMENT OF NATURAL RESOURCES

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William R. Krug and Leo B. House

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CONVERSION TABLE

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	By	To obtain
cubic foot per second (ft^3/s)	2.832×10^{-2}	cubic meter per second (m^3/s)
cubic foot per second-day (ft^3/s-day)	2,447	cubic meter (m^3)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.59	square kilometer (km^2)

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ABSTRACT

A set of daily streamflow-routing models are used to simulate streamflow at 10 sites along the Wisconsin River for water years 1915-76, to determine the effects the reservoir system has on flood discharges. Streamflow is simulated under the following two conditions: (1) No reservoirs are in the system and (2) all of the present reservoirs are in place and operated with current rules.

At Wisconsin Dells, 20 miles upstream from Portage, daily streamflow hydrographs are estimated for the 10-, 50-, 100-, and 500-year floods. These were determined from statistical analysis of the simulated daily streamflows for the condition of all reservoirs in place.

The reservoirs have a significant impact on floods. The mean annual flood peak at Wisconsin Dells is lowered about 20 percent from 43,000 cubic feet per second for the simulated, unregulated condition to 34,000 cubic feet per second for the simulated, regulated condition. The 100-year flood peak at Wisconsin Dells is reduced about 10 percent (92,000 to 82,000 cubic feet per second) between the simulated, unregulated and simulated, regulated conditions.

The 100-year flood peak at Wisconsin Dells, computed from the simulated, regulated streamflow data for the period 1915-76, is 82,000 cubic feet per second, including the effects of all the reservoirs in the river system, as they are currently operated. It also includes the effects of Lakes Du Bay, Petenwell, and Castle Rock which are significant for spring floods but are insignificant for summer or fall floods because they are normally maintained nearly full in the summer and fall and have very little storage for floodwaters.

INTRODUCTION

The Wisconsin River flows roughly north to south through the center of Wisconsin, draining 12,000 mi^2 (pl. 1). Streamflow is regulated by 21 reservoirs operated by the Wisconsin Valley Improvement Co. in the headwaters and on tributary streams in northern and central Wisconsin. These reservoirs are managed, within limits set by the State of Wisconsin, to maintain more uniform streamflow in the Wisconsin River than would occur naturally. The primary goal of the reservoir regulation is uniform streamflow for maximum dependable hydroelectric power generation. The operation also provides flood control and low-flow augmentation in the river. No power is generated at these reservoirs.

Significant flow regulation is caused seasonally by three large hydroelectric dams on the Wisconsin River in central Wisconsin. The lakes controlled by these dams (Du Bay, Petenwell, and Castle Rock) are drawn down in the winter to free some storage for spring floodwaters. During the rest of the year these pools are maintained at a nearly constant elevation and have little influence on floodflows.

Computation of flood profiles near Portage, Wis., for flood-plain zoning has raised significant questions about the accuracy of the 100-year flood estimate. In the past, flood-frequency values were determined from statistical analysis of recorded flood peaks for the Wisconsin River at Wisconsin Dells, about 20 mi upstream from Portage (pl. 1). The statistical analysis has been questioned because the three large hydroelectric dams in central Wisconsin were all constructed after 1940 and therefore may have changed the flood-frequency characteristics during the period of recorded streamflow data. These dams formed large lakes which might have changed the flood potential at Wisconsin Dells and Portage.

PURPOSE

The purpose of this study is to determine flood frequency for the Wisconsin River at Wisconsin Dells and at various points along the river. The flood frequency determined is to be consistent with the system of reservoirs and hydroelectric dams now in the basin. Flood hydrographs also are to be estimated for the 10-, 50-, 100-, and 500-year floods at Wisconsin Dells to aid the U.S. Army Corps of Engineers in determining possible interbasin flow of floodwaters near Portage.

SCOPE

To accomplish these purposes, it was necessary first to determine what the streamflow would have been at all gaging stations along the river if the reservoirs and hydroelectric dams had not regulated the flow. This was done for the years of recorded streamflow data since 1914 at all gaging stations on the river. A computer model simulated the effects of all reservoirs and large hydroelectric pools for the period October 1, 1914, to September 30, 1976. This simulation used the current operating procedures for the entire period. The daily streamflow record computed with these models was analyzed statistically to determine flood frequency at all gaging stations along the river. The simulated record at Wisconsin Dells was further analyzed to estimate flood-frequency hydrographs.

ACKNOWLEDGMENTS

Valuable assistance in this study was provided by Wisconsin Valley Improvement Co. (WVIC) and Consolidated Water Power Co. (CWPC) who furnished records of daily stage records for the reservoirs and hydroelectric pools in the basin.

L. L. Sheerar of WVIC and M. O. Andrae of Wisconsin River Power Co. gave advice and instruction on operation of the reservoir system and hydroelectric dams which was necessary for the modeling. M. J. Mezzo and T. L. Hampton of the Wisconsin Department of Natural Resources obtained the reservoir stage records from WVIC and CWPC, computed daily changes in storage, and provided these data on magnetic tape for computer processing. The U.S. Army Corps of Engineers gave advice and assistance in the statistical analysis of the simulated streamflow records and in computation of flood hydrographs for Wisconsin Dells.

DATA BASE

Data used in digital modeling consisted of (1) daily streamflow data from 18 U.S. Geological Survey gaging stations, (2) reservoir stage data from WVIC, and (3) stage data from hydroelectric pools from CWPC.

Locations of the U.S. Geological Survey gaging stations used in this report are shown on plate 1. Their full names, periods of record, and drainage areas are summarized in table 1. For simplicity all gaging stations on the Wisconsin River will be referred to by the location, for example, the Wisconsin River at Rainbow Lake near Lake Tomahawk will be referred to as Rainbow Lake. Gages on tributary streams will be referred to simply by the name of the river, unless more detail is required to avoid confusion. Locations of these gaging stations are also shown in a schematic diagram in figure 1.

Data on daily stages of the reservoirs were provided by WVIC. They also furnished capacity tables for each reservoir. Similar data on Lake Du Bay, Petenwell Lake, and Castle Rock Lake were furnished by CWPC. These data were used to compute the effects of regulation on the streamflow recorded at the gaging stations. Locations of these lakes and reservoirs are shown on plate 1. Their names, drainage areas, storage capacities, and first year of operation are summarized in table 2. Locations of the three large hydroelectric pools and one large reservoir are shown in figure 1.

MODELS

Four models are used to simulate the Wisconsin River streamflow. There are three reservoir system models used to simulate three groups of reservoirs and a channel-routing model used to simulate the parts of the river channel not included in the reservoir models.

The simulation of the entire system was in two stages. First, streamflow for water years 1915-76 was simulated at each gaging station assuming the reservoirs were not used to modify streamflow. This step was necessary for simulating ungaged inflow in each reach and for determining unregulated streamflow to be compared with regulated streamflow computed in the second stage. Second, streamflow for the same period was simulated using the three reservoir models and the channel-routing model. The result of this simulation was a consistent period of streamflow data at all gaging stations.

The four models and the way they were used are explained in the following sections.

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

Station no.	Station name[1]	Drainage area (mi^2)	Period of record
05391000	Wisconsin River at Rainbow Lake near Lake Tomahawk, Wis.[2]	744	July 7, 1935-present.
05392000	Wisconsin River at Whirlpool Rapids near Rhinelander, Wis.	1,220	Oct. 1, 1905-Sept. 30, 1961
05392400	Tomahawk River near Bradley, Wis.	422	Sept. 18, 1914-Sept. 30, 1927 Oct. 1, 1928-Sept. 30, 1929
05393000	Tomahawk River at Bradley, Wis.	544	Jan. 1, 1930-Sept. 30, 1973
05393500	Spirit River at Spirit Falls, Wis.	81.6	Apr. 10, 1942-present.
05395000	Wisconsin River at Merrill, Wis.	2,760	Dec. 1, 1902-present.
05396000	Rib River at Rib Falls, Wis.	303	May 19, 1924-Sept. 30, 1957
05397500	Eau Claire River at Kelly, Wis.	375	Jan. 1, 1914-Nov. 30, 1926 Aug. 16, 1939-present.
05398000	Wisconsin River at Rothschild, Wis.	4,020	Oct. 1, 1944-present.
05399500	Big Eau Pleine River near Stratford, Wis.	224	July 24, 1914-Dec. 31, 1926 Apr. 30, 1937-present.
05400000	Wisconsin River at Knowlton, Wis.[3]	4,530	Oct. 1, 1920-Sept. 30, 1942
05400800	Wisconsin River at Wisconsin Rapids, Wis.[4]	5,430	Oct. 1, 1957-present.
05400980[5]	Wisconsin River near Nekoosa, Wis.[4]	5,640	May 21, 1914-Mar. 31, 1950

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

Station no.	Station name[1]	Drainage area (mi^2)	Period of record
05401500	Wisconsin River near Necedah, Wis.	5,990	Dec. 1, 1902-June 30, 1914 Mar. 24, 1944-May 31, 1950
05404000	Wisconsin River near Wisconsin Dells, Wis.	8,090	Oct. 1, 1934-present.
05405000	Baraboo River near Baraboo, Wis.	609	Dec. 18, 1913-Mar. 31, 1922 Oct. 1, 1943-present.
05406000	Wisconsin River at Prairie du Sac, Wis.	9,180	Jan. 1. 1946-Dec. 5, 1954
05407000	Wisconsin River at Muscoda, Wis.	10,400	Oct. 1, 1913-present.

[1]Underlined part of name is used in text of report unless the complete name is required for clarity.

[2]Record at this station includes the flow of Gilmore Creek which enters the Wisconsin River just downstream from the gage.

[3]This site is now submerged by Lake Du Bay and is not included in summaries of regulated streamflow.

[4]These two sites are considered to be one station in the USGS files.

[5]Formerly 05401000.

Table 2.--Lakes controlled by hydroelectric dams and reservoirs and their drainage areas, usable storage capacity, and year when their operation was started

Station no.	Name	Drainage area (mi^2)	Storage capacity[1] (ft^3/s-day)	First year of operation
	Reservoirs			
05390100	Lac Vieux Desert on Wisconsin River	34.4	7,550	1908
05390150	Twin Lakes on Twin River	26	3,620	1908
05390200	Buckatabon Lakes[2] on Buckatabon Creek	16.9	1,500	1908
05390250	Sevenmile Lake on Sevenmile Creek	12.1	1,080	1908
05390300	Lower Ninemile Lake on Ninemile Creek	28.8	1,400	1908
05390350	Burnt Rollways Reservoir on Eagle River	142	9,020	1908
05390400	Long Lake on Deerskin River	22.9	4,630	1908
05390600	Deerskin Lake on Little Deerskin River	2.47	250	1908
05390650	Sugar Camp Reservoir on Sugar Camp Creek	48.4	5,450	1908
05390700	Little St. Germain Lake on Little St. Germain Creek	19	910	1908
05390750	Big St. Germain Lake on St. Germain River	73.1	2,340	1908
05390800	Pickerel Lake on St. Germain River	86.2	3,900	1935
05390900	Rainbow Lake on Wisconsin River	744	25,290	1935
05391100	South Pelican Lake on Pelican River	19.8	3,530	1909
05391300	North Pelican Lakes on North Branch Pelican River	95	2,520	1908

05392100	Minocqua Lake on Tomahawk River	72.5	7,270	1910
05392200	Squirrel Lake on Squirrel River	15.2	2,110	1908
05392300	Willow Reservoir on Tomahawk River	310	38,220	1927
05392500	Lake Nakomis[3] on Tomahawk River	544	20,930	1912
05393600	Spirit River Flowage on Spirit River	158	8,750	1923
05399600	Big Eau Pleine Reservoir on Big Eau Pleine River	363	51,590	1937
	Hydroelectric Dams			
05400295	Lake Du Bay on Wisconsin River	4,900	23,900	1942
05401400	Petenwell Flowage on Wisconsin River	5,970	57,000	1950
05403200	Castle Rock Flowage on Wisconsin River	7,056	48,500	1950

[1]Usable capacity in winter; usable capacity is reduced at many reservoirs during the summer because allowable stage ranges are limited.

[2]Spelled Buckatahpon by WVIC.

[3]Also called Rice Reservoir.

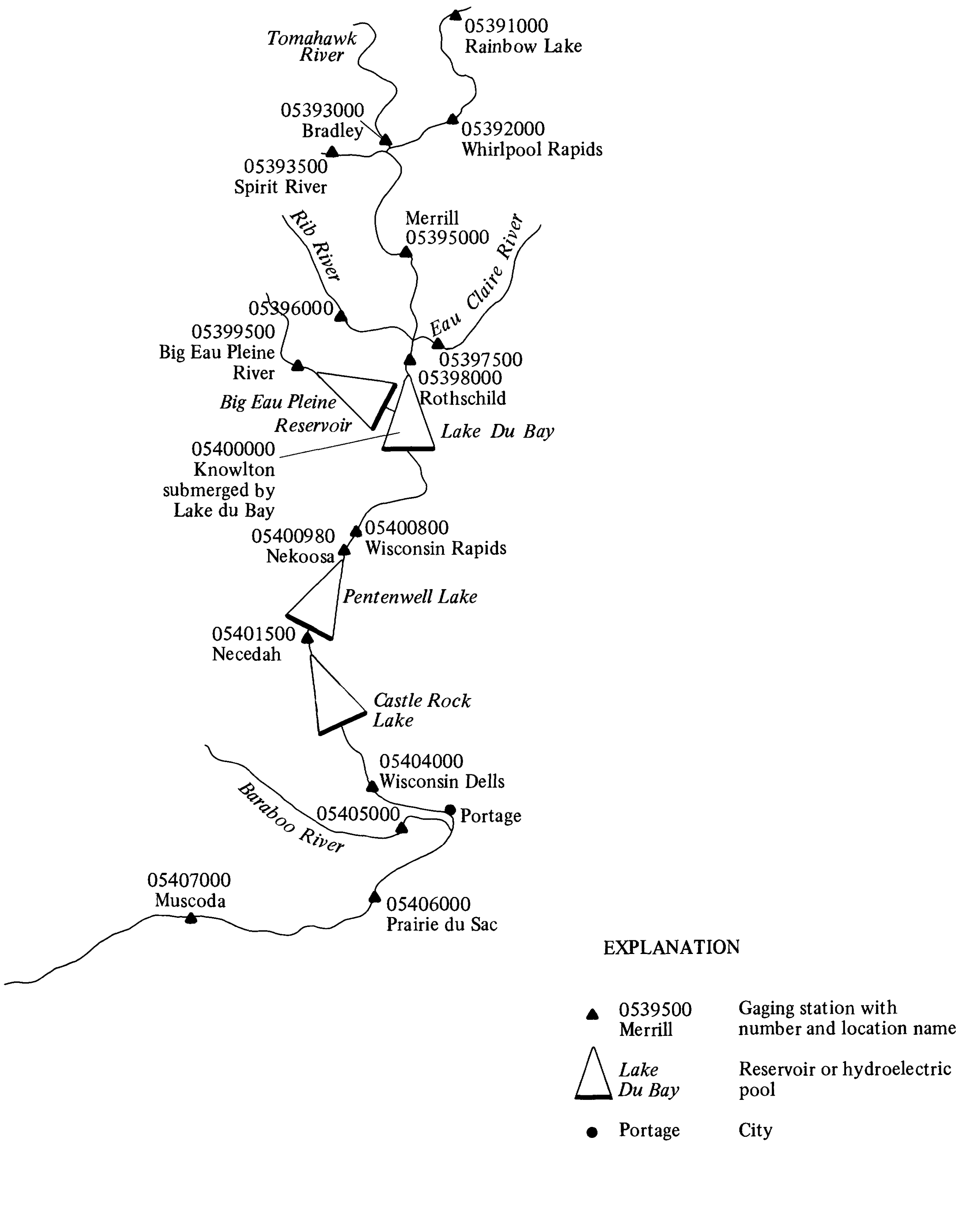

Figure 1. Schematic diagram of the Wisconsin River.

CHANNEL-ROUTING MODEL

The streamflow-routing model used in this study uses a computer program developed by the USGS (Shearman, Stiltner, and Doyle, written commun.). The model 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.

This model also is used to compute in the upstream direction. Because this computation scheme is not always stable when used in this direction, the results always must be checked more carefully than if used in the downstream direction. If the model is stable, it will accurately estimate streamflow at the upstream end of the reach from the streamflow at the downstream end of the reach. The model will usually be stable if the first daily unit-response coefficient is larger than any other coefficient.

UPPER WISCONSIN SYSTEM MODEL

The upper Wisconsin River system is considered to be the river and reservoir system upstream from Merrill, Wis. There are 20 reservoirs in the upper system. Some are manmade reservoirs, others are natural lakes modified by dams at their outlets. For the purposes of the model these 20 reservoirs were grouped into 6 conceptual reservoir units to simplify the model and to reflect WVIC's operating policy. Reservoirs also were grouped to reduce the need for detailed daily inflow information.

Reservoir 1 includes the following lakes and reservoirs: Lac Vieux Desert, Buckatabon Lakes, Twin Lakes, Sevenmile Lake, Lower Ninemile Lake, Burnt Rollways Reservoir, Long Lake, Deerskin Lake, Sugar Camp Reservoir, and Little St. Germain Lake. It was grouped to reflect WVIC's policy of treating the many small reservoirs upstream from the Rainbow Reservoir as one large pool. The model assumes that water released from reservoir 1 reaches the Rainbow Reservoir (reservoir 2) 1 day later as inflow. This appears to be a reasonable average traveltime for modeling purposes.

Reservoir 2 consists solely of the Rainbow Reservoir. This reflects its relative importance in both terms of storage and operating policy in maintaining the Merrill flow goal.

Reservoir 3 includes Minocqua Lake, Squirrel Lake, and Willow Reservoir. It represents the upper Tomahawk River system. Its three reservoirs are operated as a unit by WVIC. Water released from this reservoir is assumed to reach the Rice Reservoir (reservoir 4) 1 day later on the average.

Reservoir 4 consists solely of the Rice Reservoir, also known as Lake Nakomis. This reservoir is used in providing the water releases needed to maintain the Merrill flow and must be considered by itself.

Reservoir 5 is the Spirit River Flowage. It also is used in meeting the Merrill flow goal. Water from the Spirit River Flowage is released to meet the Merrill flow goal before other reservoirs are drawn down.

Reservoir 6 consists of the Big St. Germain Lake, Pickerel Lake, South Pelican Lake, and North Pelican Lake. These are the small reservoirs located near Rainbow that are not operated as part of either reservoir 1 or 2.

Plate 1 shows the relation of the individual reservoirs to the Wisconsin River. Figure 2 shows the conceptual arrangement of the six-reservoir-unit model actually used in the study.

Routing Procedure

When water is released from reservoirs 2, 4, 5, and 6 it is routed downstream to Merrill using the diffusion analogy technique described earlier. The model was calibrated using continuous gage records at Merrill and the release sites upstream. The upper system model was calibrated for floodflows and needs to be recalibrated if used for low-flow studies.

Storage Constraints and Assumptions

Each conceptual reservoir has a maximum allowable storage volume. If the maximum storage was exceeded in the course of the simulation, the excess water was considered to spill over and was routed downstream to the next conceptual reservoir or to Merrill.

Individual reservoirs within a conceptual reservoir group were assumed to be operated in such a fashion to prevent downstream reservoirs from spilling while those upstream had storage available. WVIC's past operating record tends to support this assumption.

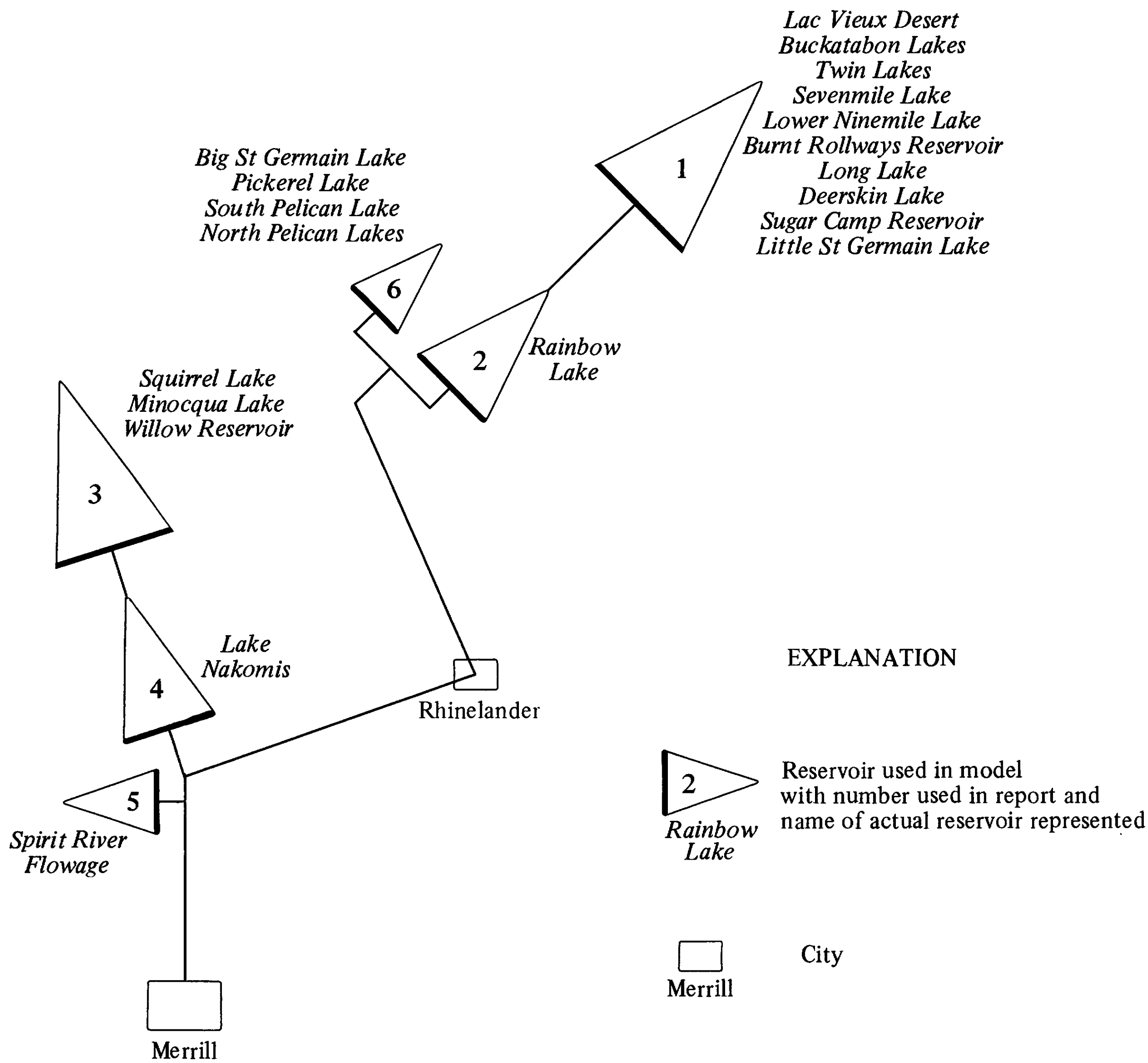

Figure 2. Diagram of the conceptual grouping of the reservoirs upstream from Merrill.

Conceptual reservoirs 1, 3, and 6 had minimum storage constraints which changed seasonally. This simulates the seasonal changes in the minimum allowable lake level. On several reservoirs the minimum allowable lake level is raised in the summer for recreation. The constraints are shown in the table below.

Minimum reservoir storage constraints
(in cubic feet per second-day)

Period	Reservoir 1	Reservoir 3	Reservoir 6
October 1-31 ------------------	3,560	0	2,640
November 1-March 31 ---------	0	0	0
April 1-30 -------------------	0	0	2,640
May 1-31 ---------------------	3,560	0	2,640
June 1-September 14 ---------	8,320	4,190	9,280
September 15-30 --------------	4,950	4,190	2,640

These storage constraints were computed from differences between usable storage capacities in summer and winter as furnished by WVIC. The various lakes making up these conceptual reservoirs have different dates for beginning and end of summer operations. In reservoir 1, the summer season is May 1-October 31 on Burnt Rollways Reservoir, June 1-September 30 on Twin Lakes and Long Lake, and June 1-September 14 on Sugar Camp Reservoir. In reservoir 6, the summer season is April 1-October 31 on South Pelican Lake and June 1-September 14 on Big St. Germain Lake, Pickerel Lake, and North Pelican Lake.

The model is designed such that minimum storage constraints will be met even if it means the flow goal at Merrill is not met. However, storage is allowed to drop below the minimum constraint to meet the regulatory minimum flow requirements. A constraint prevents storage from dropping below zero, in which case minimum flow might not be met if inflow is insufficient.

Minimum Outflow Constraints

Each conceptual reservoir has a minimum outflow constraint to be met. The model meets this outflow constraint by a combination of releasing water from storage and passing inflow through the system. The table below summarizes the minimum outflow requirements.

Minimum outflow constraints

Reservoir number	Minimum outflow (ft^3/s)
1	40
2	100
3	50
4	30
5	10
6	15

The minimum outflow requirement reflects the flow needed to maintain water quality, recreation, and Wisconsin Department of Natural Resources (DNR) regulatory minimum flows.

System Operating Rules

The upper system model's operating rules to determine and meet the target flow at Merrill are based on the policy of the WVIC in effect during 1978. The following is an outline of the operation procedures for the upper reservoir system. Beginning in late September water is released from all of the reservoirs to lower all of them to their minimum levels by the last week in March. The rate of release is adjusted to maintain steady flow in the Wisconsin River at Merrill. When spring runoff starts, discharge from the reservoirs is reduced to a minimum to store water for release later in the year. During this period the rate of filling is adjusted to maintain adequate flow in the Wisconsin River. After the spring fill, a discharge goal is set for Merrill based on the total volume of water in storage. This goal is normally between 1,200 and 2,000 ft^3/s. The goal may be lowered during the summer if reservoir stages fall too rapidly.

During the summer, the discharge at Merrill is controlled by adjusting the discharges from Spirit, Rice, and Rainbow Reservoirs. As these reservoirs are drawn down, water is released from upstream reservoirs to maintain the storage level in Rice Reservoir. Some water is also released from reservoirs upstream from Rainbow Reservoir but the amount of water available is small because of constraints on lake levels between June 1 and September 15. Spirit Reservoir, because it has a small storage capacity relative to its drainage area, is most easily refilled from summer rainfall. For this reason, when reservoir releases are required, water is released first from Spirit Reservoir, until it is drawn down about 3 ft below the maximum allowable level. Then water is released from all three main reservoirs to maintain a balance of storage in the whole system.

The above procedures are simulated by the model. The model does not attempt to simulate the actual day-to-day decisions as to which of the upstream reservoirs is to be used for release. It also does not simulate hourly, or even daily, changes in reservoir releases which are made in response to changes in power demand. Weekly averages are simulated fairly well however.

Figure 3 is a comparison of observed and simulated discharges at Merrill for a period including one of the larger spring floods. This period was used to verify the model and is typical of the agreement between observed and simulated discharges.

DU BAY-BIG EAU PLEINE MODEL

A computer model was developed to simulate operations of Lake Du Bay hydroelectric pool and the Big Eau Pleine Reservoir.

The Big Eau Pleine Reservoir, on the Big Eau Pleine River in central Wisconsin, is tributary to Lake Du Bay on the Wisconsin River (pl. 1). It has no power generation facilities. It is operated by WVIC to maintain steady flow in the Wisconsin River downstream from Lake Du Bay. Lake Du Bay is an artificial lake formed upstream from a hydroelectric dam operated by CWPC. It is operated for hydroelectric power generation.

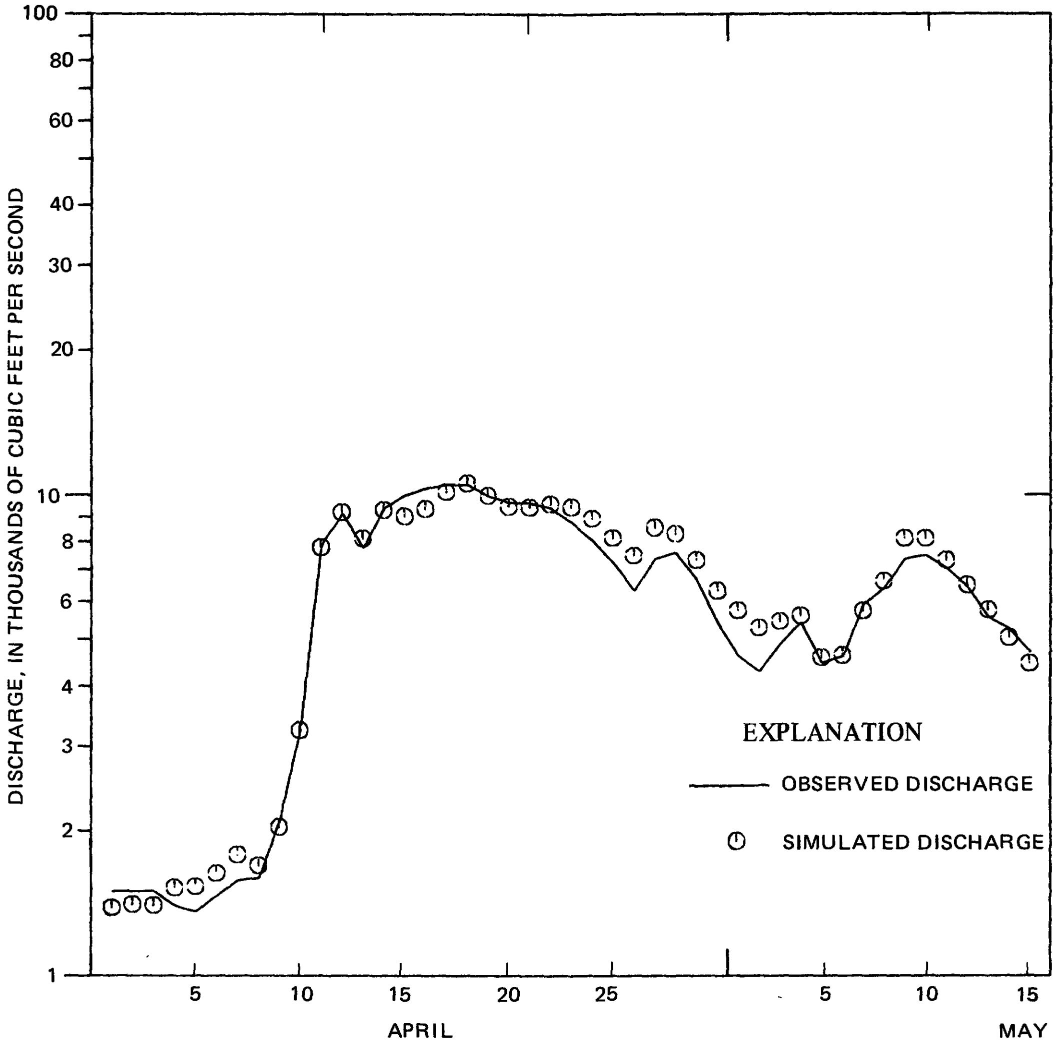

Figure 3. Comparison of observed and simulated, regulated discharge for Wisconsin River at Merrill (0539500) for period April 1, to May 15, 1965.

The general operating schedule for the Big Eau Pleine Reservoir includes three seasons. From September through late March the reservoir is emptied. The rate of emptying is adjusted to maintain steady flow at Wisconsin Rapids. During spring runoff, when flow in the Wisconsin River exceeds what can be used for power production, the reservoir is filled as much as possible. During the summer, water is released from the reservoir as needed to maintain flow at Wisconsin Rapids at about 3,000 ft^3/s. This flow goal is increased in wet years and decreased in dry years.

Lake Du Bay has both maximum and minimum stage limits that vary seasonally. From June 15 through January 31, the allowable range in stage is 1.5 ft (from 1,113.70 to 1,115.20 ft above mean sea level). From February 1 through April 30, the minimum stage limit is lowered 4.5 ft (to 1,109.20 ft above mean sea level). From March 15 through June 14, the maximum stage limit is raised 1 ft (to 1,116.20 ft above mean sea level). During February and early March, the stage is normally lowered in anticipation of spring runoff. If a large amount of runoff is expected, the lake is lowered to near the minimum stage. If less runoff is expected, the stage is not lowered as much. If there is significant runoff, the lake is filled rapidly to the maximum stage. After June 15, the lake has little affect on floodflows. Changes in lake stage are primarily due to variations in power demand.

The simulation follows these operating rules with some simplification. The model drains the Big Eau Pleine Reservoir uniformly through the winter, while maintaining steady flow at Wisconsin Rapids. The reservoir is filled as much as possible by spring runoff. For determining the flow goal at Wisconsin Rapids, the model measures wet versus dry years by the amount of water in storage, and adjusts the flow goal accordingly, within the range of about 1,500 to 3,500 ft^3/s. The relation of discharge goal to storage is based on a correlation of recorded reservoir stages and recorded discharges at Wisconsin Rapids for periods unaffected by significant runoff. The equation used to compute the flow goal is: $goal = 1,048 \times (1.0002646)^S$, where S is storage in cubic feet times 10^{-6} and goal is in cubic feet per second.

For Lake Du Bay the model ignores fluctuations in power generation and holds lake stage nearly constant through the summer and fall. The model makes no attempt to predict the volume of spring runoff. After February 1, the lake stage is lowered to the winter minimum by late March. This drawdown is simulated together with the Big Eau Pleine drawdown so that nearly steady flow is released from Lake Du Bay throughout the period. After drawdown is complete, Lake Du Bay is slowly refilled to reach its minimum summer level by April 30. If the discharge at Rothschild--upstream from Lake Du Bay--exceeds 25,000 ft^3/s, the simulation is shifted to a flood-storage routine which fills Lake Du Bay to its maximum allowable spring stage in 5 days. After this rapid fill, storage is varied with discharge within the allowable range (storage is raised to near maximum levels on high discharges or lowered to near summertime minimum levels for very low discharges). After June 15 simulated operation shifts to summer rules and little change in storage is allowed.

The model includes channel routing of flow from Lake Du Bay to Wisconsin Rapids. This part of the model was calibrated and verified earlier. Simulated ungaged inflow between Lake Du Bay and Wisconsin Rapids is added.

PENTENWELL-CASTLE ROCK MODEL

One model was used to simulate operations of Petenwell Lake and Castle Rock Lake. Their operating rules are similar and the outflow from Petenwell Lake is inflow to Castle Rock Lake through a short reach of river (pl. 1).

The operation and constraints of Petenwell Lake and Castle Rock Lake are similar to those for Lake Du Bay. Both are restricted to a 1 ft fluctuation in stage during the summer and fall (922.90 to 923.90 ft above mean sea level for Petenwell, 880.90 to 881.90 ft for Castle Rock). After January 1 the minimum stage on Petenwell Lake is lowered 4 ft (to 918.90 ft above mean sea level). After February 1 the minimum stage on Castle Rock Lake is lowered 5 ft (to 875.90 ft above mean sea level). The minimum stage on both lakes returns to the summer level on May 1. The maximum stage on both lakes is raised by 1 ft from March 15 to June 14 (to 924.90 ft above mean sea level for Petenwell and 882.90 ft for Castle Rock).

The actual winter drawdown on these lakes is variable, depending on the amount of snow on the ground, ground-water levels, frost depth, and other factors affecting runoff. If a large volume of spring runoff is expected, both lakes are lowered to near the minimum level. If less runoff is expected, the stage is kept higher. Both lakes are refilled rapidly during spring runoff and are kept near their spring maximum levels unless flooding is anticipated because of rainfall or flooding upstream.

The simulation of these pools is similar to the simulation of Lake Du Bay. Their stages are held nearly constant through the summer and fall. After January 1 for Petenwell Lake and after February 1 for Castle Rock Lake, stages are lowered to winter minimum elevations by late March. During the last week in March and through April, the pools are slowly filled to reach the summer minimum level by April 30. If a discharge greater than 25,000 ft^3/s is observed upstream at Wisconsin Rapids, the drawdown or slow fill is interrupted and the pools are filled to store potential floodwaters. Simulated discharge from Castle Rock Lake is adjusted daily based on preceding discharge and discharge at two gaging stations upstream. Simulated discharge from Petenwell Lake is adjusted based on flows upstream and the discharge from Castle Rock Lake to fill Petenwell Lake a little more slowly than Castle Rock.

After both pools are filled to their maximum spring level, they are kept nearly full as long as discharge is high. If the discharge from Castle Rock falls below 10,000 ft^3/s between March 25 and June 10, the model lowers stage in the lakes to allow for some storage during later floods.

In any event, both pools are lowered to summer levels by June 15 when summer operation begins.

CALIBRATION AND VERIFICATION OF MODELS

The channel-routing model parameters C_o and K_o determined for each reach were determined from estimates of average slope, width, and the slope of the stage-discharge relation for the reach, and may not be exactly right for the nonuniform channel and flood plains in the reach. For each reach, a short period of record selected to emphasize significant high flows was used to calibrate the channel routing. Various combinations of C_o and K_o close to the values originally computed were tried on the reach to see which would give the best fit to the observed data.

For each reach between gaging stations, a period of less than 2 years was selected for calibration, when record was available at both gaging stations. The calibration period was selected to include at least one significant flood. Daily flows from the upstream gaging station were routed to the downstream gaging station, combined with an estimate of ungaged inflow (explained in a later section), and compared to the observed daily flows at the downstream station. The modeling parameters were adjusted to improve the agreement between routed and observed flows. The best set of C_o and K_o was considered to be the one which gave the best agreement in timing and shape of the flood discharges, as well as the best maximum daily discharges. Many errors in low to medium discharges were due to the effects of day to day operations at run-of-the-river powerplants and were not considered in the calibration. At larger discharges the powerplant operations become insignificant in comparison to the total discharge.

The three reservoir models were calibrated in a similar manner. The models were used to simulate as much as 2 years of regulated streamflow. The simulated streamflow was compared with observed streamflow. Various parameters in the models and details of the modeling procedure were adjusted until the simulated streamflow agreed as closely as possible with observed streamflow.

The four models were verified by applying them for a short period, different from the period used in calibration. Simulated and observed streamflow were compared to be sure the models worked properly. If there were unacceptable errors in this simulation, more calibration was required. The models then were verified with a third period.

SIMULATION OF UNREGULATED STREAMFLOW

The first step in the river-system simulation was the simulation of unregulated flow. This is the streamflow which would have occurred if the lakes and reservoirs had not regulated streamflow. This step was required to determine the ungaged inflow into each reach of the river and to determine the effect the reservoirs and large lakes have on flood frequency. The only model used in this step is the channel-routing model.

PERIODS OF MISSING RECORD ON TRIBUTARY STREAMS

All of the gaging stations on tributary streams used in this study have incomplete record for the period 1915-76. It was necessary to estimate the missing record at these stations in order to use the record from these stations to estimate tributary inflow to the Wisconsin River between gaging stations.

Three gaging stations on adjacent streams on the west side of the Wisconsin River have record for substantial parts of the period studied, but none of the records are complete. These are Spirit River at Spirit Falls, Rib River at Rib Falls, and Big Eau Pleine River near Stratford. Graphical regressions were developed to estimate the missing record at each station.

First a log plot was made from corresponding points on the flow-duration curves and high-flow and low-flow frequency curves for the Rib and Big Eau Pleine Rivers. The plotted points defined three straight relation lines for low, medium, and high flows. A plot of daily flows and monthly flows were fairly scattered about the relation line but approximated the general shape of the line.

This three-segment relation line then was used to simulate missing record at the two gaging stations. Although a comparison of daily streamflows (simulated and observed) for periods of concurrent record showed some errors in daily flows--especially during runoff due to rainfall, the high- and low-flow frequency and duration curves for the observed flows and simulated flows were nearly identical.

Streamflow records simulated in this way are an approximation of what actually happened in a specific year. However, they are representative of the flow characteristics of the site and are satisfactory for simulating tributary inflow for a model to be used to determine streamflow characteristics.

A similar relation was developed between Rib River and Spirit River. In this case a four-segment relation line was used.

No satisfactory correlation could be found with the Eau Claire River at Kelly. The missing record for this station could not be simulated.

The two gaging stations on the Tomahawk River both have incomplete record. Unregulated flow was simulated at each gaging station by adjusting the recorded daily flows at that station to account for the change in storage in reservoirs upstream from the station. The daily change in storage at each reservoir was converted into an equivalent daily discharge. The equivalent daily discharge was positive when storage increased and negative when storage decreased. The equivalent daily discharge for each reservoir was routed downstream to all gaging stations using the channel-routing model calibrated earlier. The routed equivalent daily discharges were added algebraically to the recorded daily discharges at each gaging station. The sum is the simulated, unregulated flow for each gaging station for the period of record.

Unregulated flow for the Tomahawk River at Bradley was determined from streamflow and reservoir records for January 1, 1930, to September 30, 1973. For October 1, 1914, to September 30, 1927, and October 3, 1928, to September 30, 1929, streamflow was routed from the unregulated flow for the station further upstream, Tomahawk River near Bradley. A ratio of 0.289 (drainage-area ratio) times the discharge at the upstream station was used to simulate inflow between the two stations. The rest of the record (October 1, 1927, to October 2, 1928; October 1, 1929, to December 31, 1929; October 1, 1973, to September 30, 1976) was simulated by multiplying the unregulated flow for the Wisconsin River at Rainbow Lake by 0.780 (this ratio was determined from the unregulated annual flow volumes from Tomahawk River at Bradley and Wisconsin River at Rainbow Lake).

PERIODS OF REGULATED FLOW AND MISSING RECORD ON WISCONSIN RIVER

Unregulated flow was simulated at each gaging station on the Wisconsin River by adjusting the recorded daily flows at that station to account for the change in storage in reservoirs upstream from the station. This procedure is the same as was used for the Tomahawk River stations.

This adjustment for reservoir storage gave a complete record for water years 1915-76 only at Merrill and Muscoda. At all other gaging stations, additional simulation was necessary to fill in the missing record. This included routing simulated, unregulated flow from the next gaging station upstream and adding an estimate for ungaged inflow between the two gaging stations. Unregulated flow simulated in this way was merged with the unregulated flow simulated previously to produce a single continuous simulation of unregulated flow.

Ungaged inflow between gaging stations was simulated using a combination of (1) streamflow records on tributary streams, (2) streamflow at the upstream gaging station on the main stem, and (3) differences between observed streamflow at a downstream gaging station and streamflow routed from an upstream gaging station. In several instances, missing record on tributary streams was filled in by a graphical regression with streamflow data from a gaging station on a nearby stream.

A summary of the methods used to simulated unregulated flow at each gaging station is included in Appendix A. The maximum instantaneous unregulated discharge was selected for each year for all 10 gaging stations and are also listed in Appendix B.

SIMULATION OF REGULATED STREAMFLOW

The second step in simulating the Wisconsin River System was simulating the entire system using current operating procedures. This includes all of the reservoirs and large hydroelectric power dams, for water years 1915-76. In this simulation the three reservoir models were used sequentially from upstream to downstream. The channel-routing model was used between reservoirs where it was needed to simulate the remaining channel reaches. The inflow for each model was computed from the outflow simulated by the models upstream and from the unregulated flow and tributary flow determined in the previous step. The detailed computation of inflow is explained below.

SIMULATED INFLOW FOR MODELS

Upper Wisconsin System Model

The prime input data needed to use the model is the daily inflow at each reservoir site, plus uncontrolled inflow between the reservoirs and Merrill. The inflows to sites downstream from a conceptual reservoir are computed as the sum of the uncontrolled inflow plus the water released and routed down from the upstream site. The model therefore requires seven uncontrolled inflow files as input, one for each conceptual reservoir plus one for Merrill. The following paragraphs briefly review how the inflow files were obtained. Refer to figure 2 for the reservoir system's configuration.

The simulated, unregulated flow at Rainbow Lake was determined by use of the historical gage record at Rainbow Lake and the converted stage data for the upstream reservoirs. This gave the simulated, unregulated inflow to the Rainbow Lake site as if reservoir 1 did not exist, that is, no upstream control.

The simulated, unregulated flow at Rainbow Lake then was divided using a drainage-area ratio to form the uncontrolled inflow files for reservoirs 1 and 2. The ratio used was that of the controlled drainage area upstream from Rainbow Lake to the total drainage area at Rainbow Lake.

The uncontrolled inflow file at reservoir 6 was based on a drainage-area ratio times the simulated, unregulated flow at Rainbow Lake.

The uncontrolled inflow file at reservoir 4 was based on the simulated, unregulated flow for the Tomahawk River at Bradley. As with Rainbow, this simulated, unregulated flow was divided between reservoirs 4 and 3 by use of a drainage-area ratio.

Inflow to reservoir 5 was computed as 1.94 times the flow of the Spirit River at Spirit Falls. The ratio was determined from drainage areas of the gaging station and the reservoir. Part of the flow record for the Spirit River was computed from correlation with the Rib River.

The uncontrolled inflow between the reservoirs and Merrill was computed from the difference between the inflow to the reservoirs and the simulated, unregulated flow at Merrill. The simulated, unregulated flow at Rainbow Lake, plus the part of the inflow to reservoir 6 which is not included in the gaging station records at Rainbow Lake, were routed to Merrill. The simulated, unregulated flow for the Tomahawk River at Bradley, and the total inflow to reservoir 5 also were routed to Merrill and added to the flow routed from Rainbow Lake. This sum was subtracted from the simulated, unregulated flow at Merrill to produce the simulated, uncontrolled inflow.

Using a drainage-area ratio technique to estimate the daily inflows at an individual reservoir would be unreliable. However, using such a ratio to estimate the average daily inflow to a group of reservoirs in a conceptual unit is much more defensible because the spatial variability of inflow to the various small reservoirs is averaged out by combining inflows to several reservoirs. This provides another rationale for grouping the upper system 20 reservoirs into 6 units. It should be noted that reservoirs that stand on their own in the model (Rainbow Lake, Rice and Spirit Reservoirs) have reliable daily inflow values based on predominantly gaged records at the site, rather than drainage-area ratios.

Du Bay-Big Eau Pleine Model

Inflow for this model was computed from flow at Rothschild, flow for the Big Eau Pleine River, and the ungaged inflow previously computed between Rothschild and Knowlton, and between Knowlton and Wisconsin Rapids. Simulated inflow for the Big Eau Pleine Reservoir is the sum of flow measured for the Big Eau Pleine River near Stratford and 0.486 times the ungaged inflow between Rothschild and Knowlton. Simulated inflow for Lake Du Bay is the sum of:

1. outflow from the Big Eau Pleine Reservoir,
2. flow at Rothschild, routed to the inlet of Lake Du Bay,
3. 0.514 times the ungaged inflow between Rothschild and Knowlton, and
4. 0.411 times the ungaged inflow between Knowlton and Wisconsin Rapids.

The ratios were computed from the drainage areas of the various sites.

Petenwell-Castle Rock Model

Inflow for this model was computed from flow at Wisconsin Rapids, and the ungaged inflow previously computed between Wisconsin Rapids and Necedah and between Necedah and Wisconsin Dells. Inflow for the Petenwell part of the model is simulated flow at Wisconsin Rapids plus the ungaged inflow between Wisconsin Rapids and Necedah. Inflow for the Castle Rock part of the model is the computed outflow from Petenwell plus 0.508 times the ungaged inflow between Necedah and Wisconsin Dells. This ratio was determined from the drainage areas.

SIMULATED, REGULATED FLOWS

Simulated, regulated daily discharge was computed at all stations with the three reservoir simulation models and the channel-routing model. At each gaging station the ungaged inflow as computed in a previous step was added to the

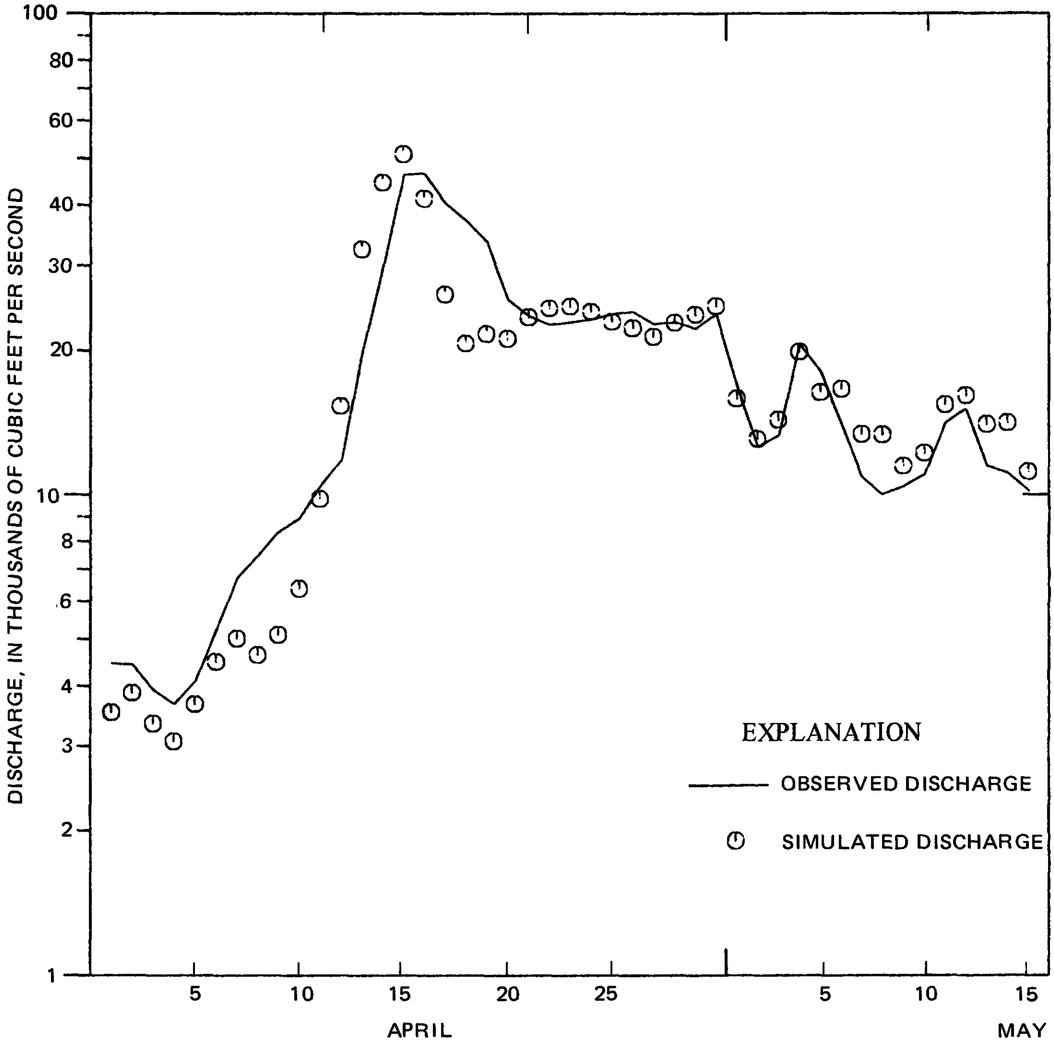

Figure 4. Comparison of observed and simulated, regulated discharge for Wisconsin River near Wisconsin Dells (05404000) for the period April 1, to may 15, 1965.

simulated, regulated flow in the Wisconsin River (routed from the next station upstream) to simulate the total flow. These models were run as separate computer programs.

Figure 4 is an illustration of the agreement between simulated, regulated discharge computed with the entire set of models and observed discharge for the Wisconsin River at Wisconsin Dells. The period shown includes one of the larger spring floods which occurred after all the dams were in operation. The fit for this period is about average for the period of record.

The maximum instantaneous regulated discharge was selected for each year at all nine gaging stations and are listed in Appendix B. The site of the gage at Knowlton was submerged by Lake Du Bay and is not included in the table of regulated discharge.

FLOOD FREQUENCY OF SIMULATED FLOWS

Flood-frequency analyses were conducted for all gaging stations from both the simulated, unregulated flows and the simulated, regulated flows. Flood-frequency curves were computed from annual maximum daily flows and converted to instantaneous peak-flow frequency by a relation developed from correlation of observed maximum daily flows and corresponding instantaneous peak flows for each station. An example of this regression is shown in figure 5 for Wisconsin River at Wisconsin Dells.

Flood frequency for simulated, unregulated daily flows was determined using a log-Pearson Type III distribution as described in Bulletin 17A (Water Resources Council, 1977). Generalized skew was selected from the map in Bulletin 17A, at the centroid of the basin, and a weighted average made with the station skew.

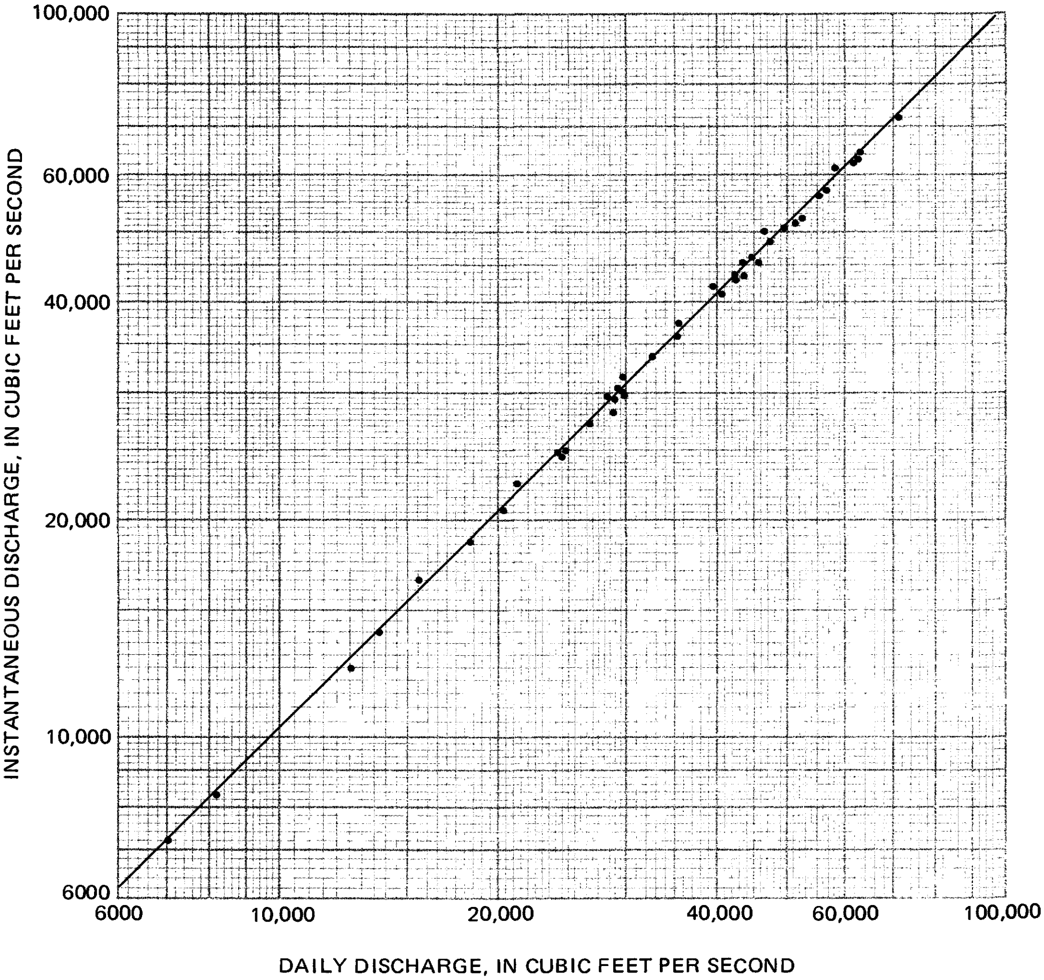

Figure 5. Comparison of annual maximum daily discharge and instantaneous maximum discharge for Wisconsin River at Wisconsin Dells (05404000) for the period 1935-76.

Flood frequency for the simulated, regulated streamflow at Wisconsin Dells was computed by the Corps of Engineers as part of their study of the hydraulics of the Wisconsin River near Portage. They used the 62 years of simulated streamflow generated by the model described above to compute this flood frequency.

Flood frequencies for the simulated, regulated streamflow at other gaging stations along the Wisconsin River were computed using a log-Pearson Type III distribution, as described above for the simulated, unregulated streamflow. The frequency curves were checked by various comparisons because this distribution does not necessarily apply to regulated streamflow and because seasonal changes in reservoir operations may divide spring and summer floods into distinct populations.

The first comparison was a correlation between annual maximum daily flows for regulated and unregulated, simulated streamflow. The equation for the least-squares fit of these data was used to adjust the frequency curve for simulated, unregulated streamflow to the simulated, regulated condition. The difference between this adjusted regulated frequency curve and the log-Pearson frequency curve, computed directly from the regulated streamflow, was much less than the standard error of the least-squares line used to adjust the unregulated frequency curve.

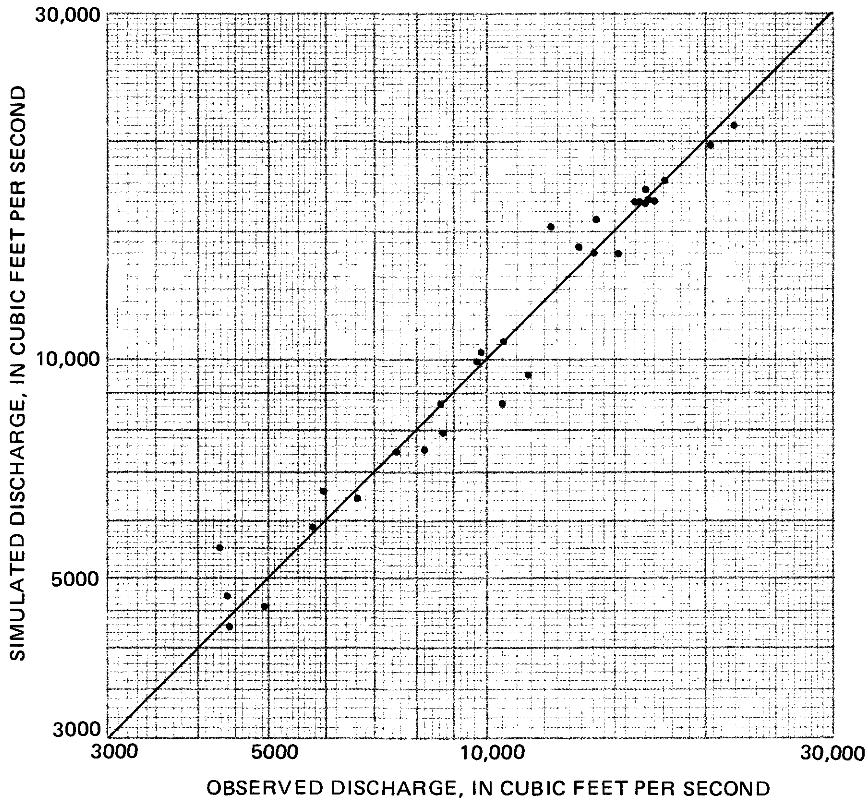

Figure 6. Comparison of simulated and observed annual maximum daily discharge for Wisconsin River at Merrill (05395000) for water years 1952-76.

The second comparison was to plot the annual maximum simulated, regulated flows, using the Weibull plotting position formula, and compare them visually with the computed frequency curve. In all cases, the computed frequency curve fit the data very well.

The third comparison involved analyzing spring and summer annual maximum flows separately. Reservoir storage varies seasonally, so it is possible that spring and summer maximum flows represent two separate populations. Frequency curves were computed separately for the two seasons, using the log-Pearson Type III distribution. The two frequency curves were then combined into one joint annual frequency curve. The differences between this frequency curve and the one computed using just the annual maximum flows were less than the differences in the first comparison.

The three comparisons all indicate that using the log-Pearson Type III distribution on annual maximum flows is adequate. The frequency curves resulting from all of the methods agree, within the accuracy of the methods. The log-Pearson Type III distribution was used to provide consistent frequency curves at all the gaging stations.

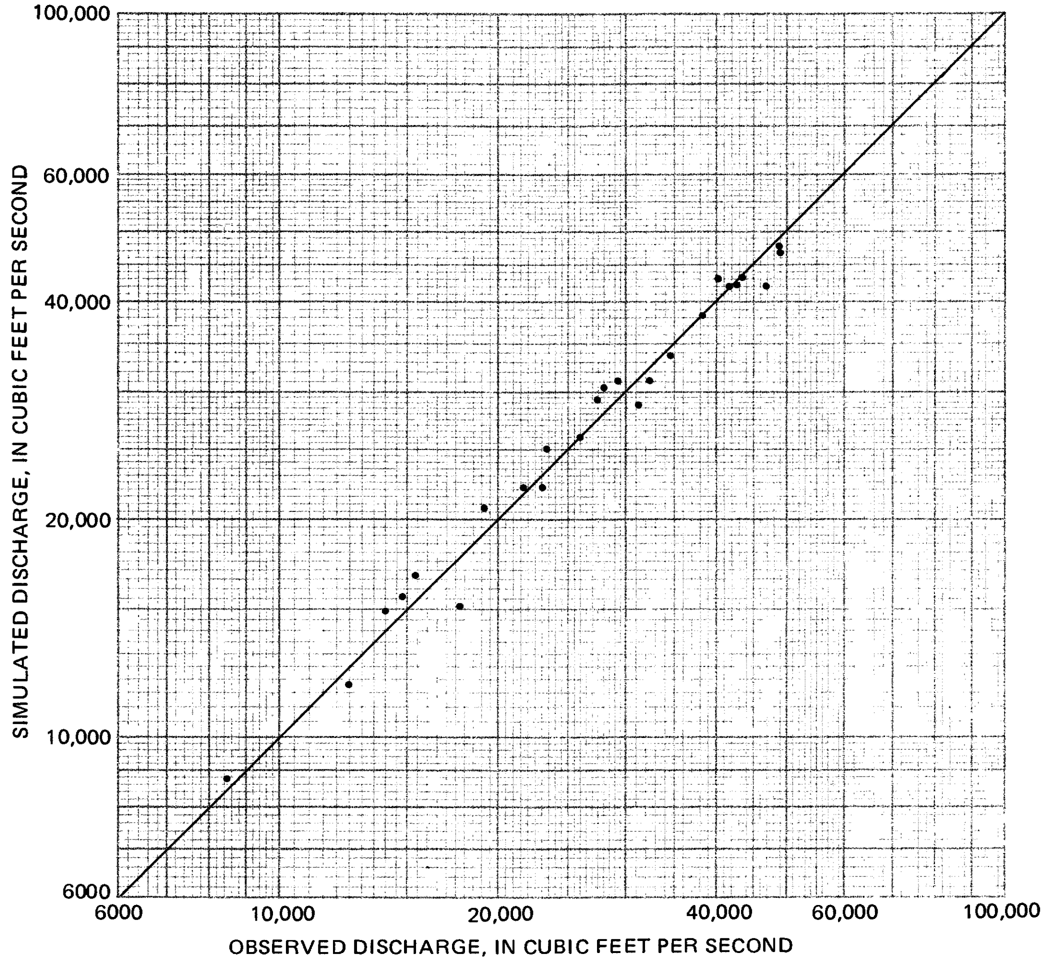

Figure 7. Comparison of simulated and observed annual maximum daily discharge for Wisconsin River at Rothschild (05398000) for water years 1952-76.

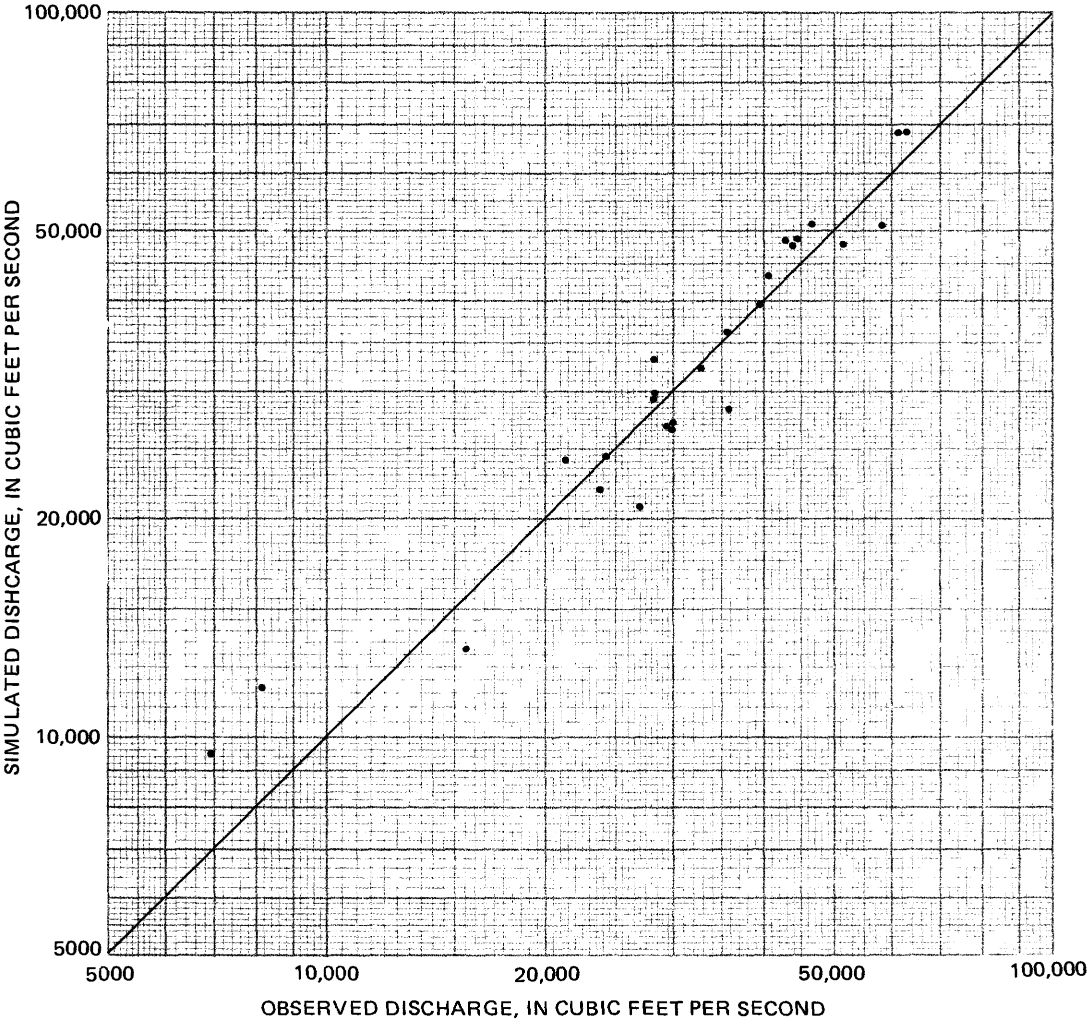

Figure 8. Comparison of simulated and observed annual maximum daily discharge for Wisconsin River near Wisconsin Dells (05404000) for water years 1952-76.

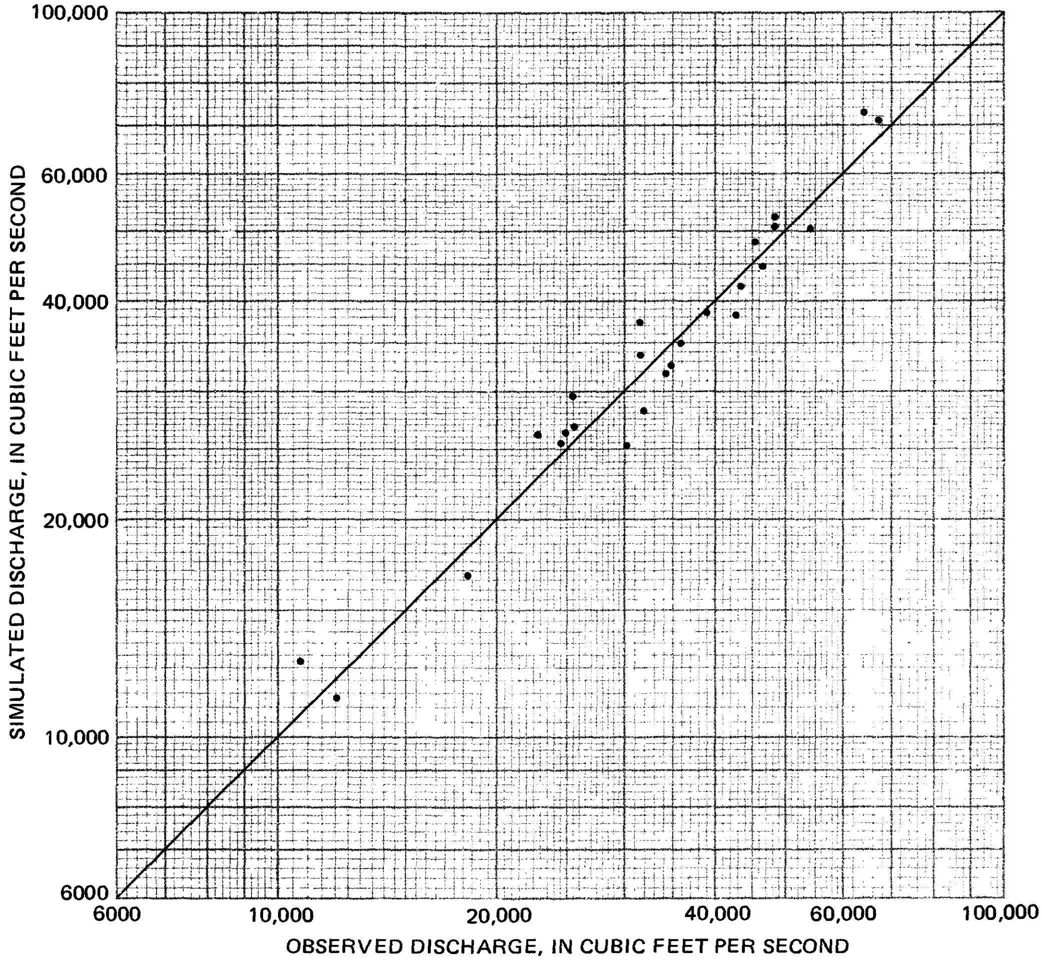

Figure 9. Comparison of simulated and observed annual maximum daily discharge for Wisconsin River at Muscoda (05407000) for water years 1952-76.

The computed frequency curves are summarized in tables 3, 4, and 5. Tables 3 and 4 contain summaries of the frequency curves for simulated unregulated and simulated regulated conditions, respectively. Table 5 contains the summary of the frequency curves for the simulated regulated condition with the expected probability adjustment (Water Resources Council, 1977).

ACCURACY OF SIMULATED FLOOD FREQUENCY

A verification of all the models was made by comparing the observed annual maximum daily flows from gaging-station records with the simulated, regulated flows. This comparison was made for the 25-year period 1952-76, when all the reservoirs and hydroelectric dams were operating. The following stations had records for this period: Merrill, Rothschild, Wisconsin Dells, and Muscoda. The comparisons are plotted in figures 6 to 9. Each of these figures includes a 45° line, representing perfect agreement, for comparison.

A statistical test of this comparison was made as follows. For each year the ratio of simulated, regulated maximum flow to the observed maximum flow was computed. The mean and standard deviation of the ratios was determined and the means ranged from 1.003 to 1.018 and were not significantly different from 1.0 at the 90 percent level. Thus, there is not a significant statistical difference between the simulated and observed maxima.

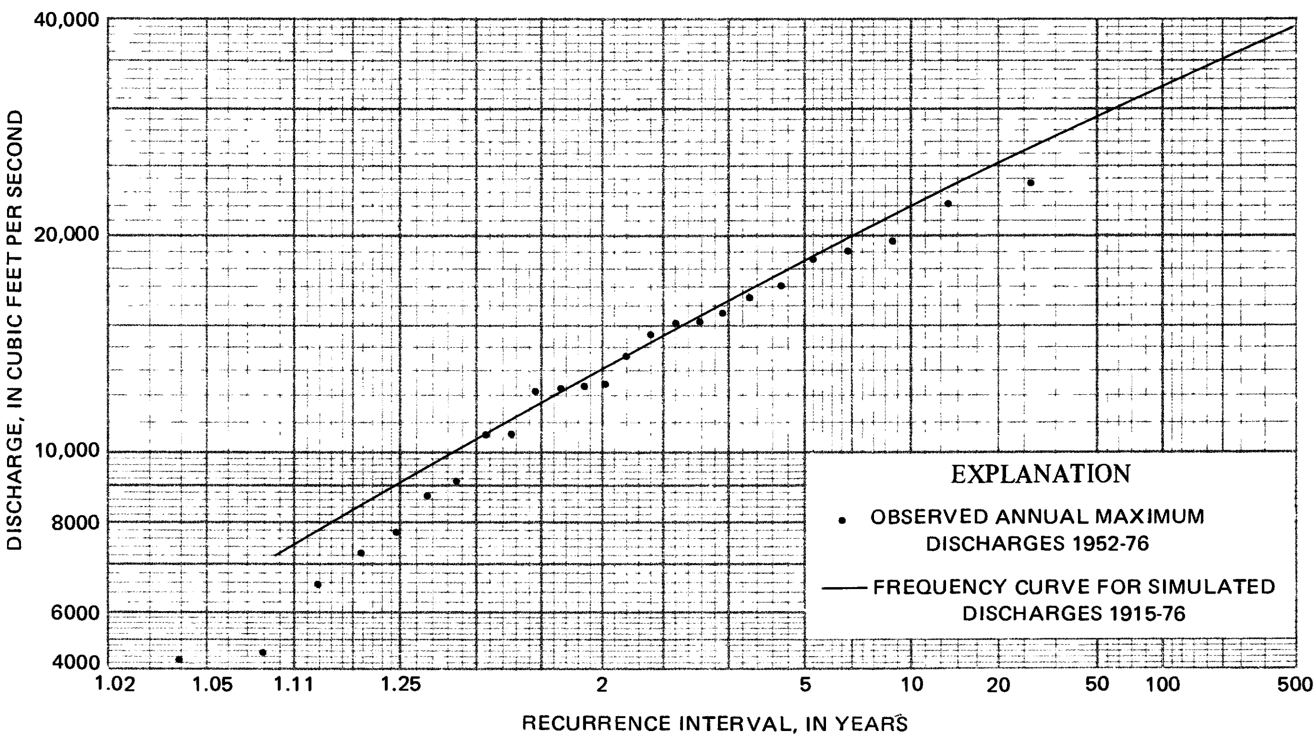

Figure 10. Comparison of observed annual maximum discharges (1952-76) with the frequency curve for simulated, regulated annual maximum discharges (1915-76) for the Wisconsin River at Merrill (05395000).

Table 3.--Summary of frequency curves for simulated, unregulated annual maximum flows for gaging stations on the Wisconsin River

Station no.	Station name	Recurrence interval, in years				
		2	10	50	100	500
05391000	Wisconsin River at Rainbow Lake near Lake Tomahawk	2,960	4,020	4,740	5,000	5,600
05392000	Wisconsin River at Whirlpool Rapids near Rhinelander	4,570	6,080	7,170	7,600	8,500
05395000	Wisconsin River at Merrill	17,000	26,000	34,000	37,000	43,000
05398000	Wisconsin River at Rothschild	31,000	49,000	63,000	68,000	80,000
05400000	Wisconsin River at Knowlton	35,000	56,000	70,000	75,200	86,000
05400800	Wisconsin River at Wisconsin Rapids	40,000	64,000	80,000	86,000	98,000
05401500	Wisconsin River near Necedah	39,500	63,000	80,000	85,000	98,000
05404000	Wisconsin River near Wisconsin Dells	43,000	69,000	86,000	92,000	105,000
05406000	Wisconsin River at Prairie du Sac	47,000	74,000	91,000	98,000	111,000
05407000	Wisconsin River at Muscoda	46,000	70,000	86,000	92,000	102,000

Table 4.--Summary of frequency curves for simulated, regulated annual maximum flows for gaging stations on the Wisconsin River

Station no.	Station name	Recurrence interval, in years				
		2	10	50	100	500
05391000	Wisconsin River at Rainbow Lake near Lake Tomahawk	2,000	2,800	3,400	3,600	4,200
05392000	Wisconsin River at Whirlpool Rapids near Rhinelander	3,200	4,600	5,700	6,200	7,200
05395000	Wisconsin River at Merrill	13,000	22,000	29,000	32,000	38,000
05398000	Wisconsin River at Rothschild	27,000	45,000	59,000	64,000	76,000
05400800	Wisconsin River at Wisconsin Rapids	32,000	54,000	70,000	76,000	89,000
05401500	Wisconsin River near Necedah	31,000	54,000	71,000	77,000	90,000
05404000	Wisconsin River near Wisconsin Dells[1]	34,000	54,000	73,000	82,000	101,000
05406000	Wisconsin River at Prairie du Sac	36,000	62,000	80,000	86,000	100,000
05407000	Wisconsin River at Muscoda	35,000	58,000	74,000	80,000	93,000

[1]Flood frequency computed by Corps of Engineers from streamflow simulated in this study.

Table 5.--Summary of frequency curves for simulated, regulated annual maximum flows for gaging stations on the Wisconsin River including the expected probability adjustment

Station no.	Station name	Recurrence interval, in years				
		2	10	50	100	500
05391000	Wisconsin River at Rainbow Lake near Lake Tomahawk	2,000	2,800	3,500	3,700	4,300
05392000	Wisconsin River at Whirlpool Rapids near Rhinelander	3,200	4,600	5,800	6,300	7,400
05395000	Wisconsin River at Merrill	13,000	22,000	30,000	33,000	40,000
05398000	Wisconsin River at Rothschild	27,000	45,000	60,000	66,000	79,000
05400800	Wisconsin River at Wisconsin Rapids	32,000	54,000	72,000	78,000	91,000
05401500	Wisconsin River near Necedah	31,000	54,000	72,000	79,000	93,000
05404000	Wisconsin River near Wisconsin Dells[1]	34,000	55,000	75,000	85,000	106,000
05406000	Wisconsin River at Prairie du Sac	36,000	63,000	82,000	88,000	103,000
05407000	Wisconsin River at Muscoda	35,000	59,000	76,000	83,000	95,000

[1]Flood frequency computed by Corps of Engineers from streamflow simulated in this study.

For an additional verification, the recent, fully regulated, observed peak discharges (water years 1952-76) were plotted on the frequency curves computed from the simulated, regulated flows (figs. 10 to 13). In each case, these curves appear reasonable considering they are computed from 62 years of record, rather than the shorter period represented by the plotted points.

FLOOD HYDROGRAPHS

At Wisconsin Dells, typical flood hydrographs for the 10-, 50-, 100-, and 500-year floods were estimated by the U.S. Army Corps of Engineers from data simulated with these models. These are shown on figure 14. These hydrographs will be used by the U.S. Army Corps of Engineers to determine the effects of possible overtopping of the levees near Portage. They are required for the complex hydraluic analysis needed to determine flood elevations in the Portage area.

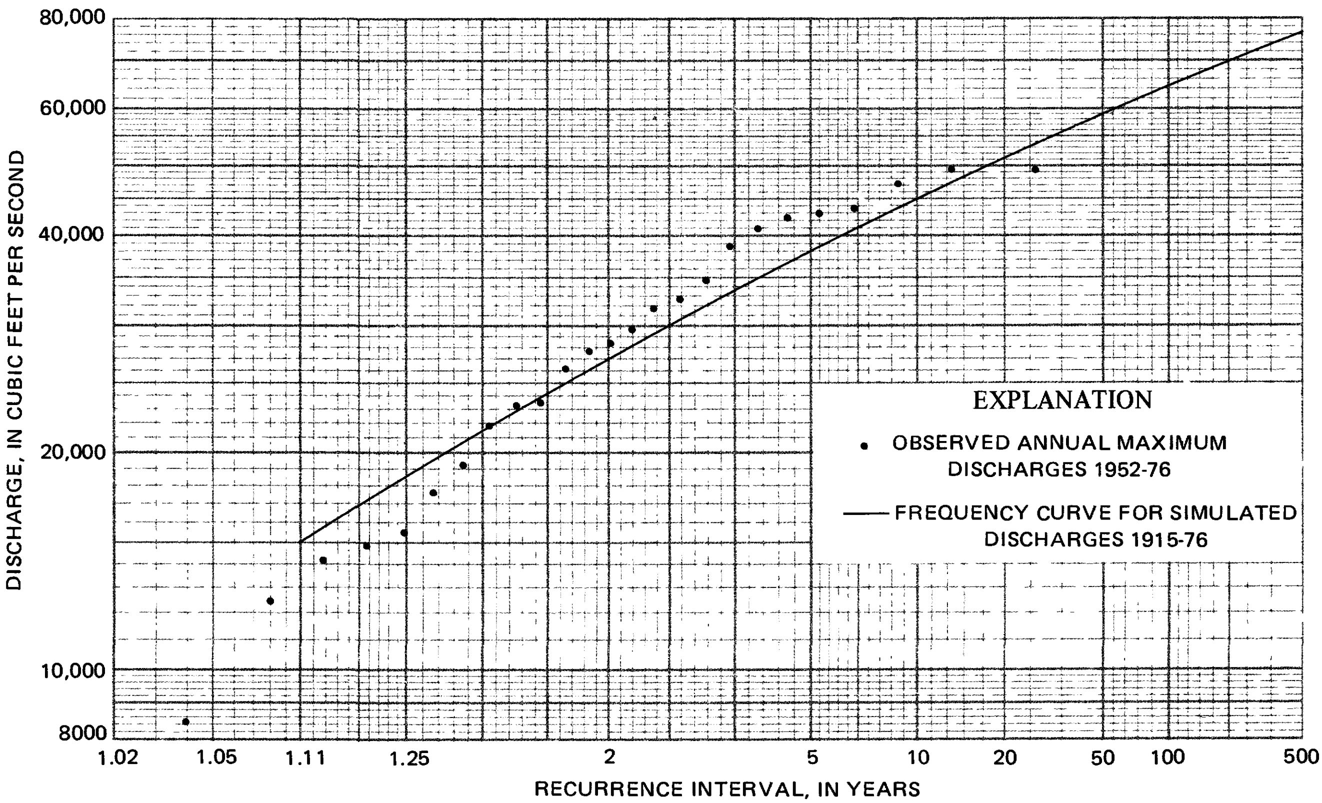

Figure 11. Comparison of observed annual maximum discharges (1952-76) with the frequency curve for simulated, regulated annual maximum discharges (1915-76) for Wisconsin River at Rothschild (05398000).

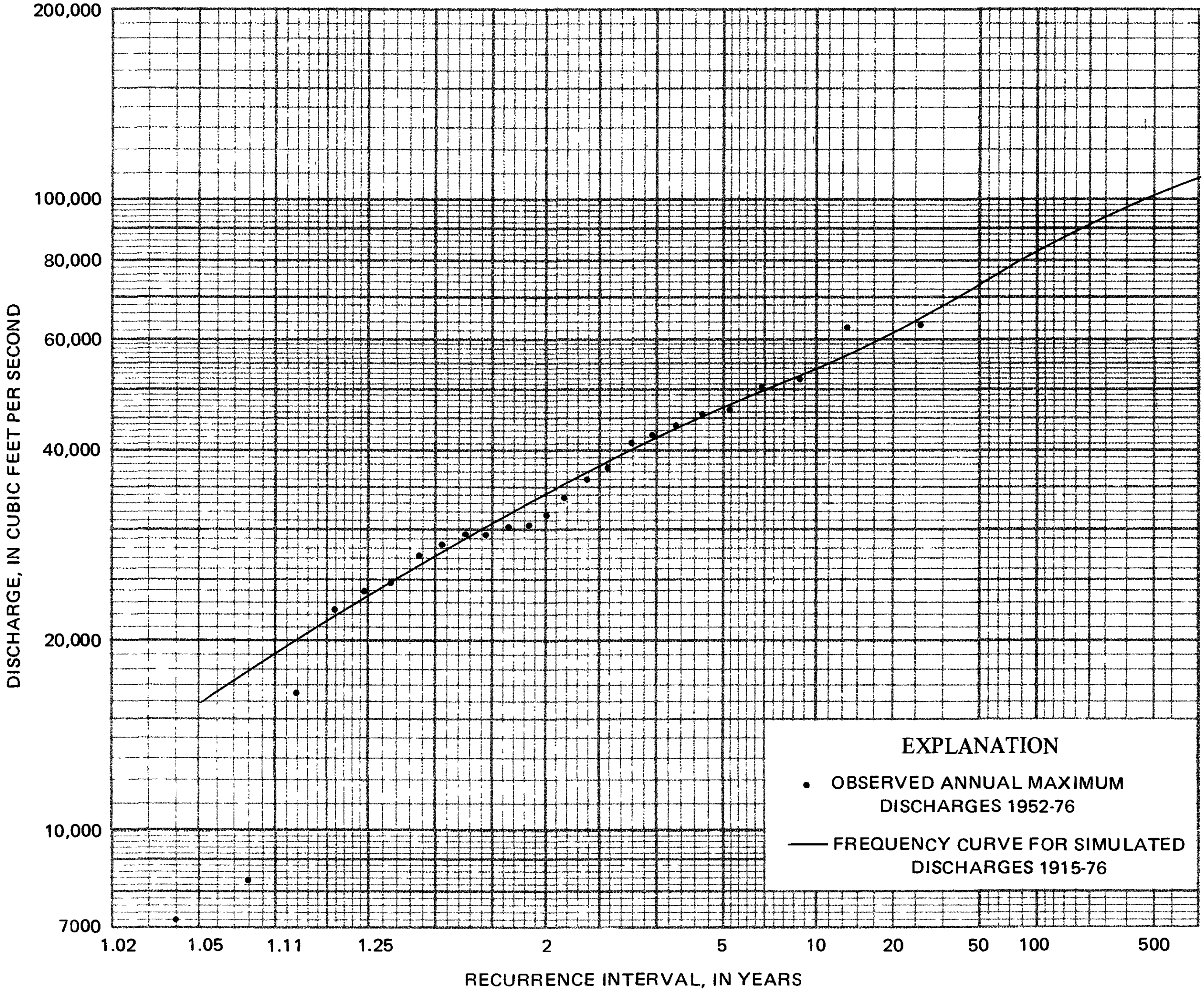

Figure 12. Comparison of observed annual maximum discharges (1959-76) with the frequency curve for simulated, regulated annual maximum discharges (1915-76) for the Wisconsin River near Wisconsin Dells, (05404000).

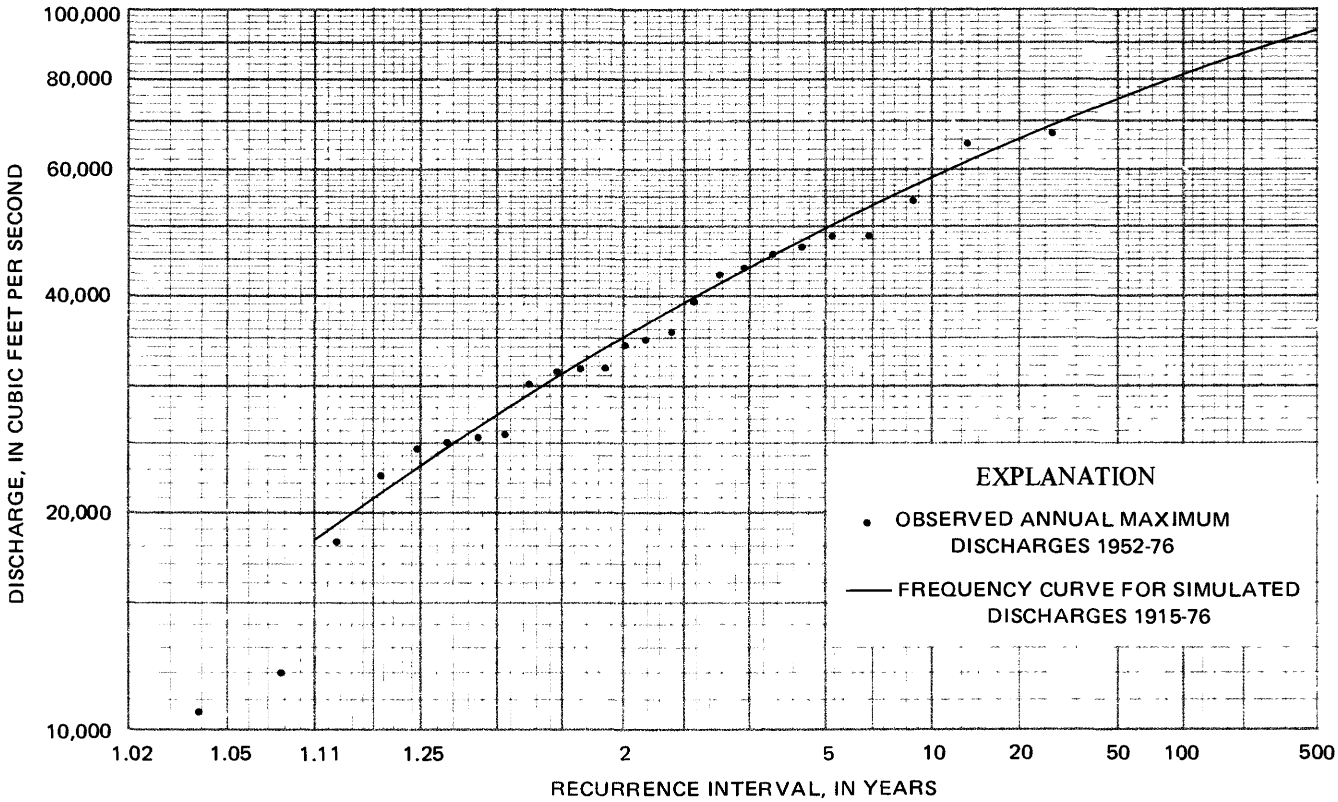

Figure 13. Comparison of observed annual maximum discharges (1952-76) with the frequency curve for simulated, regulated annual maximum discharges (1915-76) for the Wisconsin River at Muscoda (05407000).

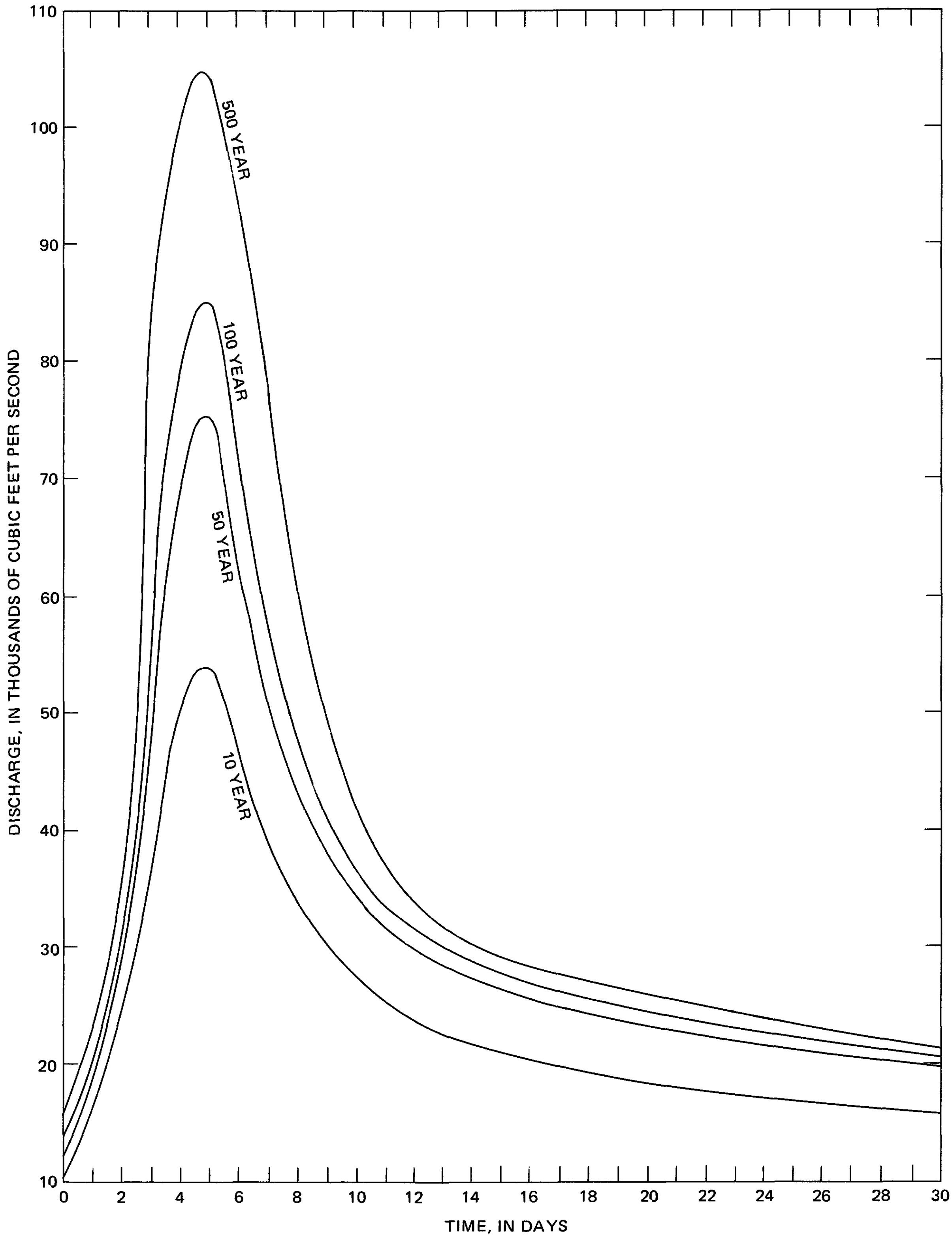

Figure 14. Flood-frequency hydrographs for the Wisconsin River near Wisconsin Dells (05404000).

CONCLUSIONS

The models used in this study simulate streamflow for a 62-year period for both unregulated and regulated conditions. The series of simulated, regulated streamflow is consistent at all gaging stations on the Wisconsin River and includes the effects of reservoir and hydroelectric dam operation. Flood frequency computed from this simulated, regulated streamflow is a better representation of the true flood frequency than estimates based on streamflow records collected over shorter periods with different regulation by reservoirs.

The reservoir system reduces natural flood peaks of all magnitudes. Comparison of the flood frequencies in table 3 (unregulated) and table 4 (regulated) shows that the reservoirs reduce the magnitude of flood peaks at all frequencies. At Wisconsin Dells the 2-year flood is reduced 9,000 ft^3/s or 21 percent (from 43,000 to 34,000 ft^3/s) and the 100-year flood is reduced by 10,000 ft^3/s or 11 percent (from 92,000 to 82,000 ft^3/s).

There are times, however, when reservoir regulation has little effect on individual flood peaks. This occurs when precipitation is concentrated in areas not controlled by reservoirs or when the reservoirs are too full, because of earlier runoff, to store a significant amount of water.

In general, the reservoirs have a greater effect on spring flood peaks than on summer or fall floods. The reservoirs and the lakes controlled by hydroelectric dams are generally near their minimum elevation in late winter and have storage available for spring floodwaters. During the summer the reservoirs and lakes are normally much fuller and have less storage available for additional water from floods.

The main purpose of models used in this study was to simulate flood discharge and storage. The models simulated a continuous record of daily discharge at all stations. The models were calibrated and verified to give an accurate simulation of flood discharges and of total volume. During calibration, some attention was given to low-flow periods as well but the simulation of low flows is not as accurate as the simulation of floodflows. The models have potential for simulating low flows but more work is necessary to improve the calibration and the data base for low-flow simulation.

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APPENDIX A

SUMMARY OF METHODS USED TO SIMULATE UNREGULATED FLOW

At Rainbow Lake

From July 7, 1936, through water year 1976 simulated, unregulated flow was computed from streamflow records and reservoir records. For water year 1915 through July 6, 1936, unregulated flow was simulated by routing simulated, unregulated flow from Whirlpool Rapids upstream to Rainbow Lake with the ungaged inflow simulated by 0.641 times the flow at Rainbow Lake. This method was calibrated and verified with records from 1937-61.

At Whirlpool Rapids

For water years 1915-61 simulated, unregulated flow was computed from streamflow and reservoir records. For water years 1962-76 unregulated flow was simulated by routing simulated, unregulated flow from Rainbow Lake to Whirlpool Rapids and adding 0.641 times the simulated, unregulated flow at Rainbow Lake. The ratio for ungaged inflow was determined from the drainage area. This method also was calibrated and verified with records from 1937-61.

At Merrill

For the entire period, water years 1915-76, unregulated flow was simulated from streamflow and reservoir records.

At Rothschild

For water years 1945-76 unregulated flow was simulated from streamflow and reservoir records. This is the first of three methods used to simulate unregulated flow at this station.

The second method was used for water years 1915-26 and 1940-44. Simulated, unregulated flow was routed from Merrill to Rothschild. Ungaged inflow was simulated by 1.73 times the flow of the Rib River plus 1.96 times the flow of the Eau Claire River. These ratios were determined from drainage areas, using the Rib River to represent the area west of the Wisconsin River and using the Eau Claire River to represent the area to the east. This method was calibrated and verified with records from 1945-76.

The third method was used for water years 1927-39, when there were no streamflow records for the Eau Claire River. No satisfactory correlation could be found to simulate this period of record for the Eau Claire River. Simulated, unregulated flow was routed from Merrill to Knowlton. Flow for the Big Eau Pleine River was lagged by 1 day and added to the routed flow. This sum was subtracted from the simulated, unregulated flow at Knowlton. This difference is the ungaged inflow between Merrill and Knowlton. It was multiplied by 0.695 and routed upstream from Knowlton to Rothschild. This was the simulated, ungaged inflow between Merrill and Rothschild. It was added to the simulated, unregulated flow routed from Merrill to Rothschild.

The upstream routing from Knowlton to Rothschild introduced some large oscillations in flow rate for the ungaged inflow at Rothschild. These oscillations produced significant errors in daily flow when the total simulated flow at Rothschild was less than 10,000 ft^3/s. These errors were reduced by taking a 3-day moving average of the simulated, unregulated flow at Rothschild, with an adjustment to assure that the total volume of flow is not changed. This average replaced the daily flow at the middle day of the averaging period whenever flow was less than 10,000 ft^3/s.

The ratio used to adjust Merrill-Knowlton inflow to simulate Merrill-Rothschild inflow was not the same as the ratio of drainage areas. The total annual flow volume for the Wisconsin River at Merrill, Rothschild, Knowlton, Wisconsin Rapids, and Nekoosa, and for the Big Eau Pleine River prove that the ungaged infow in these reaches was not proportional to the drainage area. The ratios used for the ungaged inflows for this entire reach are based on increases in the annual flow volume between these stations.

This third method of simulating unregulated flow at Rothschild was calibrated and verified by comparing the simulated flow at Rothschild by this method with the flow simulated by the second method for the periods 1921-26 and 1940-42. No direct comparison could be made with the first method because the gages at Rothschild and Knowlton were never operated at the same time.

At Knowlton

For water years 1921-42 unregulated flow was simulated from streamflow and reservoir records.

For the rest of the period 1915-76 the simulation was similar to the third method of simulation at Rothschild. For water years 1915-20 and 1943-49 simulated, unregulated flow was routed from Rothschild to Knowlton. Big Eau Pleine River flow was lagged 1 day and added to the routed flow. This sum was the basis for the simulation at Knowlton. The sum also was routed from Knowlton to Nekoosa, where it was subtracted from the simulated, unregulated flow at Nekoosa. The difference was multiplied by 0.354 and routed upstream from Nekoosa to Knowlton, where it was added to the flow routed from Rothschild and the Big Eau Pleine River to simulate the unregulated flow at Knowlton. This method was calibrated and verified with streamflow records from 1921-42.

For water years 1950-76 the same procedure was used, with Wisconsin Rapids substituted for Nekoosa and the ratio changed to 0.403. No direct calibration was possible, but the changes from the routing to Nekoosa are very small. Before this could be completed it was necessary to simulate unregulated flow for water years 1950-57 at Wisconsin Rapids as explained below.

At Wisconsin Rapids

For water years 1958-76 unregulated flow was simulated from streamflow, reservoir, and Lake Du Bay records.

For water years 1950-57 unregulated flow was simulated by a method similar to the one used at Rothschild and at Knowlton. Simulated, unregulated flow at Rothschild was routed to Knowlton. Big Eau Pleine River flow was lagged 1 day and added to the routed flow. The sum then was routed to Wisconsin Rapids, where it was the basis for the simulation there. The sum then was routed from Wisconsin Rapids to Wisconsin Dells and subtracted from the simulated, unregulated flow near Wisconsin Dells. The difference was multiplied by 0.414 and routed upstream from Wisconsin Dells to Wisconsin Rapids. This simulation of the ungaged inflow was added to the flow routed from Rothschild and the Big Eau Pleine River to simulate the unregulated flow at Wisconsin Rapids. This method was calibrated and verified with records from 1958-76.

For water years 1915-49 simulated, unregulated flow was routed from Knowlton to Nekoosa and subtracted from the simulated, unregulated flow at Nekoosa. The difference was multiplied by 0.811 to simulate the ungaged inflow between Knowlton and Wisconsin Rapids. The simulated, unregulated flow at Knowlton was routed to Wisconsin Rapids and added to the ungaged inflow simulation to simulate the unregulated flow at Wisconsin Rapids.

Near Nekoosa

For water years 1915-49 unregulated flow was simulated from streamflow, reservoir, and Lake Du Bay records.

For water years 1950-76 simulated unregulated flow was routed from Knowlton to Wisconsin Rapids and subtracted from the simulated, unregulated flow at Wisconsin Rapids. The difference was multiplied by 1.23 to simulate the ungaged inflow between Knowlton and Nekoosa. Simulated, unregulated flow was routed from Knowlton to Nekoosa and added to the ungaged inflow simulation to simulate the unregulated flow near Nekoosa.

The ratio used for ungaged inflow simulation is based on drainage area. There was not sufficient data on annual flow volumes to determine a ratio significantly different from the drainage-area ratio.

Near Necedah

For water years 1945-50 unregulated flow was simulated from streamflow, reservoir, and Lake Du Bay records.

For water years 1915-44 and 1951-76 the procedure was similar to that used for Rothschild, Knowlton, and Wisconsin Rapids. Simulated, unregulated flow was routed from Nekoosa to near Wisconsin Dells and subtracted from the simulated, unregulated flow near Wisconsin Dells. The difference was multiplied by 0.199 and routed upstream from near Wisconsin Dells to near Necedah to simulate ungaged inflow. Simulated, unregulated flow was routed from Nekoosa to near Necedah and added to the ungaged inflow simulation to simulate the unregulated flow near Necedah. This method was calibrated and verified with record from 1945-50. The ratio for ungaged inflow simulation was computed from annual flow volumes. This simulation could not be finished until after unregulated flow was simulated near Wisconsin Dells.

Near Wisconson Dells

For water years 1935-76 unregulated flow was simulated from records of streamflow, reservoir stages, and stages of Lakes Du Bay, Petenwell, and Castle Rock.

For water years 1915-34 simulated, unregulated flow was routed from Wisconsin Rapids to Muscoda and subtracted from the simulated, unregulated flow at Muscoda. The difference was multiplied by 0.478 and routed upstream from Muscoda to Wisconsin Dells to simulate ungaged inflow between Wisconsin Rapids and Wisconsin Dells. Simulated, unregulated flow was routed from Wisconsin Rapids to Wisconsin Dells and added to the ungaged inflow simulation. The ungaged inflow ratio was determined from the annual flow volume at the three stations. This method was calibrated and verified with data from 1935-76.

At Prairie du Sac

From January 16, 1946, to December 4, 1953, unregulated flow was simulated from records of streamflow, reservoir stages, and stages of Lakes Du Bay, Petenwell, and Castle Rock.

For the rest of the period, water years 1915-76, several simulation methods were tried. An attempt was made to use tributary inflow measured on the Baraboo River at Baraboo to simulate ungaged inflow, but this produced a poorer simulation than the other methods tried. The method used at several stations upstream was tried, but it was not possible to get a good calibration for peak discharge and volume with the same ratio.

The method used was to route the simulated, unregulated flow from Wisconsin Dells to Muscoda. This was subtracted from the simulated, unregulated flow at Muscoda. The ungaged inflow then was simulated by 0.8 times the difference at Muscoda minus 544 ft^3/s. This was routed upstream from Muscoda to Prairie du Sac and added to the simulated, unregulated flow routed from Wisconsin Dells to Prairie du Sac to simulate the unregulated flow at Prairie du Sac. This method was calibrated and verified with record from 1946-53.

At Muscoda

For the entire period, water years 1915-76, unregulated flow was simulated from streamflow and reservoir records.

APPENDIX B

LIST OF INSTANTANEOUS ANNUAL MAXIMUM DISCHARGES

Simulated, unregulated annual maximum instantaneous discharges for Wisconsin River

Water year	Rainbow Lake 05391000	Whirlpool Rapids 05392000	Merrill 05395000	Rothschild 05398000	Knowlton 05400000	Wisconsin Rapids 05400800	Necedah 05401500	Wisconsin Dells 05404000	Prairie du Sac 05406000	Muscoda 05407000
1915	1,640	2,950	9,000	16,500	19,000	21,200	20,600	22,300	24,600	25,000
1916	4,360	6,920	26,500	40,900	46,800	52,300	51,200	54,700	58,000	57,000
1917	1,990	3,430	12,900	18,400	21,500	25,000	25,300	28,800	32,800	33,600
1918	2,420	3,950	16,500	27,800	31,900	36,100	36,400	40,200	45,600	43,200
1919	2,210	3,600	15,200	24,600	24,300	26,000	25,700	33,300	44,600	43,800
1920	3,620	5,650	23,400	31,600	39,800	53,900	54,500	59,700	65,500	65,700
1921	2,880	4,670	16,800	31,500	39,900	39,700	37,700	42,700	44,700	40,400
1922	3,600	5,770	22,000	43,800	50,600	61,500	62,800	67,400	76,300	75,400
1923	3,840	5,930	24,500	38,400	40,700	47,600	49,000	51,200	56,400	56,400
1924	2,590	4,220	16,700	33,300	37,500	39,900	38,800	42,500	44,600	44,200
1925	1,860	3,220	8,450	17,000	15,000	19,000	18,900	22,600	27,600	26,500
1926	3,370	5,870	17,200	38,200	48,700	52,700	43,300	54,500	50,900	45,300
1927	2,560	4,100	20,700	28,700	33,200	40,300	42,400	42,600	46,200	44,800
1928	2,960	4,810	20,300	36,400	45,200	49,300	46,700	55,500	59,400	56,600
1929	4,050	6,400	26,000	36,600	44,300	49,900	48,500	54,200	57,300	56,700
1930	1,880	3,190	13,800	34,200	39,400	40,200	33,700	44,700	44,900	41,800
1931	1,940	3,370	11,000	13,600	11,800	13,300	12,200	13,600	13,500	13,500
1932	2,410	3,920	15,100	26,300	35,700	39,200	37,400	43,300	45,100	44,100
1933	3,080	4,930	11,000	18,700	21,500	21,900	20,800	24,800	31,500	32,200
1934	2,700	4,300	14,200	30,700	34,800	39,500	36,400	41,200	40,300	38,200
1935	3,030	4,750	20,200	40,400	50,600	64,900	66,200	68,000	64,600	64,600
1936	3,080	4,900	16,800	33,400	40,200	47,400	43,100	48,300	49,500	49,600
1937	2,760	4,700	15,700	21,800	23,300	26,800	26,500	28,800	32,900	31,900
1938	3,730	5,860	19,100	44,700	49,500	63,000	63,900	72,700	80,700	80,800
1939	3,150	5,120	21,300	38,800	43,200	49,400	50,000	54,300	57,800	55,900
1940	2,660	4,090	18,600	40,500	40,300	48,300	47,100	51,000	53,100	51,000
1941	3,410	5,220	41,700	73,700	57,400	58,000	53,000	47,400	51,800	47,500
1942	4,460	5,220	30,300	53,400	46,500	56,100	50,600	54,300	56,600	54,200
1943	3,710	5,910	16,300	35,600	45,400	55,400	54,500	63,700	66,400	62,800
1944	2,450	4,030	13,400	19,800	19,800	21,600	22,800	23,200	28,000	30,000
1945	3,470	4,540	14,400	33,900	41,800	46,600	48,200	54,900	60,000	57,600

Simulated, unregulated annual maximum instantaneous discharges for Wisconsin River--Continued

Water year	Rainbow Lake 05391000	Whirlpool Rapids 05392000	Merrill 05395000	Rothschild 05398000	Knowlton 05400000	Wisconsin Rapids 05400800	Necedah 05401500	Wisconsin Dells 05404000	Prairie du Sac 05406000	Muscoda 05407000
1946	3,490	5,610	22,700	32,500	36,900	40,700	41,900	54,400	64,200	59,200
1947	2,490	3,910	13,900	26,200	27,300	30,900	32,200	31,700	39,400	37,300
1948	1,890	3,060	9,590	19,900	21,700	24,600	26,600	31,000	34,900	35,600
1949	2,350	3,820	13,400	18,100	16,900	17,900	13,400	15,500	17,300	16,900
1950	3,420	6,170	23,300	34,700	34,500	35,000	34,200	35,300	34,400	36,100
1951	4,670	7,460	23,800	38,700	50,300	56,200	60,800	74,800	84,800	79,100
1952	3,610	5,530	17,600	31,900	35,000	39,200	42,900	52,900	59,700	54,500
1953	3,490	4,570	15,600	35,800	41,500	42,500	44,300	49,200	52,500	49,300
1954	4,100	5,470	19,700	32,900	34,800	35,400	36,300	40,100	44,000	40,900
1955	3,250	4,290	13,900	25,300	24,900	26,500	27,300	30,600	32,800	33,100
1956	2,220	3,390	13,100	29,700	36,800	39,600	40,000	45,200	50,900	50,000
1957	1,700	3,210	7,100	11,900	11,300	12,300	12,800	14,700	16,300	16,500
1958	3,190	3,950	10,600	18,100	21,900	24,800	22,100	21,200	21,600	21,500
1959	3,280	5,450	21,000	44,100	49,200	54,800	51,300	49,600	40,600	38,300
1960	3,990	5,730	20,100	44,600	50,300	60,400	61,000	68,700	74,400	71,900
1961	2,240	3,480	14,300	38,200	43,600	53,900	51,800	48,000	55,900	53,100
1962	2,330	3,790	12,600	23,400	27,100	33,300	34,600	39,800	47,100	44,900
1963	2,190	3,120	10,100	17,000	26,900	39,000	37,500	36,000	41,000	39,400
1964	2,550	3,370	7,540	14,000	14,300	20,400	19,900	19,600	21,300	21,900
1965	3,170	4,930	16,600	50,900	58,000	66,400	63,200	71,800	76,300	69,800
1966	2,920	4,320	17,000	28,600	34,400	39,100	36,500	37,700	41,100	40,500
1967	4,070	6,190	30,300	53,000	69,500	77,500	78,200	76,600	81,600	76,500
1968	2,770	4,050	17,200	27,700	33,500	37,900	38,300	38,300	41,800	40,900
1969	3,190	4,860	21,300	35,000	38,300	44,800	44,700	47,700	51,400	49,400
1970	3,240	4,270	8,070	17,600	21,800	26,500	24,800	26,300	27,400	27,200
1971	3,300	5,170	24,100	44,900	50,200	56,000	55,900	55,400	59,500	57,200
1972	3,700	5,590	23,000	48,300	52,600	56,400	55,700	56,900	64,400	62,800
1973	3,410	5,160	25,100	48,300	53,700	61,000	64,600	75,700	81,900	78,100
1974	2,290	3,450	13,600	20,700	23,400	30,000	30,700	33,500	36,700	36,100
1975	3,630	5,600	20,400	35,200	35,000	40,300	38,700	40,900	50,100	49,100
1976	3,470	5,090	23,400	48,400	54,400	58,900	55,000	54,500	60,000	58,300

Simulated, regulated annual maximum instantaneous discharges for Wisconsin River

Water year	Rainbow Lake 05391000	Whirlpool Rapids 05392000	Merrill 05395000	Rothschild 05398000	Wisconsin Rapids 05400800	Necedah 05401500	Wisconsin Dells 05404000	Prairie du Sac 05406000	Muscoda 05407000
1915	1,830	2,960	7,300	14,900	18,700	18,500	19,000	20,400	21,200
1916	2,600	4,730	21,900	36,000	41,600	43,000	47,800	51,600	50,700
1917	1,920	2,710	9,740	15,700	17,900	17,700	20,800	24,200	24,300
1918	2,190	3,700	15,400	26,600	32,600	31,300	36,000	40,400	39,300
1919	1,570	2,810	11,900	21,400	24,800	25,000	27,100	38,000	37,700
1920	1,740	3,200	17,500	25,400	41,900	41,300	43,700	50,300	48,300
1921	1,970	3,550	15,100	30,000	32,200	29,100	31,200	33,100	32,100
1922	1,630	2,830	17,700	40,200	52,600	55,300	59,000	65,200	65,300
1923	1,810	3,260	20,600	34,600	37,700	35,000	35,700	44,700	44,500
1924	1,620	2,800	13,100	29,400	29,700	28,600	30,400	33,600	33,600
1925	1,940	2,050	5,850	20,100	13,800	14,500	18,600	24,200	23,200
1926	1,460	2,670	11,300	33,500	40,400	39,000	48,100	45,100	39,700
1927	2,270	3,190	15,700	23,600	35,200	34,800	33,900	36,000	33,700
1928	2,880	4,620	19,400	35,900	43,900	45,700	51,800	56,400	55,500
1929	2,650	5,030	20,700	31,800	40,600	42,500	47,300	50,300	49,600
1930	1,930	2,820	10,900	31,400	35,200	31,700	40,200	41,600	38,600
1931	1,310	1,980	8,180	11,000	10,000	7,960	7,590	7,920	8,430
1932	2,300	2,760	10,500	21,700	29,800	24,600	24,700	27,300	28,900
1933	2,300	3,240	8,660	16,000	17,600	16,600	17,600	21,900	23,100
1934	1,370	2,120	9,440	25,500	26,000	19,500	23,200	21,200	21,200
1935	2,140	3,580	16,600	36,900	51,600	43,200	43,900	43,400	44,100
1936	2,380	4,160	13,600	28,600	31,300	27,300	25,600	29,100	30,100
1937	1,520	2,330	12,400	18,200	22,500	21,800	25,400	29,100	28,400
1938	2,770	3,900	17,300	44,500	56,700	59,800	71,100	81,800	82,700
1939	2,500	4,190	14,600	32,400	34,400	32,300	33,100	35,400	34,700
1940	2,080	3,820	17,600	39,400	45,700	48,100	53,200	55,800	52,600
1941	1,450	3,070	33,700	65,800	51,600	49,900	42,700	43,600	39,200
1942	3,240	4,570	25,000	48,600	54,700	52,800	51,900	55,100	51,000
1943	3,310	5,580	14,600	32,400	49,700	49,100	57,600	58,700	56,100
1944	1,880	2,850	10,800	17,400	20,800	24,000	23,100	27,200	27,900
1945	1,900	3,410	8,640	28,500	34,100	30,300	31,800	37,500	37,000

Simulated, regulated annual maximum instantaneous discharges for Wisconsin River--Continued

Water year	Rainbow Lake 05391000	Whirlpool Rapids 05392000	Merrill 05395000	Rothschild 05398000	Wisconsin Rapids 05400800	Necedah 05401500	Wisconsin Dells 05404000	Prairie du Sac 05406000	Muscoda 05407000
1946	1,760	4,290	16,700	26,500	28,300	30,600	39,700	45,600	40,500
1947	1,380	2,480	8,620	21,500	22,800	20,800	22,200	27,000	25,700
1948	1,270	1,810	5,430	16,000	17,900	18,300	22,100	26,500	24,000
1949	1,380	1,870	7,510	12,100	12,000	11,700	11,800	13,000	12,300
1950	2,520	4,980	18,100	29,000	24,300	33,300	33,500	31,200	32,100
1951	2,440	4,040	18,100	34,600	42,800	49,500	51,900	61,500	53,700
1952	3,110	4,370	15,900	29,000	22,400	24,200	34,000	40,300	37,200
1953	2,990	4,330	10,900	31,200	24,200	23,300	22,600	26,100	25,500
1954	1,960	3,530	16,800	29,500	27,600	23,400	27,000	29,600	28,300
1955	2,730	3,900	11,400	20,800	20,800	23,900	30,100	29,300	26,800
1956	1,610	2,470	8,650	25,200	24,700	24,200	30,100	33,600	33,800
1957	1,430	2,150	5,620	8,730	7,870	7,010	9,740	10,700	11,300
1958	1,360	2,110	6,900	15,200	18,900	12,700	12,000	12,600	12,700
1959	2,990	5,150	19,400	42,400	51,800	49,400	49,900	36,900	29,400
1960	2,620	5,050	18,200	42,700	57,900	64,600	70,500	76,500	71,600
1961	2,030	3,180	9,120	33,900	40,000	35,900	28,000	35,300	34,900
1962	1,810	2,760	11,600	22,200	27,100	26,600	27,500	33,400	32,200
1963	1,550	2,400	7,690	14,900	29,100	22,800	24,600	26,100	26,100
1964	1,260	1,950	5,100	11,800	15,400	17,100	13,600	15,700	16,700
1965	2,140	3,920	12,000	47,400	57,700	51,600	52,600	57,300	52,400
1966	1,690	2,440	10,100	22,300	35,700	36,900	33,100	32,800	31,800
1967	2,630	3,790	22,800	47,600	59,300	52,400	49,100	53,100	50,300
1968	2,400	3,780	15,600	26,100	36,800	39,800	40,400	43,400	42,100
1969	1,990	2,940	17,200	30,700	43,600	45,600	49,600	53,300	48,300
1970	2,340	3,720	6,510	15,700	25,800	24,600	25,000	26,600	26,200
1971	1,590	2,630	18,900	38,800	46,600	40,300	36,900	40,100	38,800
1972	1,880	3,060	18,100	43,300	46,800	45,700	48,900	52,900	50,800
1973	2,740	4,340	21,600	42,300	54,700	58,300	70,200	76,600	73,600
1974	1,810	3,040	9,910	16,800	24,900	22,600	21,400	24,200	25,200
1975	1,520	2,410	15,600	30,700	33,400	31,000	29,200	37,400	38,200
1976	1,500	2,490	18,000	43,100	51,400	45,800	44,200	46,700	44,900