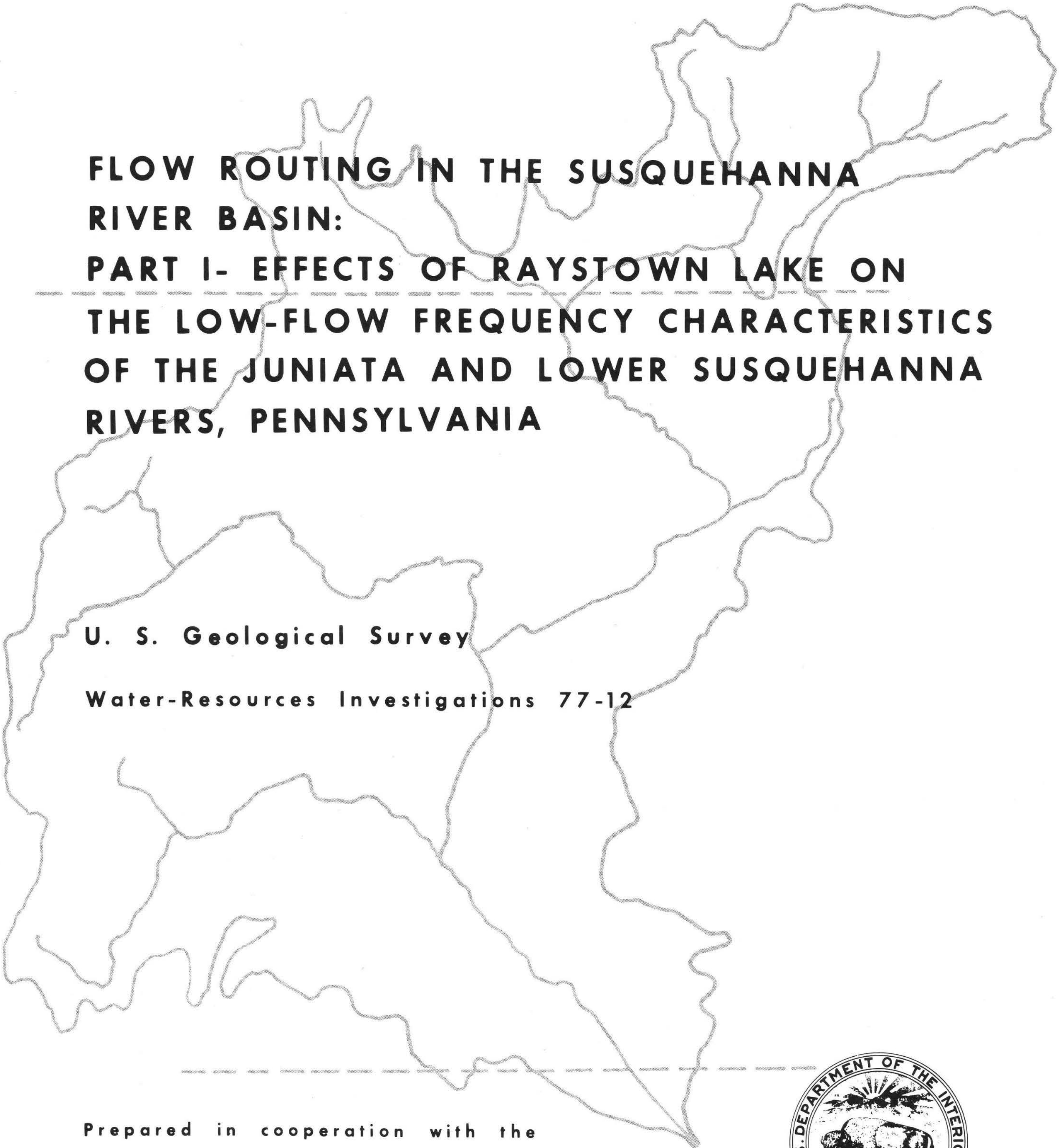

FLOW ROUTING IN THE SUSQUEHANNA RIVER BASIN: PART I- EFFECTS OF RAYSTOWN LAKE ON THE LOW-FLOW FREQUENCY CHARACTERISTICS OF THE JUNIATA AND LOWER SUSQUEHANNA RIVERS, PENNSYLVANIA

U. S. Geological Survey

Water-Resources Investigations 77-12

Prepared in cooperation with the

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April 1977

UNITED STATES DEPARTMENT OF THE INTERIOR

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GEOLOGICAL SURVEY

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FACTORS FOR CONVERTING ENGLISH UNITS TO INTERNATIONAL SYSTEM (SI) UNITS

The following factors may be used to convert the English units published herein to the International System of Units (SI).

Multiply English units	*By*	*To obtain SI units*
	Length	
inches (in)	25.4	millimeters (mm)
feet (ft)	.3048	meters (m)
	Area	
square miles (mi^2)	2.590	square kilometers (km^2)
	Flow	
cubic feet per second (ft^3/s)	.02832	cubic meters per second (m^3/s)

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ABSTRACT

A flow-routing model was used to simulate 17 water years of daily streamflows at five sites. The sites were Mapleton Depot and Newport, Pennsylvania, on the Juniata River, and Harrisburg and Marietta, Pennsylvania, and Conowingo, Maryland, on the Susquehanna River. The purpose for the simulations was to determine the effects of a new reservoir, Raystown Lake, on the low-flow frequency characteristics of these sites. Raystown Lake is on Raystown Branch Juniata River, a tributary to the Juniata River.

Output from a reservoir-regulation model of Raystown Lake was used as input to the flow-routing models. In addition, a reservoir-routing model was developed for the hydroelectric power dams on the lower Susquehanna River.

Low-flow frequency curves, based on the post-Raystown Lake simulated flows, were compared to similar curves based on pre-Raystown observed data. The comparison indicated that operation of the lake will cause estimated increases in the 7-day 10-year low flows ranging from 420 ft^3/s at Mapleton Depot to 290 ft^3/s at Marietta and Conowingo over the 7-day 10-year low flows for pre-Raystown conditions.

Although inherent modeling errors exist in all of these simulated data, the overall quality of the simulated flows and the low-flow frequency curves is considered good.

INTRODUCTION

Solutions of problems in water-resources management often require information about a future or newly implemented change in a water-resources system. When little or no data are available for evaluating or predicting the effects of a change in such a system, hydrologic models can often provide the means to solve such problems. Models must, however, be capable of reproducing, within a given degree of accuracy, what actually has or will occur in the field situation. This task is accomplished by combining computation routines based on well known and proven hydrologic concepts. The routines are generally programmed for digital computation.

In 1975, the U.S. Geological Survey and the Susquehanna River Basin Commission (SRBC) initiated a series of cooperative projects designed to calibrate flow-routing models for all major streams within the Susquehanna River basin. The flow-routing models will provide the SRBC with the capability to translate or transfer the effects of proposed water-resources developments anywhere in the basin to points downstream. This study, the first in the series, focuses on the Juniata River from Huntingdon, Pa., to its mouth and on the Susquehanna River from Sunbury, Pa., to Conowingo, Md. The purpose of the study is to determine the effects of a new reservoir, Raystown Lake, on downstream low-flow frequency characteristics. The reservoir, built by the U.S. Army Corps of Engineers, began operation in February 1975.

Although the reservoir was built primarily for flood control, it is also being used to control downstream water temperatures for natural warm-water fisheries. Such releases of water are expected to have a significant effect on downstream reaches of the Juniata and Susquehanna Rivers by increasing normal low flows.

One means of determining the effects on downstream low flows is by comparing low-flow frequency curves at downstream points both with and without the new reservoir. In this case, the pre-reservoir low-flow characteristics are described by frequency curves of the observed data. To determine the post-reservoir condition, a combination of channel and reservoir routing models are used to generate a long sequence of homogeneous, synthetic streamflows. Low-flow frequency analyses of the simulated streamflows are used to provide a comparison to observed data.

The analyses presented in this report summarize the channel and reservoir models developed, calibrated, and used to generate 17 water years of daily streamflow data that were subsequently analyzed and compared with observed streamflow data.

DESCRIPTION OF STUDY REACHES

The lower Susquehanna River is herein used to refer to the mainstem Susquehanna River from Sunbury, Pa., to Conowingo, Md., about 10 miles upstream from the mouth. In this reach there are four run-of-the-river powerplants each with a reservoir. They are located downstream from Harrisburg at York Haven, Safe Harbor, and Holtwood, Pa., and at Conowingo, Md. Also located in the reach below Harrisburg is one pumped-storage hydroelectric facility, and two nuclear powerplants. For ease of computation this reach was divided into three reaches--from Sunbury to Harrisburg, from Harrisburg to Marietta, and from Marietta to Conowingo.

The Juniata River is one of the largest tributaries of the Susquehanna River. The current study was concerned with the reach of the Juniata River from Huntingdon, Pa., to its confluence with the Susquehanna River about 14 miles north of Harrisburg. The Raystown Branch Juniata River is a major tributary to the Juniata River and flows into the Juniata about three miles downstream from Huntingdon, near Mapleton Depot, Pa. A new reservoir, known as Raystown Lake, is located on the Raystown Branch 5.5 miles upstream from its confluence with the Juniata River. Surface area of Raystown Lake at normal pool elevation is about 8,300 acres. Normal operation of the reservoir began in February 1975. During periods of high flow, the reservoir is used for flood control. During low-flow periods, reservoir releases are used to control downstream water temperature.

Data Used for Digital Modeling

Streamflow records for 29 regular gaging stations were used either directly or indirectly in the modeling of the study reaches. The stations used, their period of record, and drainage areas are listed in tables 1 (Juniata River) and 2 (Susquehanna River). Locations of the stations are shown on figure 1. Water years 1942 to 1958, inclusive, represent the period of concurrent record at the stations used directly in the modeling effort. Twelve years of data were available for simulating pre-Raystown flows at Mapleton Depot.

The operation schedule for the Raystown Dam, used to develop a Raystown regulation model, was obtained from the U.S. Army Corps of Engineers, and is summarized in table 3. The operation schedule details how water is to be released from the dam under various hydrologic conditions.

Table 1.--*Data available for use in routing study for the Juniata River reach*

Station number	Station name	Water years of record	Drainage area (mi^2)
01559000	Juniata River at Huntingdon, Pa.	1942-73	816
01559500	Standing Stone Creek near Huntingdon, Pa.	1930-58	128
01562000	Raystown Branch Juniata River at Saxton, Pa.	1912-73	756
01563000	Raystown Branch Juniata River near Huntingdon, Pa.	1947-71	957
01563200	Raystown Branch Juniata River below Raystown Dam near Huntingdon, Pa. (This station replaces 01563000.)	(*)	960
01563500	Juniata River at Mapleton Depot, Pa.	1938-73	2,030
01564500	Aughwick Creek near Three Springs, Pa.	1939-73	205
01565000	Kishacoquillas Creek at Reedsville, Pa.	1940-70	164
01566000	Tuscarora Creek near Port Royal, Pa.	1912-58	214
01566500	Cocolamus Creek near Millerstown, Pa.	1931-58	57.2
01567000	Juniata River at Newport, Pa.	1900-73	3,354

*Only part of 1975 water year can be used.

Table 2.--*Data available for use in routing study for the Susquehanna River reaches*

Station number	Station name	Water years of record	Drainage area (mi^2)
01554000	Susquehanna River at Sunbury, Pa.	1938-73	18,300
01554500	Shamokin Creek near Shamokin, Pa.	1941-73	54.2
01555000	Penns Creek at Penns Creek, Pa.	1930-73	301
01555500	East Mahantango Creek near Dalmatia, Pa.	1930-73	162
01567000	Juniata River at Newport, Pa.	1900-73	3,354
01568000	Shermans Creek at Shermans Dale, Pa.	1930-73	200
01568500	Clark Creek near Carsonville, Pa.	1938-73	22.5
01570000	Conodoguinet Creek near Hogestown, Pa.	1912-17 1930-58 1968-73	470
01570500	Susquehanna River at Harrisburg, Pa.	1891-1973	24,100
01571500	Yellow Breeches Creek near Camp Hill, Pa.	1910-18 1955-73	216
01573000	Swatara Creek at Harper Tavern, Pa.	1920-73	337
01574000	West Conewago Creek near Manchester, Pa.	1929-73	510
01575500	Codorus Creek near York, Pa.	1941-73	222
01576000	Susquehanna River at Marietta, Pa.	1932-73	25,990
01576500	Conestoga River at Lancaster, Pa.	1929-31 1934-73	324
01578310	Susquehanna River at Conowingo, Md.	1968-73	27,100

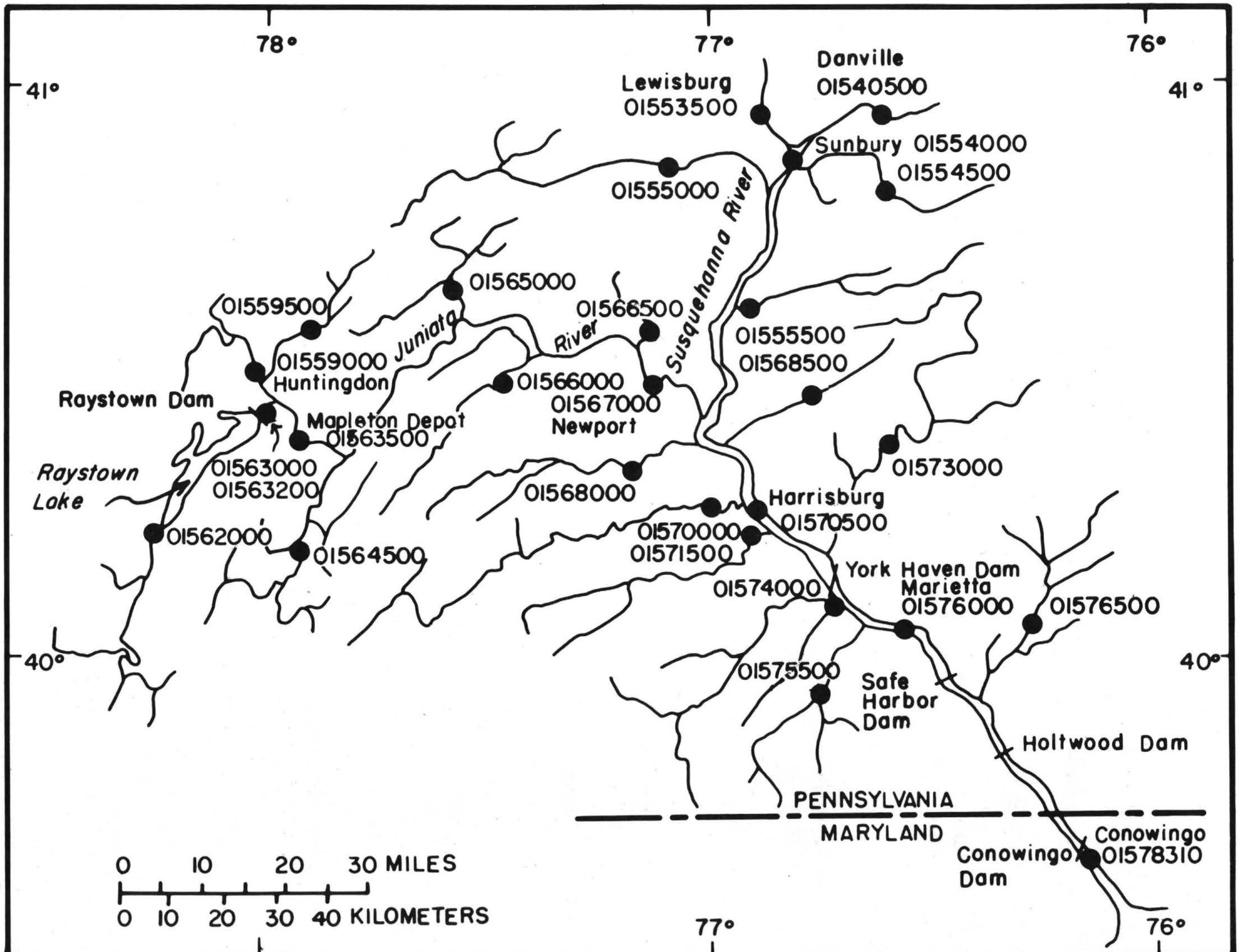


Figure 1.--Map of study area.

Table 3.--*Regulation procedures for Raystown Lake*

[Modified from U.S. Army Corps of Engineers, 1974, revised 1976. QIN, inflow to Raystown Lake; QOUT, outflow from Raystown Lake.]

For flows into Raystown Lake less than 8,000 ft^3/s

If	*Then*
QIN is less than 480 ft^3/s------------	QOUT = 480 ft^3/s.
QIN is between 480 ft^3/s and 1,420 ft^3/s.	QOUT = QIN.
QIN is between 1,420 ft^3/s and 8,000 ft^3/s.	QOUT = discharge sufficient to prevent a rise in the lake level of more than one foot. QOUT cannot be increased by more than half the existing release per hour or 1,500 ft^3/s per hour, whichever is smaller.

For flows into Raystown Lake greater than 8,000 ft^3/s

If	*Then*
Flow at Mapleton Depot is less than 30,000 ft^3/s.	QOUT is increased at a rate not greater than half the existing rate per hour or 1,500 ft^3/s, up to 20,000 ft^3/s.
Flow at Mapleton Depot is between 30,000 ft^3/s and 40,000 ft^3/s.	QOUT will be gradually reduced to prevent flow at Mapleton Depot from exceeding 40,000 ft^3/s.
Flow will exceed 40,000 ft^3/s even if all gates are closed.	QOUT = 480 ft^3/s.

Table 3.--*Regulation procedures for Raystown Lake*.--continued.

For flows into Raystown Lake greater than 8,000 ft^3/s.--continued	
If	*Then*
Flow at Mapleton Depot continues to rise.	QOUT = 480 ft^3/s unless reservoir regulation curves indicate that a release is required. The necessary releases will be made in incremental steps limited to 20,000 ft^3/s every 2 hours or in accordance with regulation curves, whichever is less.
Flow at Mapleton Depot is falling and less than 38,000 ft^3/s.	QOUT is increased gradually limiting increases to half the existing rate or 1,000 ft^3/s, whichever is less, so that a secondary rise at Mapleton Depot does not occur, until a release of 20,000 ft^3/s is reached. If regulation curves indicate a greater release, this release will be made, limiting incremental steps to 20,000 ft^3/s every 2 hours or according to regulation curves--whichever is less.
Lake level is falling---------------	Maximum release attained during the storage operation will be maintained until the lake elevation is less than 800. Thereafter, QOUT = 20,000 ft^3/s until normal pool (elevation 786) is reached.

In the Susquehanna River part of the study, powerplant records were used to verify the calibrated-channel routing models. Powerplant operation schedules or procedures were used in the development of a lower Susquehanna River reservoir-routing model. Three typical release schedules, available for use, are shown in figures 2-4 (Moyer and Raney, 1969).

Evaporation data, taken from Rahn (1973), were used in the two reservoir routing model studies.

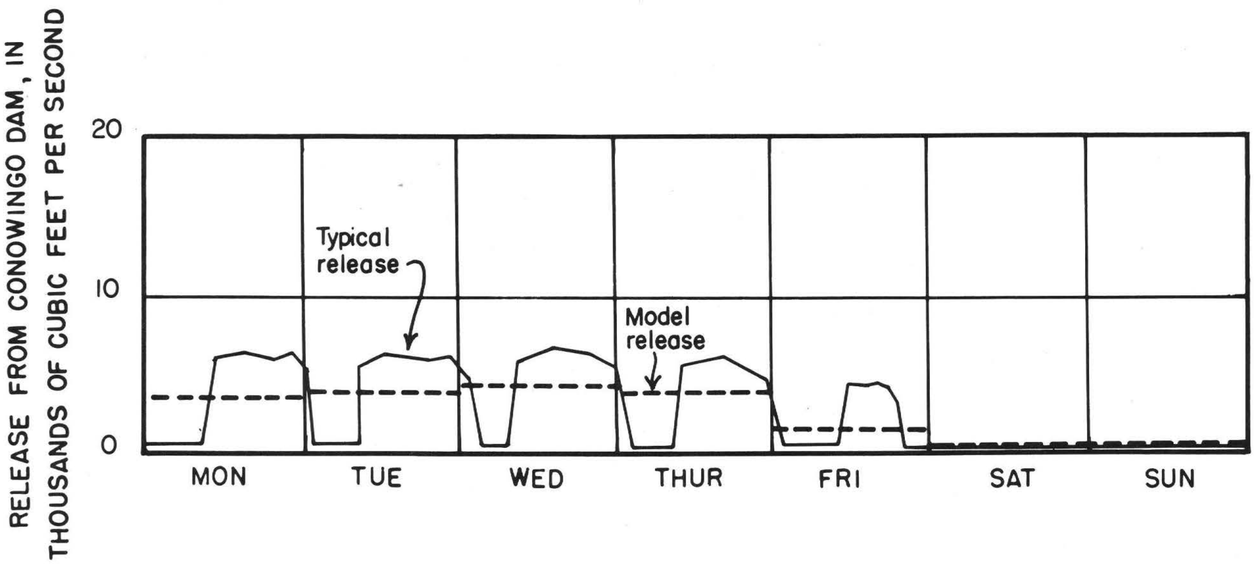


Figure 2.--Typical release schedule at Conowingo Dam when natural river flow is 2,500 ft^3/s. (From Moyer and Raney, 1969.)

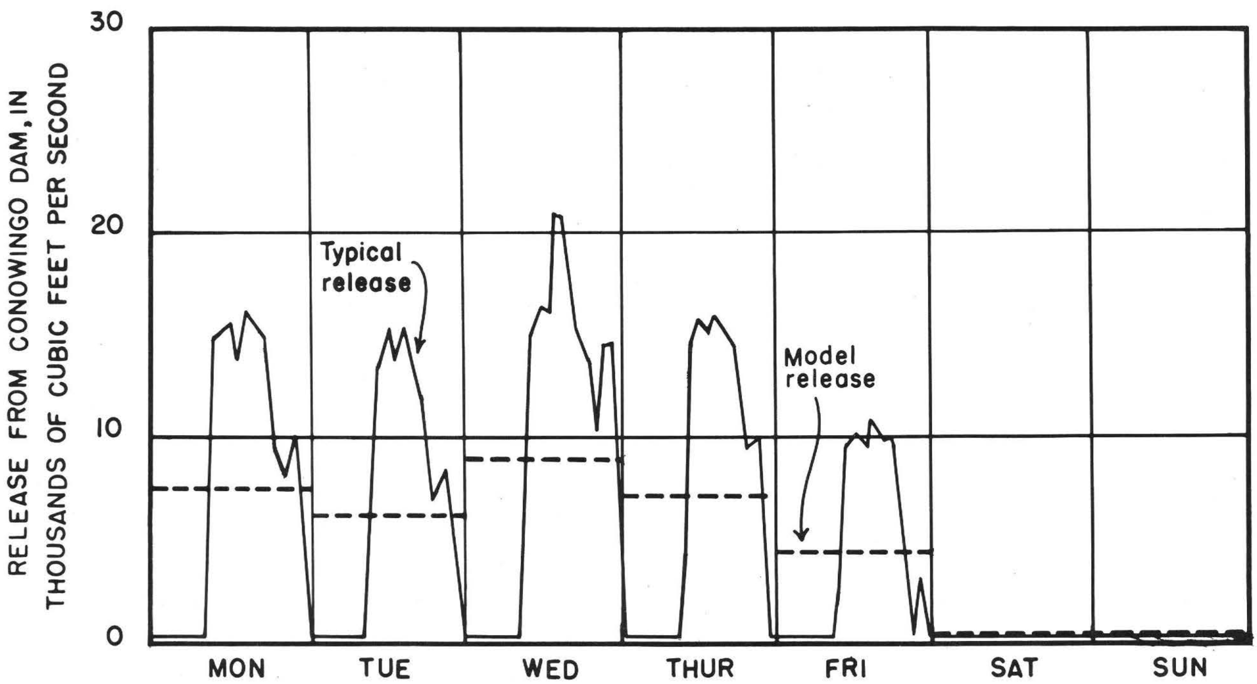


Figure 3.--Typical release schedule at Conowingo Dam when natural river flow is 5,000 ft^3/s. (From Moyer and Raney, 1969.)

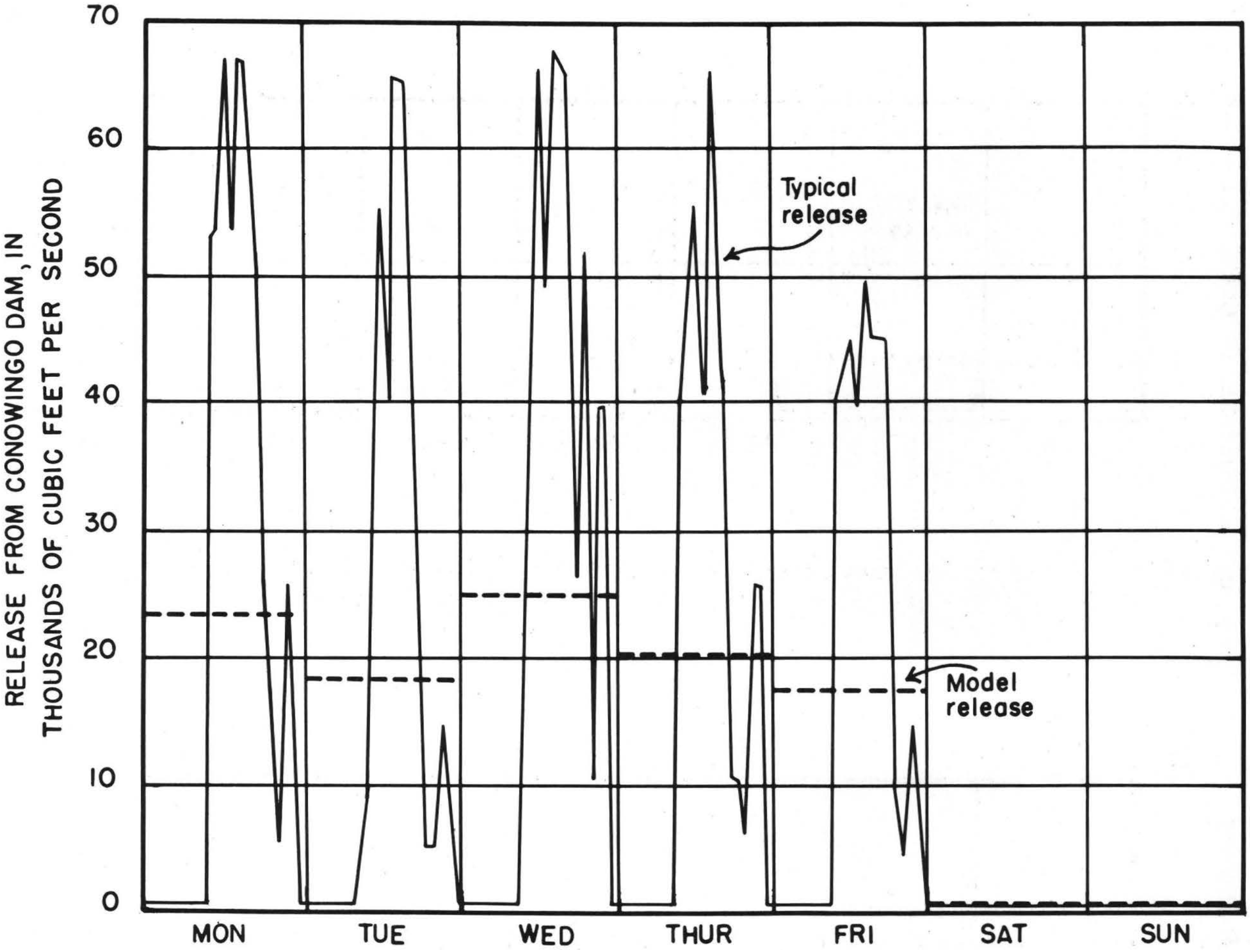


Figure 4.--Typical release schedule for Conowingo Dam when natural river flow is 15,000 ft^3/s. (From Moyer and Raney, 1969.)

DESCRIPTION OF MODELS

To determine the effects of Raystown Lake on downstream flows, two general types of models were needed to generate long sequences of daily streamflows that would simulate the altered system. The first was a reservoir-routing model and the second was a channel-routing model. The reservoir-routing model couples the principle of mass conservation with the operation of the outflow structure to determine the outflows from the reservoir. A channel-routing model was then used to route these outflows, which are presumably different from historical flows, to downstream points.

Because of the importance of the data simulated by the models, it is necessary that (1) modeling adequacy be defined as well as possible, and (2) the maximum practical degree of model adequacy be obtained. To achieve these goals, as much observed data as possible must be used to verify and evaluate these models (Shearman and Swisshelm, 1973). A period of 17 water years of concurrent, observed data were available to describe the pre-reservoir condition. These data in turn permitted the simulation of 17 water years of homogeneous pre-reservoir daily flows at Mapleton Depot, Newport, Harrisburg, Marietta, and Conowingo. Less than one year of observed post-reservoir data were available downstream from Raystown Lake; however, the reservoir outflow records that were available were compared to simulated outflows to verify the Raystown regulation model.

Simulated and observed pre-reservoir streamflows were compared at four of the five sites analyzed. (Flows at Conowingo, Md. were handled differently and will be discussed later.) In so doing, the adequacy of the models were evaluated.

The following discussion is a summary of the procedures and concepts used to determine the effects of Raystown Lake on the low-flow frequency characteristics of the Juniata and lower Susquehanna Rivers.

Channel-Routing Models

Four separate channel-routing models were developed during this study. Each was a unit-reponse flow-routing model using the diffusion analogy (Keefer, 1974) and multiple linearization (Keefer and McQuivey, 1974). A one-day routing interval was used throughout. The model has two parameters--wave celerity and wave dispersion. In very simple terms the celerity governs how fast the water wave travels downstream, and wave dispersion accounts for the attenuation or dampening of the wave.

The diffusion analogy is the mechanism used to derive the routing response functions. The multiple-linearization concept is a means to permit both variable travel time and variable attenuation of flows while using linear flow-routing models. Multiple linearization is very attractive for this study because of the wide range of discharges encountered. As shown in figure 5, the inflow hydrograph is separated into a number of segments or selected discharge ranges. Flows are routed downstream, one segment at a time, and summed to obtain the outflow hydrograph.

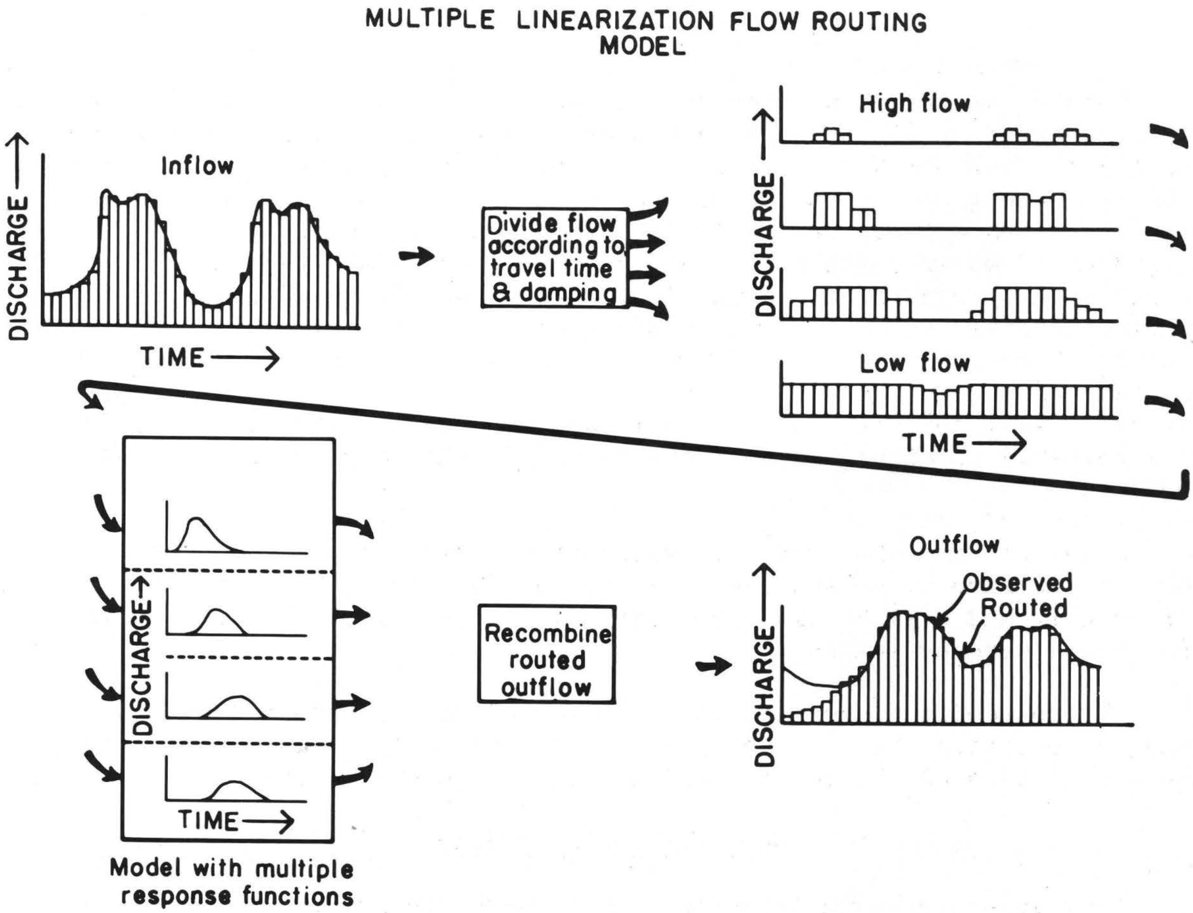


Figure 5.--Schematic diagram of the multiple linearization flow-routing model. (From Keefer and McQuivey, 1974.)

Channel-routing models were developed for the Juniata River from Mapleton Depot to Newport and for the three reaches of the lower Susquehanna River. The reaches numbered 1 through 4, respectively, each required a separate model that properly added both gaged and ungaged inflow into the reach. Ungaged flow was estimated by multiplying flows for a suitable gaged site by a drainage area ratio. The initial drainage area ratios used were determined by dividing the drainage area of a group of tributaries, gaged and ungaged, by the drainage area of a representitive gaged area. Trial and error adjustments to initial estimates were made on the basis of previous basinwide low-flow studies (Armbruster, 1976) to balance flow volumes within each reach. Determination of parameter values was required for each model.

The downstream reach of the Susquehanna River, from Marietta to Conowingo was handled differently than the other three study reaches, because in this reach there are three run-of-the-river powerplant dams, and one pumped-storage facility. The three dams are operated in a complementary fashion, that is, releases are made from one to supply the needs of the others. Because of the complexity of this system, all three of the dams were treated as one and only the farthest downstream dam was actually modeled. The release schedules of the three dams are variable and depend on the availability of water and the demand for electrical power. The dependence of releases on the power demand is a factor which cannot be handled within the scope of this study.

Six years of daily streamflows were available for the gaging station at Conowingo, Maryland, immediately downstream from Conowingo Dam. However, because releases from the reservoir do not strictly follow a set schedule, a great deal of variation between observed regulated flows and simulated regulated flows was experienced, although flow-volume balance was good. Due to time and financial constraints the observed data were not reproduced precisely at the Conowingo gage. Instead, water flowing into Conowingo Lake was released in accordance with typical operation schedules, for both pre- and post-Raystown Lake conditions. More discussion of this item will be presented in subsequent sections.

Ground-water discharges were not explicitly treated in this study. Implicitly, however, they were included because each model was calibrated using total streamflows. No noticeable errors were detected at high or low flows that could be attributed to this approach.

Reservoir-Routing Models

Two reservoir-routing models were developed. The first was for Raystown Lake, and the second was for the Conowingo Reservoir. The purpose of these models was to simulate the operation of the reservoirs. This task was accomplished by routing flows to the reservoir, and releasing water from the reservoir according to a specified set of instructions, while accounting for changes in reservoir storage.

For the Raystown Lake regulation model, the U.S. Army Corps of Engineers operation schedule (1974, revised in February, 1976) was coded for digital computation. Table 3 is a summary of the regulation procedures. Because a one-day routing interval was used throughout this study, and because the Corps regulation schedule provides for dynamic or real-time releases during floods, some simplifications in release procedures were made. No significant errors occurred in the routed daily flows because of these assumptions.

Regulation of the hydroelectric power facility dams on the lower Susquehanna River is based on water availability and electrical power demand. Figures 2-4 portray typical regulation patterns for three different inflow conditions for Conowingo reservoir. These patterns were simplified so that they could be used with a daily routing interval. The digital model constructed for this reservoir used a series of daily average inflow versus daily average outflow curves, developed for each day of the week. For inflows less than 2,500 ft^3/s several assumptions and estimates based on observed records of outflow, and the typical releases at inflows of 2,500 ft^3/s were used. For inflows between 2,500 ft^3/s and 15,000 ft^3/s, those shown in figures 2-4, interpolation was used to determine outflow for a specific day of the week. For inflows between 15,000 ft^3/s and 50,000 ft^3/s interpolation between the typical releases for inflows of 15,000 ft^3/s and an inflow equals outflow condition was used. Finally, when inflows exceeded 50,000 ft^3/s outflows were equated to inflows regardless of the day of the week.

A comparison of evaporation data (Rahn, 1973) and precipitation data available for sites near both reservoirs indicated that there was little difference between surface evaporation and precipitation onto the lake surfaces. Any improvement in overall accuracy of the model by including these two variables would probably have been offset by errors in measuring daily values of each variable. Both lake evaporation and precipitation directly onto lake surfaces were, therefore, excluded from the analyses.

MODEL CALIBRATION

Because each of the four channel-routing models required calibration, the values of wave dispersion coefficient and wave celerity and the amount of flow from ungaged areas were determined. The multiple-linearization technique that was used, required tables or lists of dispersion coefficients and celerities.

The calibration process, for each channel-routing model, was accomplished using the following trial and error procedure. In all calibrations, pre-Raystown Lake data were used.

1. Several segments of concurrent streamflow records were chosen at the upstream and downstream ends of the study reaches. The selected segments varied in length from five months to a year. The segments had to show typical rises and recessions, and low and median flows. In selecting the calibration periods, emphasis was placed on low periods because this study deals primarily with low flows.

2. Initial values of the dispersion coefficients and celerities were estimated using the relations suggested in Keefer and McQuivey (1974).

3. A trial set of drainage area ratios, for use in accounting for flows from ungaged areas, was computed. On figures 6 and 7 the coefficients applied to the O's are the drainage area ratios used.

4. Outflows from a reach were simulated using the observed inflows to the reach, the model parameter estimates, and the drainage area ratios.

5. Simulated outflows from a reach were evaluated on the basis of: a visual comparison of hydrograph plots of observed and simulated outflows; the average absolute deviations of simulated from observed daily flows; and the volume difference between observed and simulated streamflow sequences for a calibration period.

6. Model parameters and (or) drainage area ratios were adjusted and steps 4 and 5 were repeated until the errors in step 5 appeared to be at a minimum.

Figures 6 and 7 are schematic diagrams of the study reaches that show the final relations used for generation of long sequences of homogeneous streamflows for each site prior to the construction of the Raystown reservoir. Final model parameters for all four reaches are provided in table 4.

Figures 8 and 9 show typically good and poor fits of the data generated by the models to the observed data. The data shown were simulated using the relations found in figures 6 and 7.

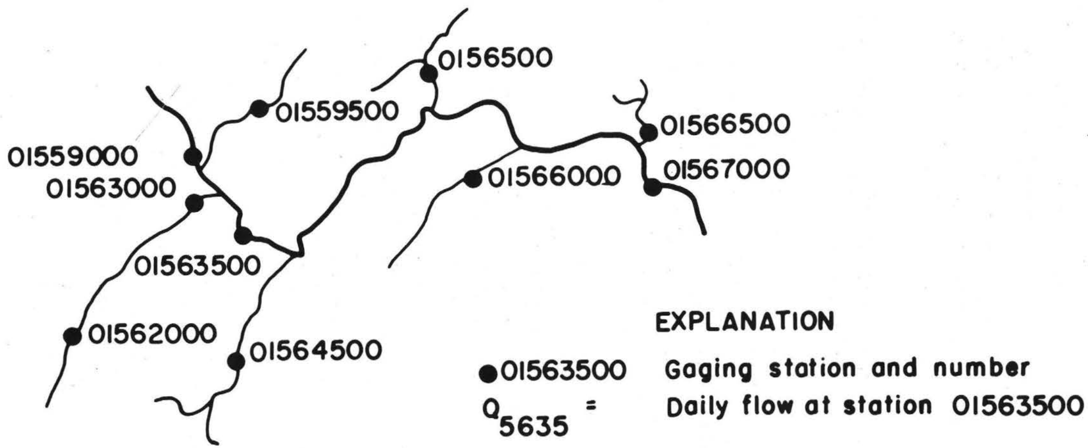
The errors discussed in step 5 above were computed using the following relations:

$$\text{Daily flow error (in percent)} = \left(\frac{\sum_{i=1}^{N} \left| \frac{Q_o - Q_s}{Q_o} \right|}{N} \right) \times 100$$

where Q_o and Q_s are the observed and simulated flows in cubic feet per second, respectively, for the ith day, N is the total number of days in a calibration period; and

$$\text{Volume error (in percent)} = \left(\frac{V_o - V_s}{V_o} \right) \times 100$$

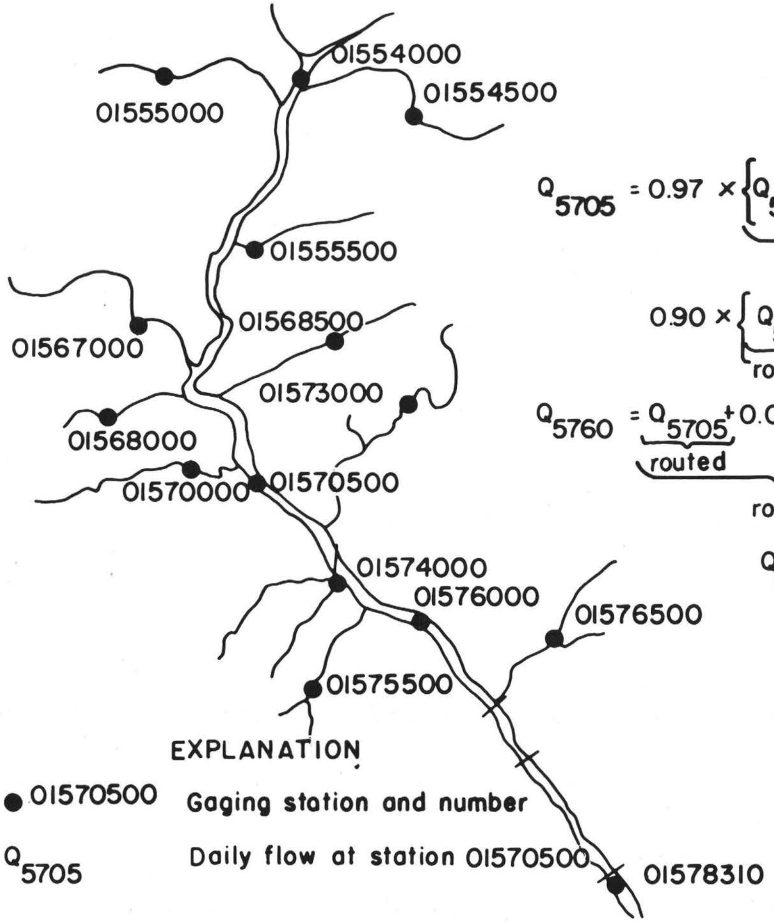
where V_o and V_s are the observed and simulated flow volumes, in cubic feet per second, respectively, for a calibration period. Several sets of typical calibration errors for each reach are given in table 5. Errors encountered in daily flows ranged from 5.6 percent in reach 3 to 10.8 percent in reach 1. Flow-volume errors ranged from -6.2 in reach 2 to +2.5 percent in reach 1.



$$Q_{5635} = Q_{5590} + 2.0 \times Q_{5595} + Q_{5630}$$

$$Q_{5670} = \underbrace{Q_{5635} + 1.9 \times Q_{5645}}_{\text{routed}} + 2.0 \times Q_{5650} + 2.2 \times Q_{5660} + 3.7 \times Q_{5665}$$

Figure 6.--Schematic diagram of Juniata River showing relations used in model calibration.



$$Q_{5705} = 0.97 \times \underbrace{\left\{Q_{5540} + 4.4 \times Q_{5545} + 3.2 \times Q_{5550} + 1.4 \times Q_{5555}\right\}}_{\text{routed}} +$$

$$0.90 \times \left\{\underbrace{Q_{5670}}_{\text{routed}} + .05 \times Q_{5670} + 1.25 \times Q_{5680} + 3.6 \times Q_{5685} + 1.10 \times Q_{5700}\right\}$$

$$Q_{5760} = \underbrace{\underbrace{Q_{5705}}_{\text{routed}} + 0.035 \times Q_{5705}}_{\text{routed}} + 1.86 \times Q_{5730} + 1.23 \times Q_{5740} + 2.51 \times Q_{5755}$$

$$Q_{5783.1} = \underbrace{\underbrace{Q_{5760}}_{\text{routed}} + 2.93 \times Q_{5765}}_{\text{routed through Conowingo Lake}}$$

Figure 7.--Schematic diagram of lower Susquehanna River showing the relations used in model calibration.

Table 4.--*Model parameters used in final channel-routing models*

[Q, flow in cubic feet per second; C, celerity in feet per second; and K, dispersion coefficient in square feet per second]

Reach 1			Reach 2			Reach 3			Reach 4		
Q	*C*	*K*	*Q*	*C*	*K*	*Q*	*C*	*K*	*Q*	*C*	*K*
500	1.70	50	3,000	1.35	3,000	3,000	1.75	4,000	3,000	1.70	5,000
2,000	2.30	1,000	5,000	1.85	6,000	5,000	1.90	7,000	5,000	1.85	8,000
4,000	2.90	4,000	20,000	2.25	20,000	20,000	2.20	22,000	20,000	2.15	24,000
8,000	4.20	14,000	30,000	2.45	29,000	30,000	2.35	30,000	30,000	2.30	35,000
15,000	6.20	34,000	250.000	8.60	226,000	250,000	8.00	230,000	250,000	7.95	240,000
25,000	8.55	54,000	-------	----	-------	-------	----	-------	-------	----	-------
40,000	11.60	84,000	-------	----	-------	-------	----	-------	-------	----	-------
54,000	14.80	112,000	-------	----	-------	-------	----	-------	-------	----	-------

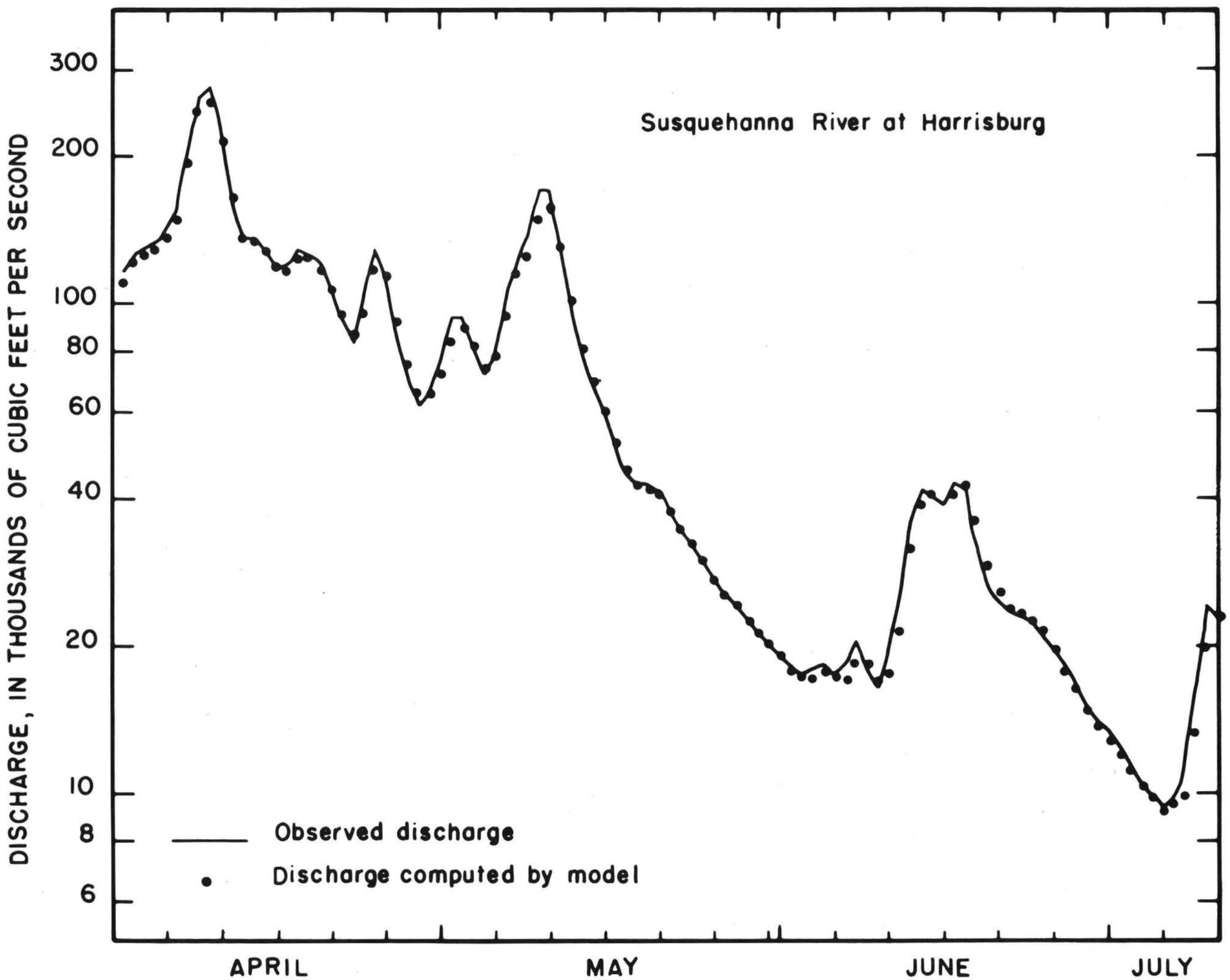


Figure 8.--Typical good fit of the model to observed data for part of a calibration period April 1, 1943, to July 10, 1943.

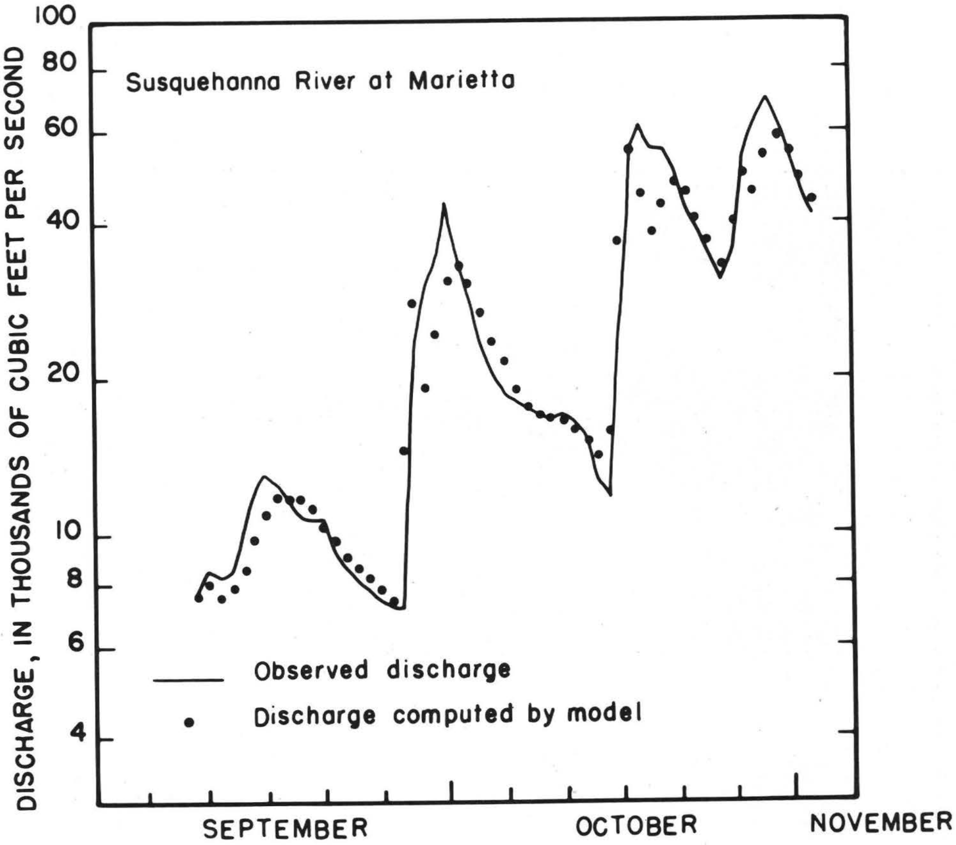


Figure 9.--Typical poor fit of the model to observed data for part of a calibration period September 9, 1942, to November 2, 1942.

Table 5.--*Examples of errors encountered during model calibration*

Reach number	Calibration period	Errors (percent)	
		Daily flows	Flow volume
1.	July 5, 1942, to June 30, 1943	9.0	-0.9
	June 5, 1947, to May 30, 1948	10.8	2.5
	Jan. 5, 1951, to Dec. 31, 1951	8.1	2.1
2.	Oct. 5, 1942, to Sept. 30, 1943	5.7	-5.1
	July 5, 1948, to Feb. 28, 1949	7.0	-6.2
	Dec. 5, 1953, to Nov. 30, 1954	7.1	-3.7
3.	July 5, 1942, to June 30, 1943	9.5	-2.4
	Aug. 5, 1944, to July 31, 1945	5.6	1.5
	Oct. 5, 1951, to Sept. 30, 1952	9.1	-2.3

Another criterion used to judge the adequacy of each model was a comparison of simulated and observed flows for the entire simulation period, October 1, 1941, to September 30, 1958 (see table 6). Errors in daily flows ranged from 6.5 percent to 9.7 percent. Flow-volume errors were between -4.5 percent and +2.6 percent.

Table 6.--*Errors in percent, between simulated and observed flows, for the pre-Raystown Lake condition, for the period October 5, 1941, to September 30, 1958*

Reach number	*Daily flows*	*Flow volume*	*Reach number*	*Daily flows*	*Flow volume*
1----	9.7	2.6	3----	7.9	-2.2
2----	6.5	-4.5	4----	(*)	(*)

*Insufficient observed data available for comparison.

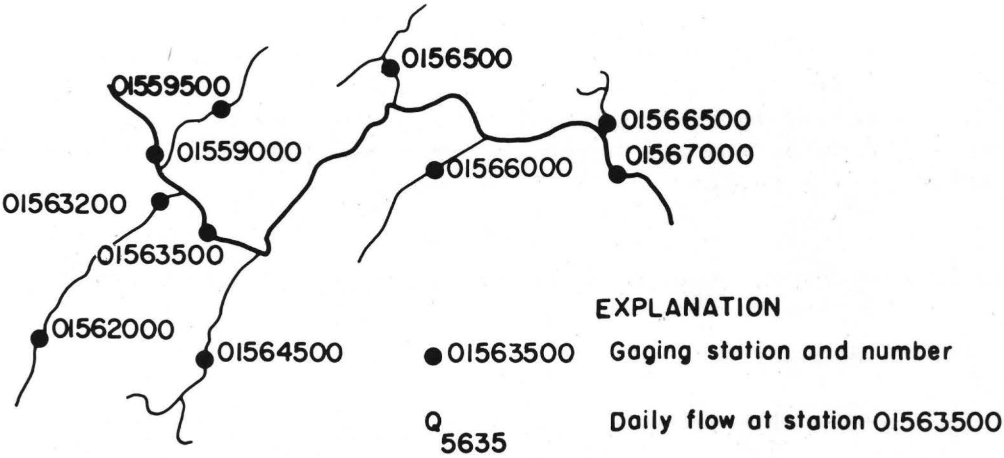
SIMULATION OF HOMOGENEOUS STREAMFLOWS

Daily streamflows for 17 water years were simulated at five sites--Mapleton Depot, Newport, Harrisburg, Marietta, and Conowingo--to determine the probable effects of outflows from Raystown Lake on downstream low-flow frequency characteristics.

Broken into individual river reaches, in the order in which they were analyzed, data were simulated in the following manner.

Reach 1 - Juniata River.--Outflows from Raystown Lake were simulated using the Raystown reservoir-routing model. Next, the outflows were combined with flows from the remainder of the Juniata River to simulate flows at Mapleton Depot. Finally, flows at Mapleton Depot were routed to Newport, with tributary flows being accounted for as shown in figure 10.

Reach 2 - Susquehanna River (Sunbury to Harrisburg.--Daily streamflows at Sunbury were added to the daily tributary flows for the upper part of this reach, see figure 11, and routed downstream to Harrisburg. Subsequently, tributary flows for the lower part of the reach, including the simulated flows from the Juniata River, as determined above, were added to the routed flows to produce total flows at Harrisburg.



$$\underbrace{Q_{5635}}_{\text{simulated}} = Q_{5590} + 2.00 \times Q_{5595} + \underbrace{Q_{5632}}_{\text{simulated}}$$

$$\underbrace{Q_{5670}}_{\text{simulated}} = \underbrace{\underbrace{Q_{5635}}_{\text{simulated}} + 1.90 \times Q_{5645}}_{\text{routed}} + 2.00 \times Q_{5650} + 2.20 \times Q_{5660} + 3.70 \times Q_{5665}$$

Figure 10.--Simulation of post-Raystown Lake streamflows of the Juniata River at Mapleton Depot and Newport.

Reach 3 - Susquehanna River (Harrisburg to Marietta).--Flows at Harrisburg were routed downstream to Marietta as shown in figure 11. The low-elevation, hydroelectric power dam at York Haven, located about mid-reach, can affect low flows at Marietta. However, modeling errors associated with a reservoir-regulation model of York Haven Dam, probably would have been of at least the same order of magnitude as modeling errors assuming no dam. Therefore, York Haven Dam was ignored. A 17 year streamflow record was simulated at Marietta and compared to the observed flows at Marietta for the same period of time. The comparison indicated that no appreciable errors could be associated with the assumption discussed above.

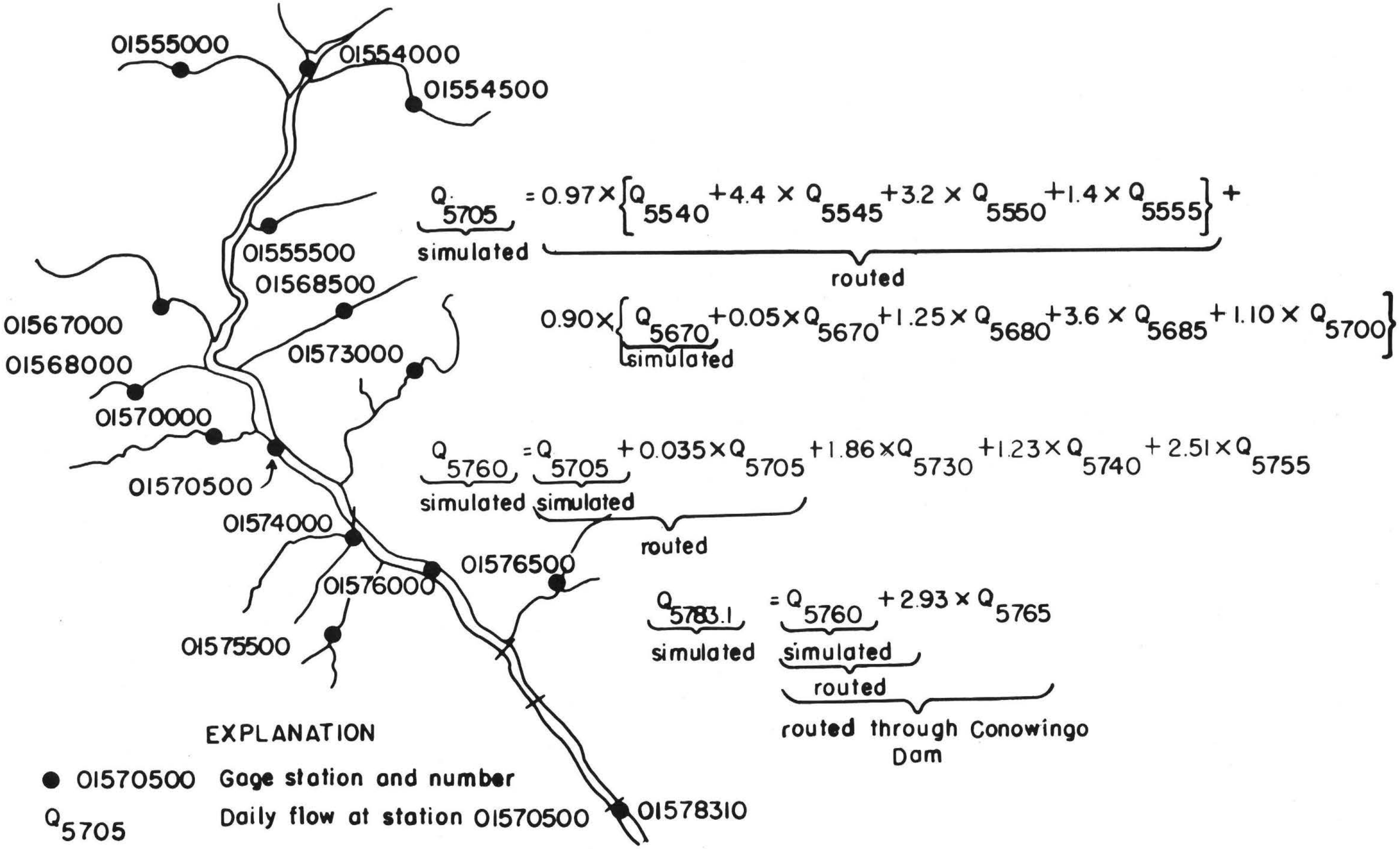


Figure 11.--Simulation of post-Raystown Lake streamflows of the Susquehanna River at Harrisburg, Marietta, and Conowingo.

Reach 4 - Susquehanna River (Marietta to Conowingo).--Although there are three run-of-the-river hydroelectric dams within this reach, the total regulation of the reach was best simulated within the limits of this study by modeling only the most downstream dam.

Daily flows at Marietta were routed to Conowingo dam and were used as input to the lower Susquehanna River reservoir-regulation model. In this model water was released below Conowingo dam according to a set schedule. A 17 year record was generated at Conowingo for two conditions, pre- and post-Raystown Lake. Figure 12 shows a comparison of typical simulated flows versus observed flows at the Conowingo station, below the dam. Because little data were available at Conowingo, a comparison of the two generated sequences of flows provides some insight into the effects of Raystown Lake on flows into Chesapeake Bay. There are three two-day periods on figure 12 where there is a large difference between observed and computed flows. All three periods are weekends. The power companies for a variety of reasons, must sometimes deviate from normal operating schedules. Such was the case for the three periods. Unfortunately, there is no way to account for these sporadic deviations from normal procedures.

VERIFICATION OF MODELS

The primary goal of this study was to determine the probable effects of Raystown Lake on downstream low-flow frequency characteristics. The most commonly used method of describing these flow characteristics, and the method used in this analysis, is a frequency curve of annual minimum flows for 7-day duration periods. In low-flow analyses the climatic year (April 1 to March 30) is generally used. The year is designated as the one in which the year begins. Because only 16 climatic years of data can be obtained from 17 water years, all subsequent analyses will be made using 16 years of data.

The adequacy of the models developed were, therefore, verified by comparing low-flow frequency curves at each site, prepared from observed data and data generated by the models, for similar hydrologic conditions. Figures 13-16 are low-flow frequency plots of both observed and simulated streamflows at Mapleton Depot, Newport, Harrisburg, and Marietta, respectively, for pre-Raystown Lake conditions. Visual inspection of these plots reveals that the simulated data generally reproduce the observed data very closely. Table 7 summarizes the average error between observed and simulated pre-Raystown annual minimum flows.

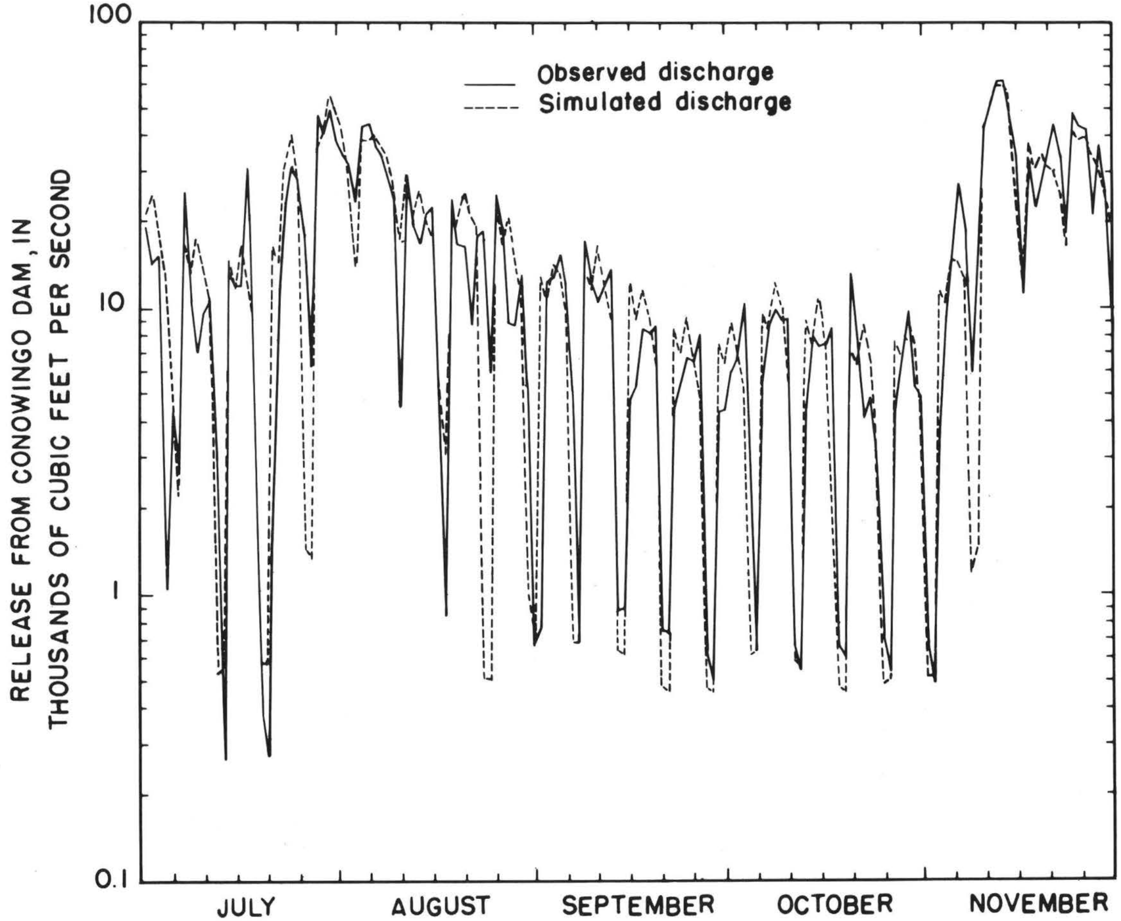


Figure 12.--A comparison of typical simulated versus observed flows of the Susquehnna River at Conowingo July 1, 1969, to November 30, 1969.

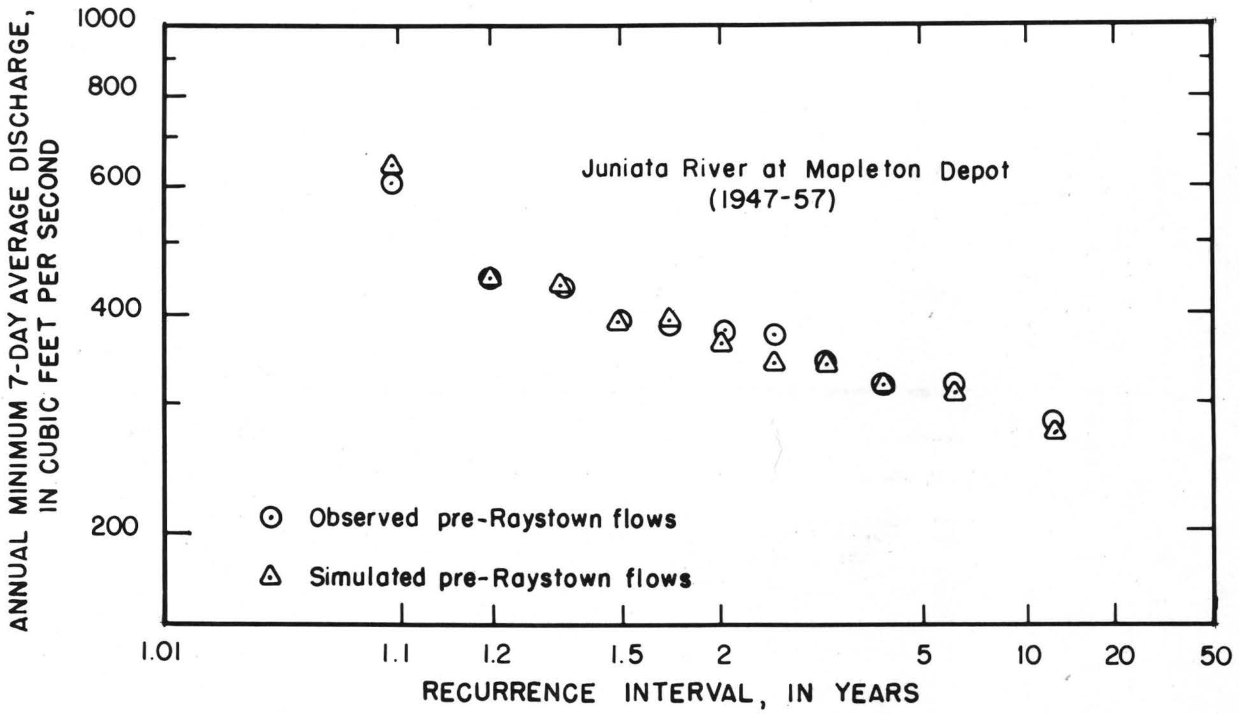


Figure 13.--Comparison of observed and simulated 7-day low-flow frequency curves, for station 01563500, for pre-Raystown Lake condition.

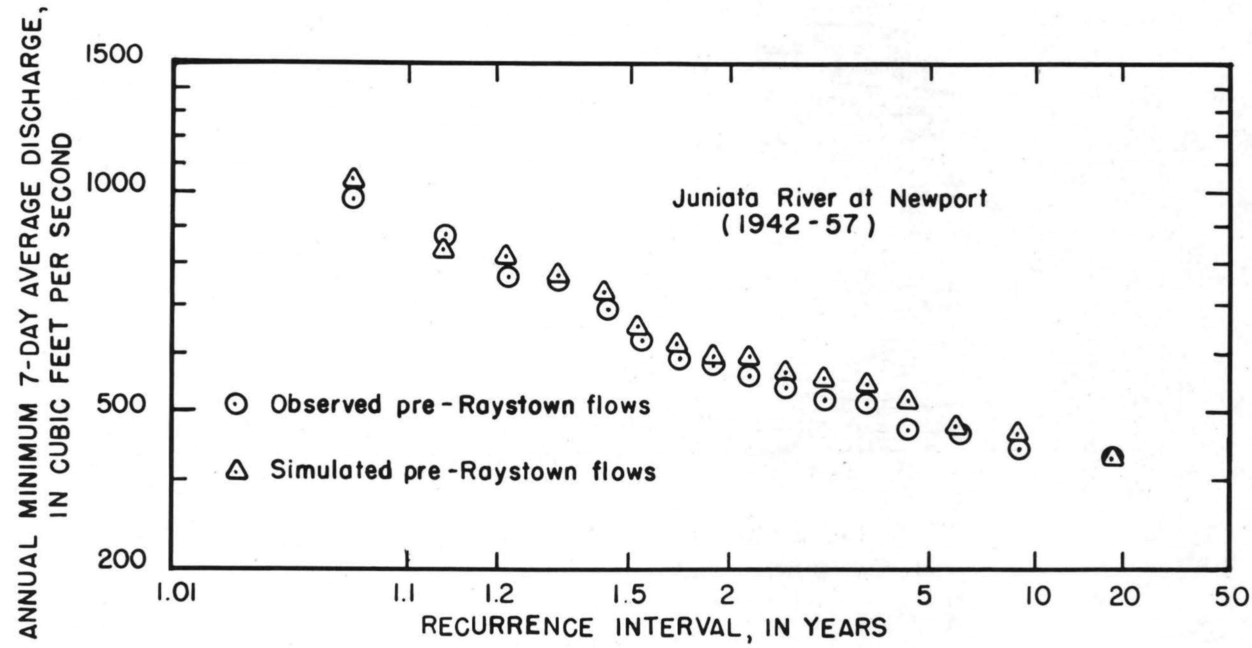


Figure 14.--Comparison of observed and simulated 7-day low-flow frequency curves, for station 01567000, for pre-Raystown Lake condition.

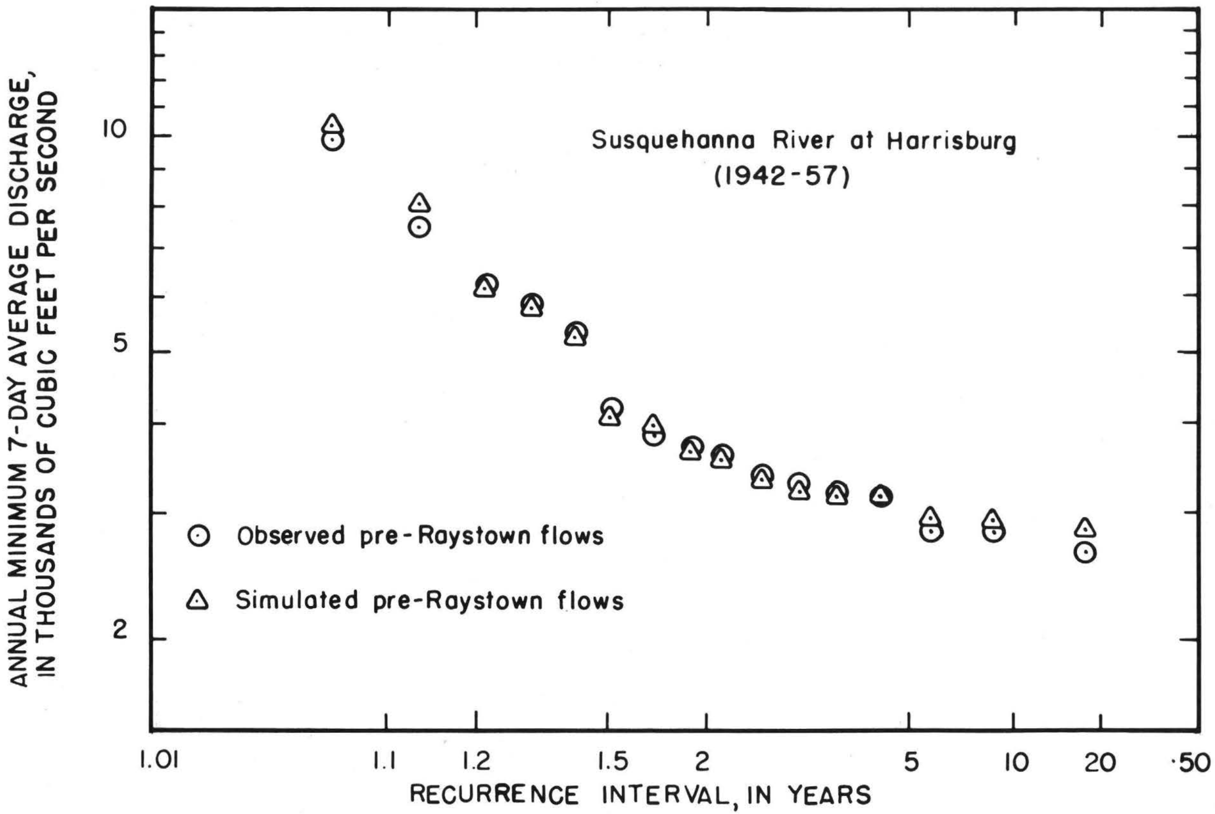


Figure 15.--Comparison of observed and simulated 7-day low-flow frequency curves, for station 01570500, for pre-Raystown Lake condition.

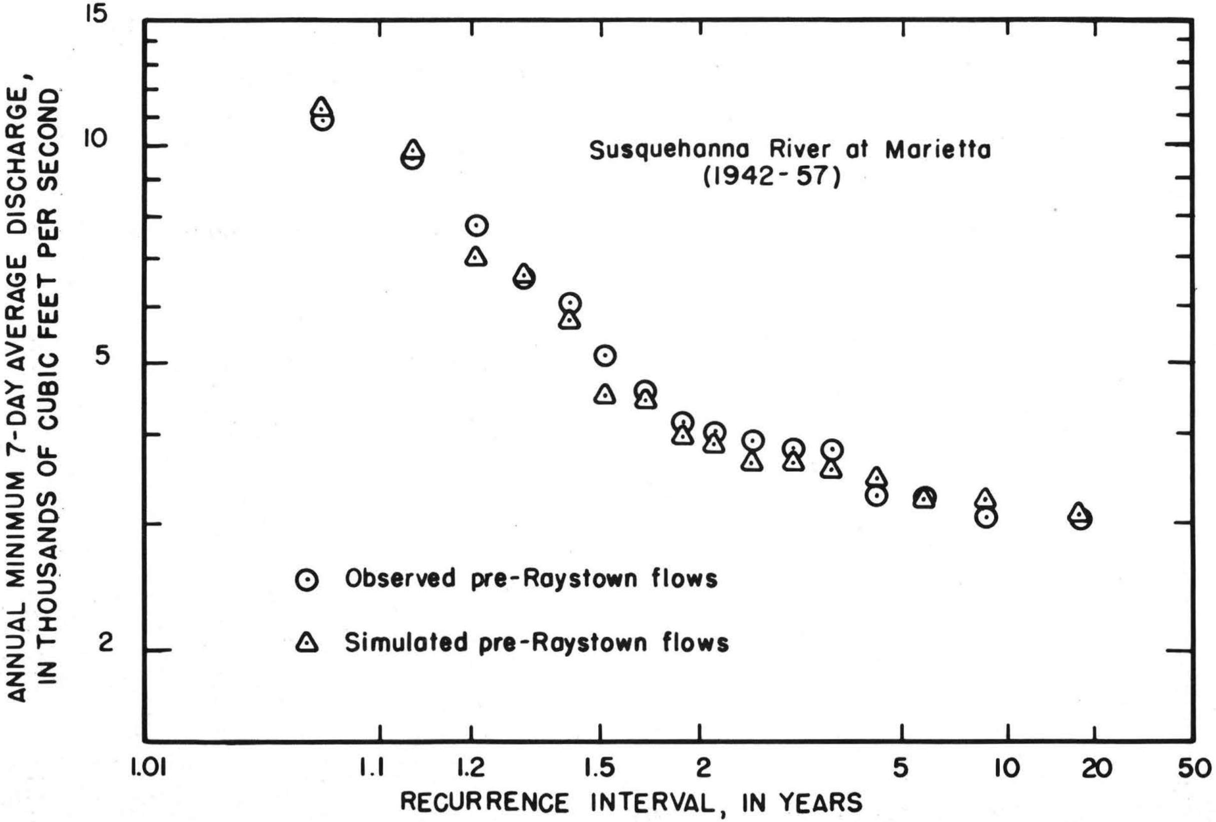


Figure 16.--Comparison of observed and simulated 7-day low-flow frequency curves, for station 01576000, for pre-Raystown Lake condition.

Table 7.--*Summary of average absolute errors between observed and simulated pre-Raystown annual minimum flows*

Station	Average absolute error of annual low flows, in percent		
	1 day[1/]	3 day	7 day
01563500[2/]------------	19.0	5.7	4.6
01567000--------------	12.2	9.1	6.5
01570500--------------	4.2	3.3	3.6
01576000--------------	7.5	6.3	5.6
01578310--------------	(3)	(3)	(3)

1/ 1-day values always subject to higher errors because of short term effects.
2/ Results for this station are based on 11 years of data.
3/ Insufficient data for adequate comparison.

APPLICATION OF MODELS

As part of the model verification phase of this study, 7-day low-flow frequency curves, prepared from pre-Raystown Lake observed and simulated flows, were compared. Having thus verified the model, it was then possible to generate a long (16 climatic years) sequence of daily flows at downstream sites by successively routing flows downstream. The first reach analyzed was on the Juniata River. Input to the flow-routing model was the output from the Raystown Lake reservoir-regulation model. Use of these simulated outflows permitted the effects of the new reservoir to be entered into the overall analysis at the first step. Successive routings then transferred those effects downstream. Figures 17-21 show the 7-day low-flow frequency curves for 2 points on the Juniata River and 3 points on the Susquehanna River. In all cases except one, simulated post-Raystown data were compared to simulated pre-Raystown data. Simulated, rather than observed, pre-Raystown data were shown because if there were any model bias, the bias would be the same in both curves. Figures 13-16, show that there is essentially no difference between pre-Raystown observed and simulated low-flow frequency curves. On figure 17 observed pre-Raystown and simulated post-Raystown data were compared because only 11 years of simulated pre-Raystown data were available.

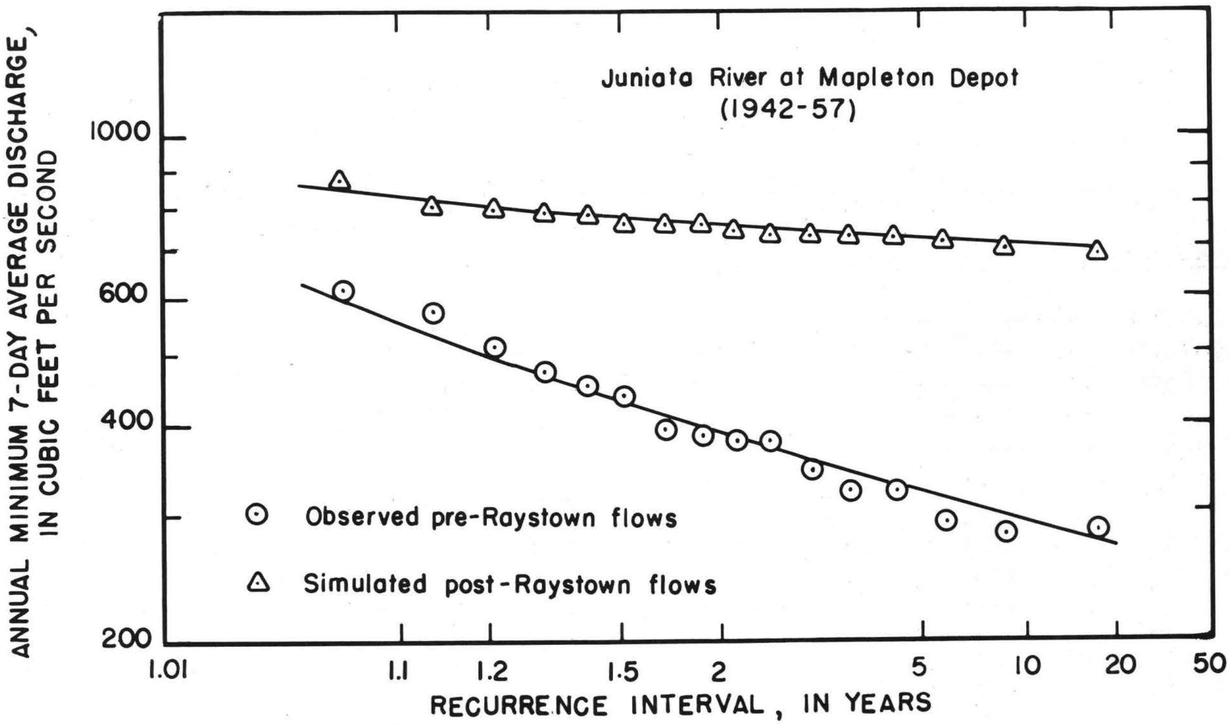


Figure 17.--Comparison of pre- and post-Raystown Lake 7-day low-flow frequency curves for the Juniata River at Mapleton Depot.

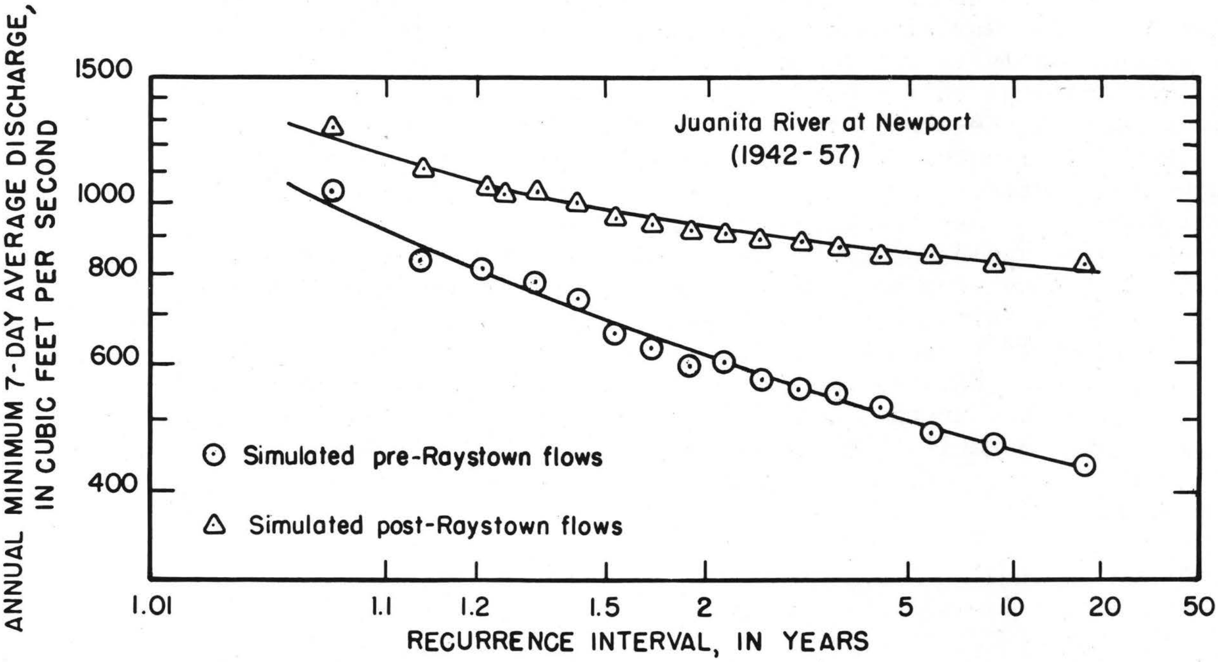


Figure 18.--Comparison of pre- and post-Raystown Lake 7-day low-flow frequency curves for the Juniata River at Newport.

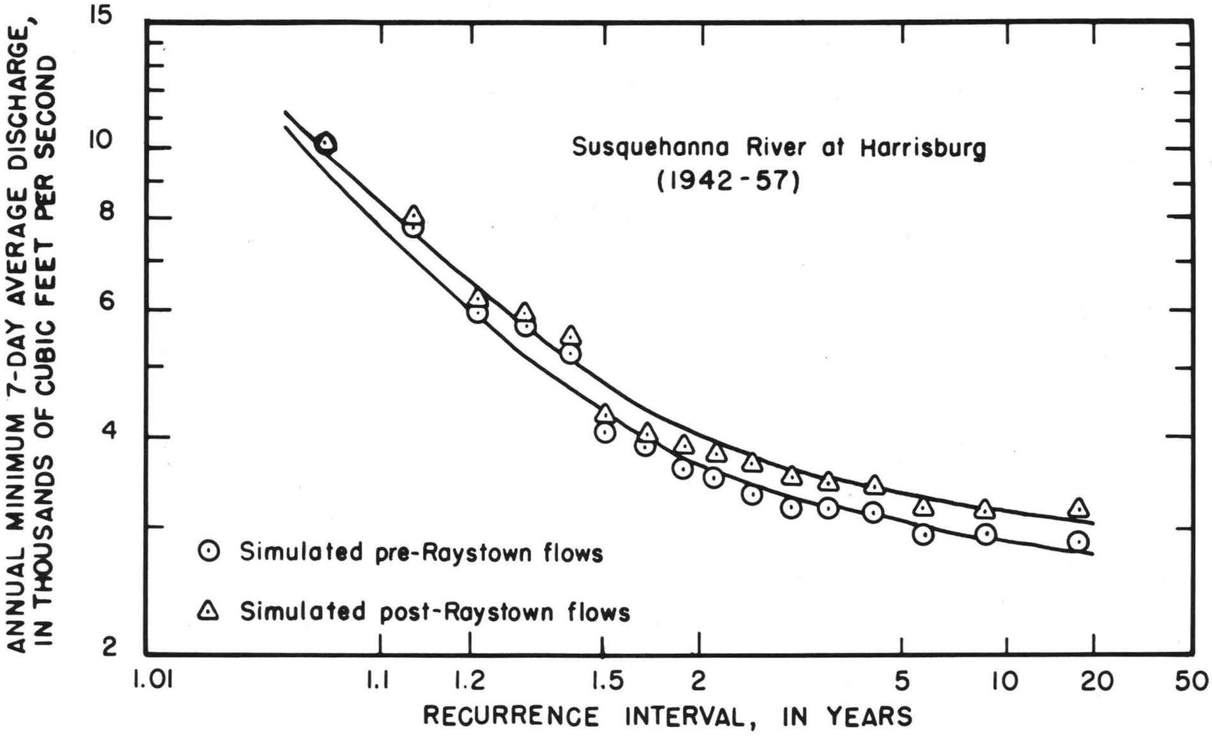


Figure 19.--Comparison of pre- and post-Raystown Lake 7-day low-flow frequency curves for the Susquehanna River at Harrisburg.

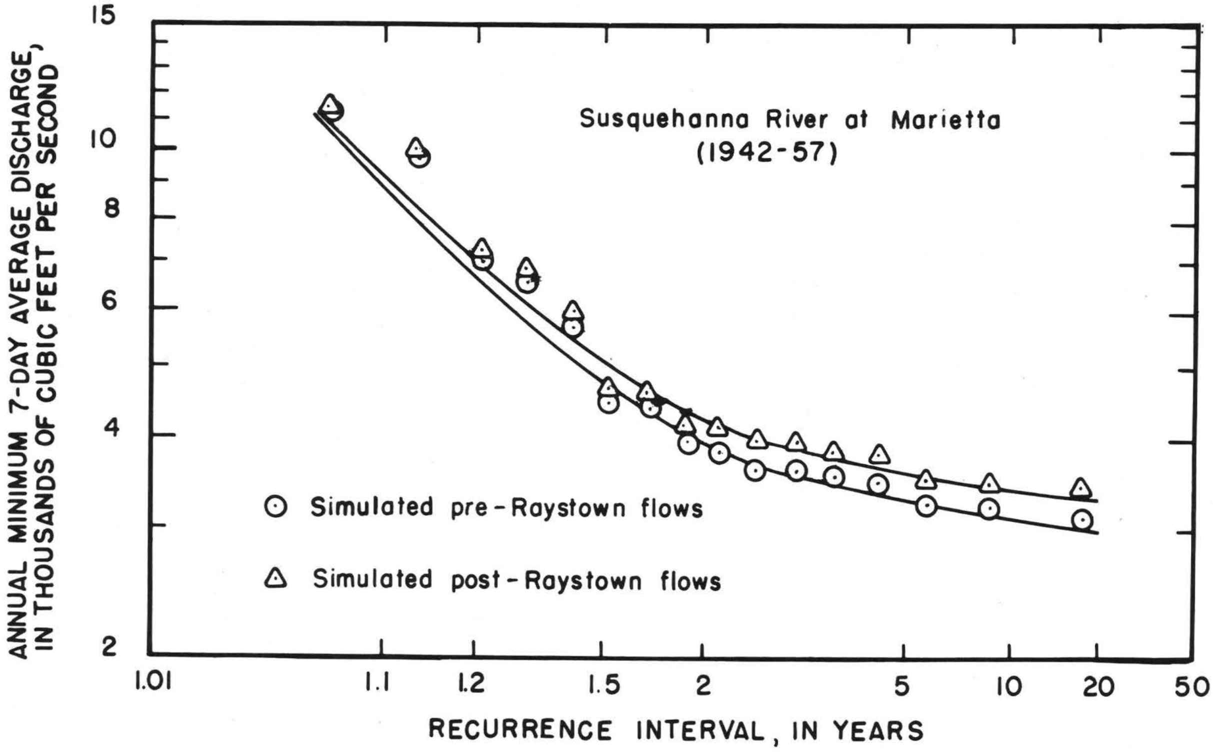


Figure 20.--Comparison of pre- and post-Raystown Lake 7-day low-flow frequency curves for the Susquehanna River at Marietta.

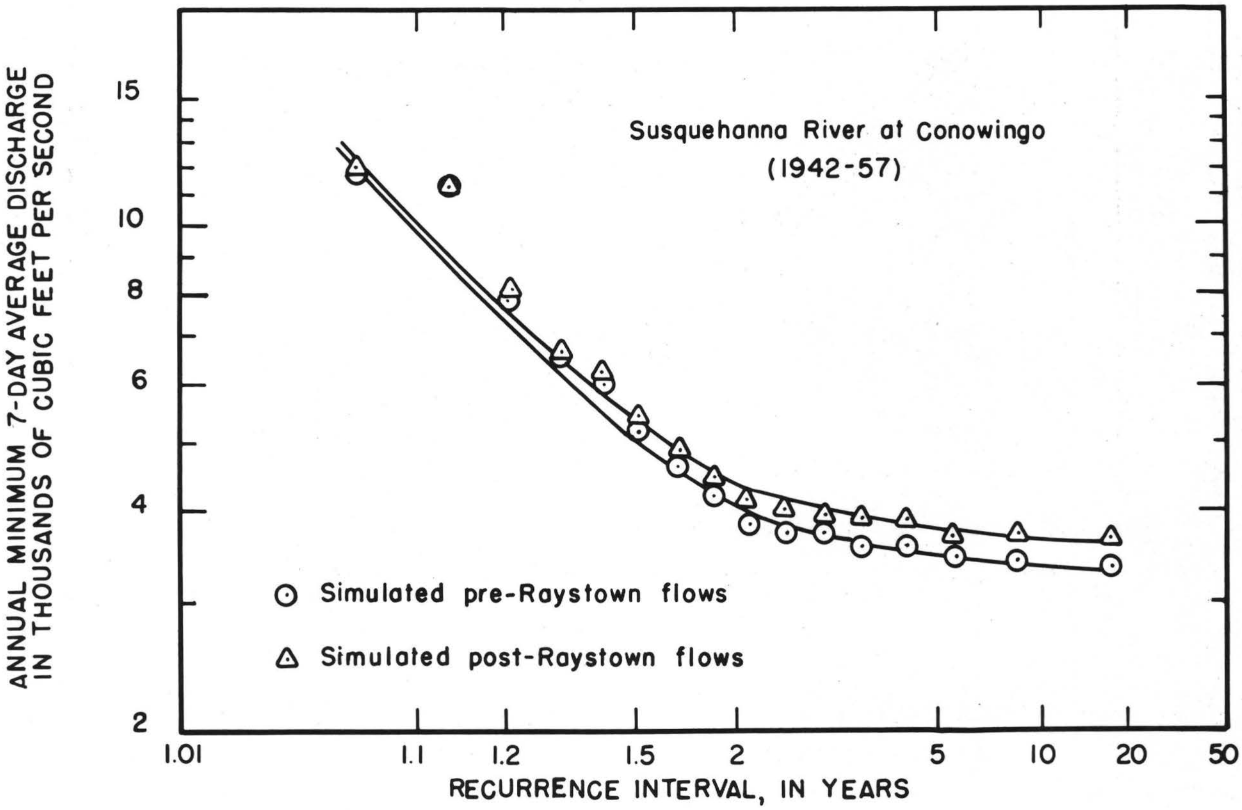


Figure 21.--Comparison of simulated pre- and post-Raystown Lake 7-day low-flow frequency curves for the Susquehanna River at Conowingo.

Figures 17-21 illustrate that the simulated post-Raystown 7-day low-flow frequency curves, in all cases, plot above the simulated pre-Raystown curves (also the observed pre-Raystown curves). At Mapleton Depot, the pre-Raystown 7-day 10-year low flow, for example, was 280 ft^3/s whereas the post-Raystown simulated flow was 700 ft^3/s. The significant increase in this low-flow characteristic reflects the effects of the high, 480 ft^3/s minimum release from Raystown Lake.

Low flows at points downstream from Mâpleton Depot will also be higher with Raystown Lake in operation. The 7-day 10-year low flow was increased by about 350 ft^3/s at Newport, by about 300 ft^3/s at Harrisburg, and by about 290 ft^3/s at both Marietta and Conowingo. A decrease in the effects of Raystown Lake at points progressively farther downstream is to be expected because of evaporation, channel losses, and other factors. Also, changes in flow, such as flood peaks or low flow troughs, are naturally dampened or attenuated with time and (or) distance downstream.

There are inherent modeling errors in all of the simulated data presented here, especially since the post-Raystown data were based on strict adherence to reservoir-regulation schedules at both Raystown Lake and the lower Susquehanna River power dams. The frequency curves shown in figures 17-21 represent very good estimates of the low-flow frequency characteristics for long-term, post-Raystown Lake conditions.

Other uses could be made of the basin models developed here. For example, the effects of several different Raystown Lake reservoir-regulation schedules could be examined by simply changing the reservoir-regulation model. Successive downstream flow routing would then transfer the effects of the alternate regulation schedules to downstream points.

River basin models, such as the ones described here, might also be used to translate the results of stochastic flow simulations to downstream sites.

To satisfy low-flow augmentation regulations, it might be necessary to study the timing of releases from an upstream reservoir, during periods of low flow. Basin models like the ones described in this report could be used in these types of analyses. Shearman and Swisshelm (1973) present several other possible applications of reservoir- and channel-routing models.

CONCLUSIONS

A combination of reservoir-regulation and channel-routing models have been used to estimate the long-term effects of a new reservoir; Raystown Lake, on downstream low-flow characteristics. In all, five different locations were analyzed; the Juniata River at Mapleton Depot and Newport, and the Susquehanna River at Harrisburg, Marietta, and Conowingo. A comparison of low-flow frequency curves prepared from data simulated for the pre- and post-Raystown Lake conditions indicates that the low flows at each of the sites analyzed, will be significantly higher with Raystown Lake in operation. The amount of increase of low flows will vary with distance downstream from the Lake and with recurrence interval. At the 10-year recurrence interval, the amount of increase in the 7-day low flow will vary from 420 ft^3/s at Mapleton Depot to 290 ft^3/s at Marietta and Conowingo. This amounts to about a 150 percent increase at Mapleton Depot and about a 10 percent increase at Marietta. Increases in low flows of the magnitude discussed here are to be expected because the minimum release from Raystown Lake is on the order of 400 ft^3/s higher than the natural 7-day 10-year low flow.

Although there are inherent modeling errors in all of these simulated data, the overall quality of the simulated stream records and low-flow frequency curves is considered good. Models of this type can be used to provide insight into a variety of other related problems. One example is the study of effects of alternative reservoir-regulation schedules on downstream low flows.

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