FLOW ROUTING IN THE SUSQUEHANNA RIVER BASIN: PART II– LOW-FLOW FREQUENCY CHARACTERISTICS OF THE SUSQUEHANNA RIVER BETWEEN WAVERLY, NEW YORK AND SUNBURY, PENNSYLVANIA

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UNITED STATES DEPARTMENT OF THE INTERIOR

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

Multiply Inch-pound units	By	To obtain SI units
feet per second (ft/s)	.3048	meters per second (m/s)
square feet per second (ft^2/s)	.09290	square meters per second (m^2/s)
cubic feet per second (ft^3/s)	.02832	cubic meters per second (m^3/s)

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ABSTRACT

Six flow-routing models were developed, calibrated, and verified for the Susquehanna River between Waverly, New York, and Sunbury, Pennsylvania. The models give the Susquehanna River Basin Commission tools to estimate effects of water-resource developments upstream from Waverly upon four gaged sites and two ungaged sites within the study reach. The models were used to simulate a 32-year record of daily flows at ungaged sites A and B. Low-flow frequency curves for simulated flows at sites A and B were used to estimate 7-day low-flows at the 10-year recurrence interval of 540 and 770 ft^3/s, respectively.

The model errors, differences between model results and observed streamflow at gaged sites, are considered to be within reasonable limits and overall quality of simulated streamflow and low-flow frequency curves is considered good.

INTRODUCTION

In 1975 the U.S. Geological Survey and the Susquehanna River Basin Commission (SRBC) initiated a series of cooperative projects designed to provide SRBC with tools for effective water-resources management. The tools were to be a series of flow-routing models for all the major streams within the Susquehanna River basin which would give SRBC the capability to translate effects of proposed water-resource developments anywhere in the basin to points downstream. Models completed by Armbruster (1977) provide SRBC with coverage of the Juniata River and Susquehanna River below Sunbury, Pennsylvania.

The primary objective of this study, second in the series, is the development, calibration, and verification of flow-routing models for the Susquehanna River from Waverly, New York, to Sunbury, Pennsylvania. These models will permit SRBC to estimate the effects of water-resource developments upstream from Waverly at six locations on the Susquehanna River. They were also used to simulate streamflow for existing conditions at two ungaged sites.

DESCRIPTION OF STUDY REACHES

The Susquehanna River from Waverly, New York, to Sunbury, Pennsylvania will be referred to in this report as the Susquehanna River. In this portion of the river, gaging stations are located on the mainstem at Waverly, Towanda, Wilkes-Barre, Danville, and Sunbury. These stations define four reaches: 1) Waverly to Towanda, length 18.0 mi; 2) Towanda to Wilkes-Barre, length 82.7 mi; 3) Wilkes-Barre to Danville, length 52.1 mi; and 4) Danville to Sunbury, length 15.0 mi (fig. 1). The reaches from Towanda to Wilkes-Barre and from Wilkes-Barre to Danville were each split into two reaches by selecting two ungaged sites referred to hereafter as sites A and B. The two ungaged sites were selected because they were near the center of the reach or near a tributary or some other feature which would provide an intermediate point for water-resources management decisions.

Site A, located immediately upstream from Tunkhannock Creek, divided reach 2 into reaches 2a (length 52.8 mi) and 2b (length 29.9 mi). Site B located immediately upstream from Wapwallopen Creek, divided reach 3 into reaches 3a (length 21.8 mi) and 3b (length 30.3 mi).

DATA USED FOR DIGITAL MODELING

Streamflow records for 14 stations for water years 1942-73 were used in the modeling. The stations, their period of record, and drainage areas are listed in Table 1.

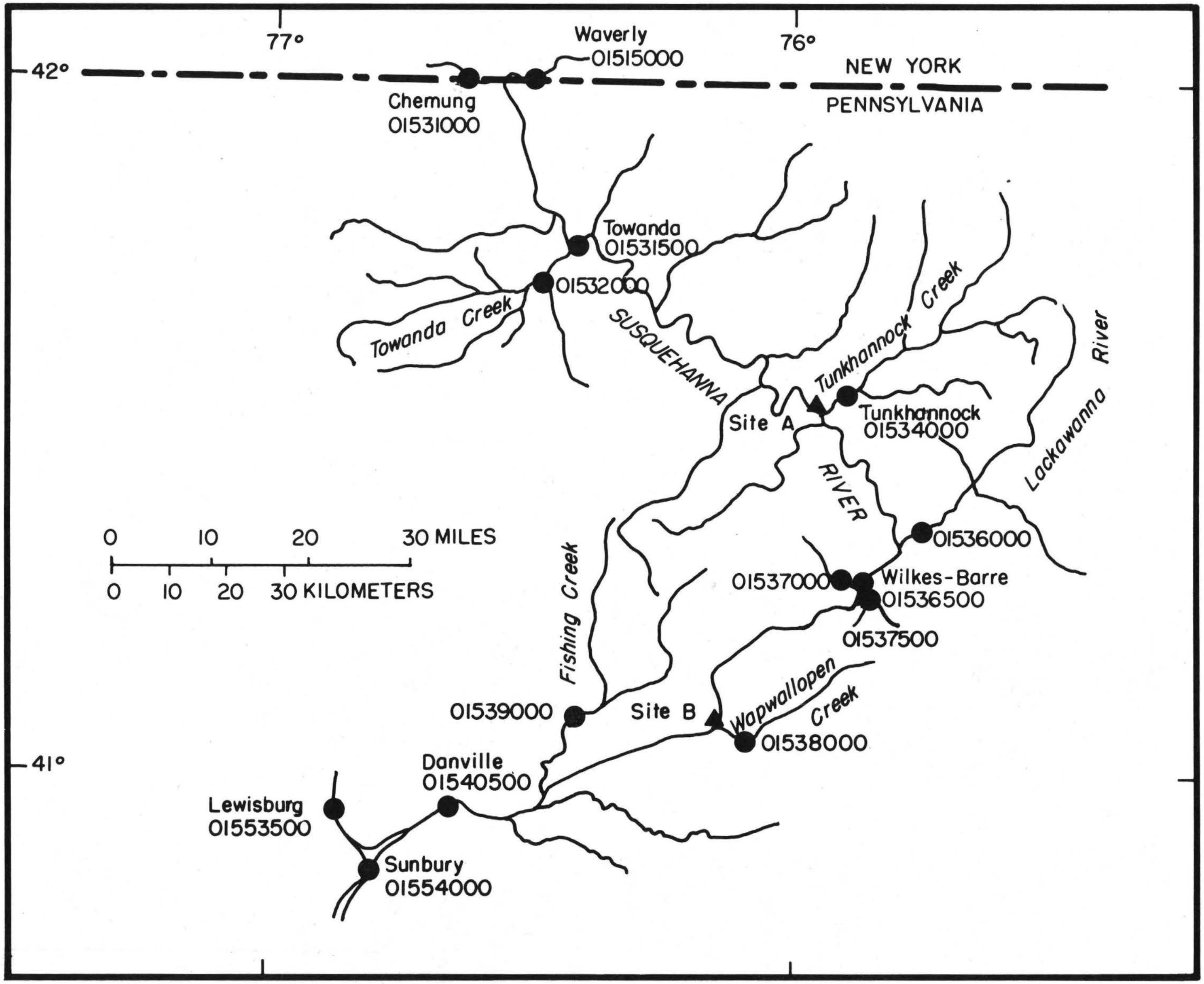


Figure 1.--Map of study area.

Table 1.--Data available for use in routing study for the Susquehanna River reaches

Station number	Station name	Water years of record	Drainage area (mi^2)
01515000	Susquehanna River near Waverly, N.Y.	1938-73	4,773
01531000	Chemung River at Chemung, N.Y.	1904-73	2,506
01531500	Susquehanna River at Towanda, Pa.	1914-73	7,797
01532000	Towanda Creek near Monroeton, Pa.	1915-73	215
01534000	Tunkhannock Creek near Tunkhannock, Pa.	1915-73	383
01536000	Lackawanna River at Old Forge, Pa.	1939-73	332
01536500	Susquehanna River at Wilkes-Barre, Pa.	1900-73	9,960
01537000	Toby Creek at Luzerne, Pa.	1942-73	32.4
01537500	Solomon Creek at Wilkes-Barre, Pa.	1941-73	15.7
01538000	Wapwallopen Creek near Wapwallopen, Pa.	1920-73	43.8
01539000	Fishing Creek near Bloomsburg, Pa.	1939-73	274
01540500	Susquehanna River at Danville, Pa.	1900-73	11,200
01553500	West Branch Susquehanna River at Lewisburg, Pa.	1940-73	6,847
01554000	Susquehanna River at Sunbury, Pa.	1938-73	18,300

DESCRIPTION OF FLOW-ROUTING MODELS

To determine the low-flow characteristics at the two ungaged sites, a flow-routing model was developed and calibrated for each of the six reaches. A period of 32 water years of concurrent, observed data were used to provide as much data as possible to verify and evaluate the models.

Each model was a unit-response, flow-routing model that used the diffusion analogy (Keefer, 1974) and multiple linearization (Keefer and McQuivey, 1974). A one-day routing interval was used throughout the reaches. The two model parameters--wave celerity and wave dispersion--have been described by Armbruster (1977). Celerity describes the speed of the simulated water wave traveling downstream and wave dispersion defines the amount of damping or attenuation of the wave.

The diffusion analogy is the mechanism used to derive the routing-response functions. Multiple linearization is a means to allow for both variable travel time and attenuation of flows while using linear flow-routing models. Multiple linearization is useful for this study because a wide range of discharges are encountered. As shown in figure 2, the inflow hydrograph is separated into a number of segments or selected discharge ranges. Flows are routed downstream, one segment at a time, and then summed to obtain an outflow hydrograph.

Flow-routing models were first developed for reaches 1, 2, 3, and 4. Each required a separate model to properly account for both gaged and ungaged inflow into the reach. Flow from ungaged areas was estimated by multiplying the flow at an index station by a suitable ratio. Initial estimates of this ratio were derived by dividing the drainage area of a group of tributaries, gaged and ungaged, by the drainage area of the index station. Trial and error adjustments to the ratio were made to balance flows within each reach. Model parameters also were determined for each model.

Subsequently, the flow-routing model for reach 2 was divided into two models for reaches 2a and 2b and the model for reach 3 was divided into two models for reaches 3a and 3b. New model parameters were determined for each of these four models.

Groundwater discharge, not treated as a separate item in the model input, was implicitly included as total streamflow was used in the calibrations. No errors were noted that could be attributed to this method.

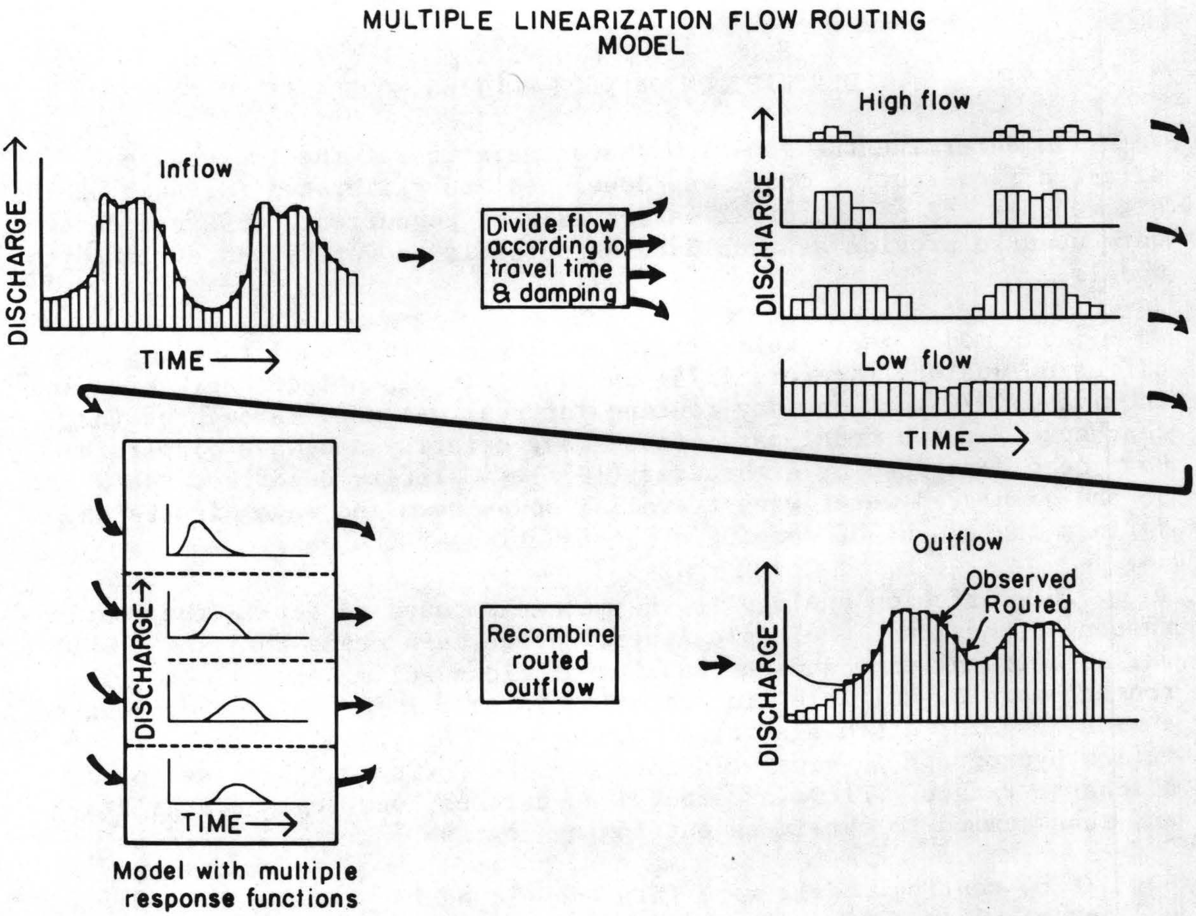


Figure 2.--Schematic diagram of the multiple linearization flow-routing model. (From Keefer and McQuivey, 1974.)

MODEL CALIBRATION

Each of the six flow-routing models was calibrated by adjusting the preliminary values for the wave dispersion coefficient, the wave celerity, and amount of flow from ungaged areas. The calibration process, as discussed by Shearman and Swisshelm (1973) and Armbruster (1977), consisted of the following trial and error procedure.

1. Several segments of at least one year's duration of concurrent streamflow record were selected. Each segment contained at least one significant rise and recession. The segments exhibited a wide range of flows; however, due to the objectives of the study, flows in the low-to-medium flow range were emphasized.

2. Preliminary values for dispersion coefficients and celerities were estimated using the methods published by Keefer and McQuivey (1974).

3. To account for flow from ungaged areas, a preliminary set of ratios was calculated.

4. Simulated outflows from a reach were produced by the models, using observed inflows to the reach, preliminary model parameters, and preliminary ratios as input to the models.

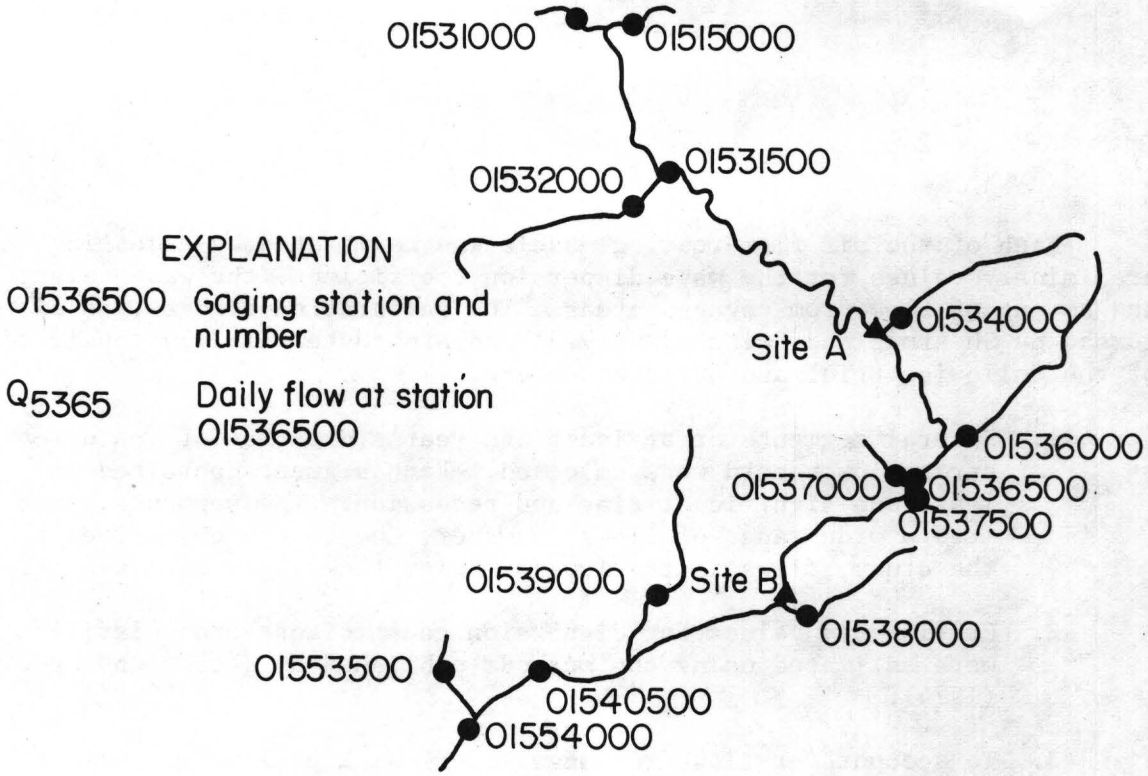
5. The simulated outflows for each reach were then evaluated by:

    a. A visual comparison of hydrograph plots of observed and simulated outflows.
    b. An analysis of average absolute deviations between observed and simulated daily flows.
    c. A comparison of volume differences between the observed and simulated hydrographs for the calibration period.

6. Steps 4 and 5 were repeated until adjustments of the ratios and model parameters provided minimum errors.

Figure 3 is a schematic diagram of the study area that shows the final ratios used in the calibration of the models. Table 2 lists the final model parameters used for each reach.

Figures 4 and 5 present comparisons of observed and simulated hydrographs for parts of two water years for the Susquehanna River at Sunbury (01554000) station. Data for the simulated hydrograph were obtained by routing observed data from Waverly through all six models. Both figures show good agreement between observed and simulated data, which indicates good calibration of the model.



$$Q_{5315} = \underbrace{1.02(Q_{5150}) + 1.16(Q_{5310})}_{\text{routed}}$$

$$Q_{\text{site A}} = \underbrace{1.00(Q_{5315}) + 2.41(Q_{5320})}_{\text{routed}}$$

$$Q_{5365} = \underbrace{1.00(Q_{\text{site A}}) + 2.03(Q_{5340})}_{\text{routed}} + 1.96(Q_{5360})$$

$$Q_{\text{site B}} = \underbrace{1.00(Q_{5365}) + 5.76(Q_{5370}) + 5.92(Q_{5375})}_{\text{routed}}$$

$$Q_{5405} = \underbrace{1.00(Q_{\text{site B}}) + 2.38(Q_{5380})}_{\text{routed}} + 2.77(Q_{5390})$$

$$Q_{5540} = \underbrace{1.01(Q_{5405})}_{\text{routed}} + 1.03(Q_{5535})$$

Figure 3.--Schematic diagram of the Susquehanna River showing the relations used in flow-routing models.

Table 2.--Model parameters used in final flow-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 2a		Reach 2b		Reach 3a		Reach 3b		Reach 4	
Q	C	K	C	K	C	K	C	K	C	K	C	K
400	2.5	2,000	1.5	500	1.5	500	1.7	2,000	1.7	1,500	1.2	1,300
800	3.2	4,000	2.0	1,000	2.0	1,000	2.6	4,000	2.1	3,000	1.4	2,500
2,000	3.7	6,000	3.6	2,000	3.6	2,000	3.0	7,000	2.5	5,000	1.5	4,500
4,000	4.2	9,000	3.8	6,000	3.8	6,000	3.1	12,000	2.8	8,000	1.8	5,000
10,000	5.3	15,000	4.7	15,000	4.7	15,000	3.9	22,000	3.6	17,000	2.4	12,000
20,000	6.2	27,000	5.6	32,000	5.6	32,000	4.7	40,000	4.4	28,000	3.0	22,000
50,000	8.7	61,000	7.7	75,000	7.7	75,000	6.4	80,000	5.9	60,000	4.2	50,000
80,000	10.5	90,000	9.4	120,000	9.4	120,000	7.5	130,000	6.3	90,000	4.9	78,000
110,000	11.9	121,000	10.7	160,000	10.7	160,000	8.5	180,000	6.6	124,000	5.4	107,000

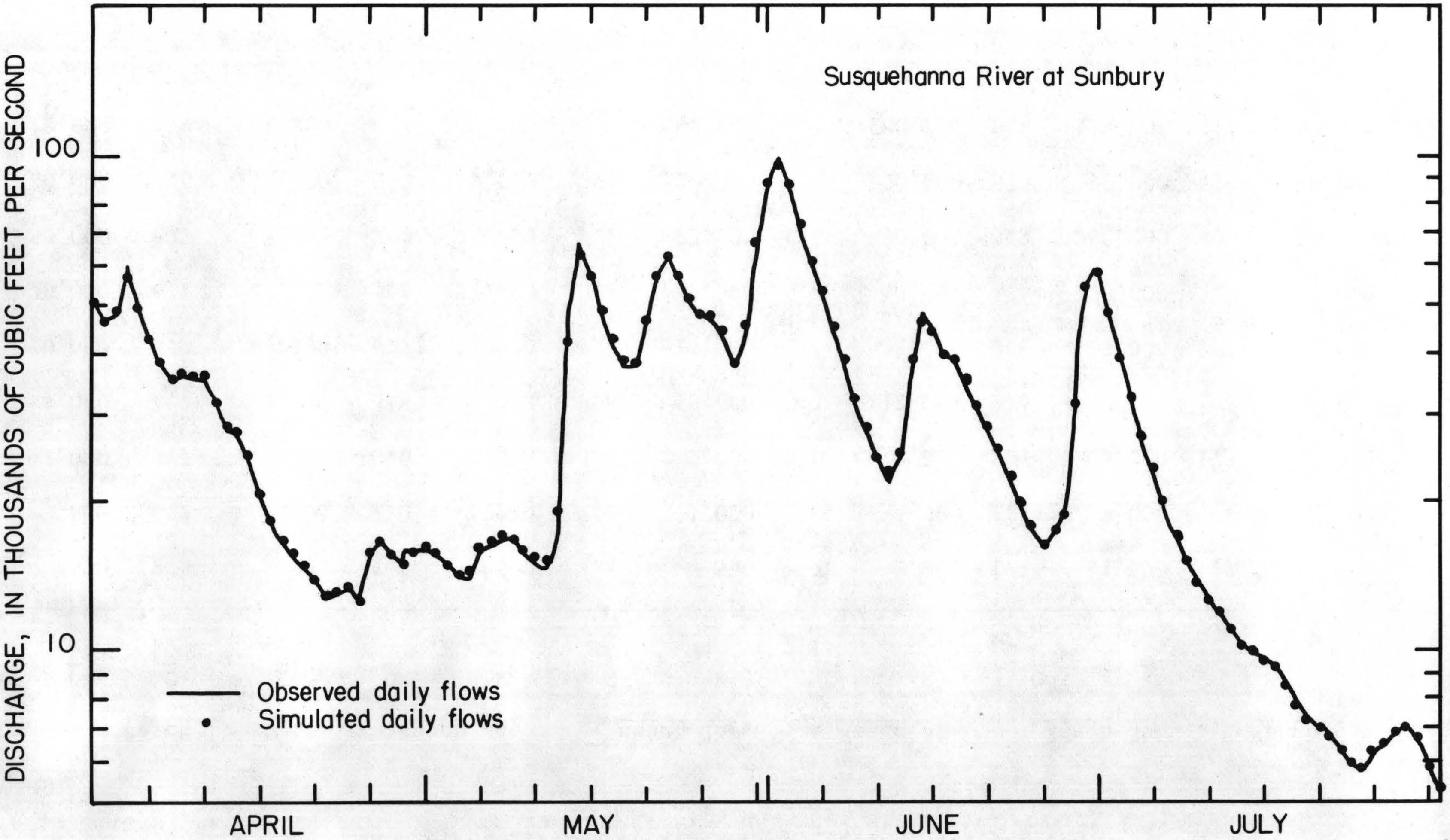


Figure 4.--Comparison of observed and simulated daily flows at station 01554000, April - July, 1968.

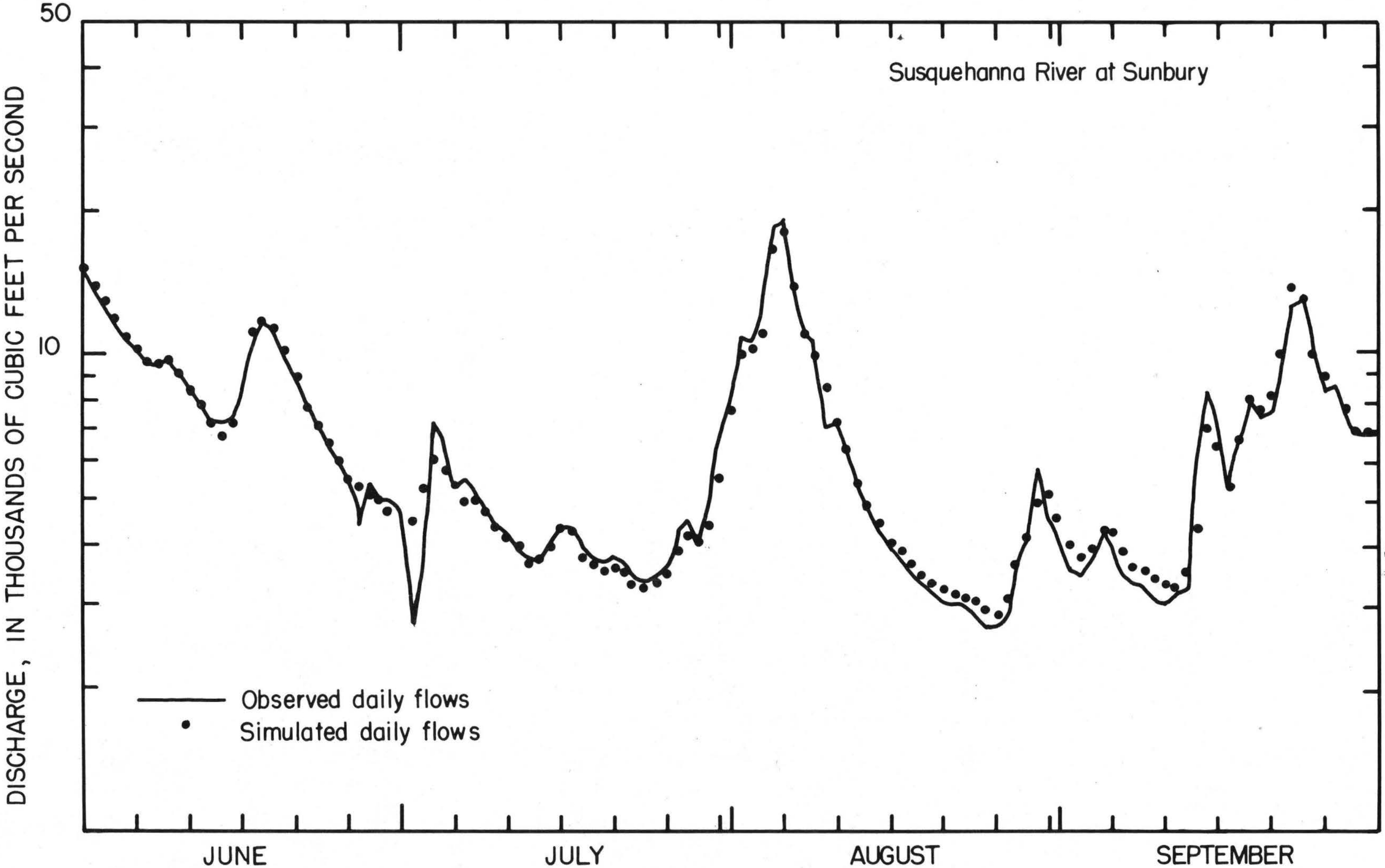


Figure 5.--Comparison of observed and simulated daily flows at station 01554000, June - September, 1971.

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

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

where Q_{obs} and Q_{sim} are the observed and simulated flows respectively for the <u>ith</u> day and N is the number of days in the calibration period; and

$$\text{Volume error (in percent)} = \frac{V_{obs}-V_{sim}}{V_{obs}} \times 100$$

where V_{obs} and V_{sim} are the volumes of observed and simulated flows respectively for the calibration period. Several sets of typical calibration errors for each reach are given in table 3. Errors for reaches 2 and 3 are given for both undivided and divided conditions. Daily flow errors ranged from 3.2 percent in reach 4 to 9.3 percent in undivided reach 2. Flow-volume errors ranged from -3.0 percent in reaches 1, 2a + 2b, and undivided reach 2, to 2.3 percent in reaches 3a + 3b undivided reach 3.

VERIFICATION OF MODELS

To verify the models, daily streamflows for 32 water years were simulated at all six sites. The data were simulated in the following manner:

<u>Reach 1 - Susquehanna River (Waverly to Towanda)</u>.--Observed daily streamflows at Waverly were added to daily streamflows for the Chemung River at Chemung, N.Y., and routed 18.0 mi to Towanda.

<u>Reach 2a - Susquehanna River (Towanda to Site A)</u>.--Simulated flows at Towanda were added to observed flows from Towanda Creek and routed 52.8 mi to site A (immediately upstream from Tunkhannock Creek). Reach 2 was divided at this point to provide low-flow frequency data at an ungaged site.

Table 3.--Examples of errors encountered during model calibration

Reach number	Calibration period	Errors (percent)	
		Daily flows	Flow volume
1	Oct. 5, 1964, to Sept. 29, 1965	6.2	0.3
	Oct. 5, 1967, to Sept. 28, 1968	7.2	-3.0
	Oct. 5, 1970, to Sept. 29, 1971	5.1	1.3
	Oct. 5, 1971, to Sept. 28, 1972	5.4	0.6
2a + 2b 1/	Oct. 5, 1964, to Sept. 29, 1965	9.1	0.1
	Oct. 5, 1967, to Sept. 28, 1968	6.2	-1.3
	Oct. 5, 1970, to Sept. 29, 1971	7.1	-3.0
	Oct. 5, 1971, to Sept. 28, 1972	6.9	-2.6
2 2/	Oct. 5, 1964, to Sept. 29, 1965	9.3	0.1
	Oct. 5, 1967, to Sept. 28, 1968	6.7	-1.3
	Oct. 5, 1970, to Sept. 29, 1971	6.9	-3.0
	Oct. 5, 1971, to Sept. 28, 1972	6.7	-2.6
3a + 3b 1/	Oct. 5, 1964, to Sept. 29, 1965	5.7	0.8
	Oct. 5, 1967, to Sept. 28, 1968	5.3	2.3
	Oct. 5, 1970, to Sept. 29, 1971	5.3	0.1
	Oct. 5, 1971, to Sept. 28, 1972	6.1	0.6
3 2/	Oct. 5, 1964, to Sept. 29, 1965	5.5	0.8
	Oct. 5, 1967, to Sept. 28, 1968	4.9	2.3
	Oct. 5, 1970, to Sept. 29, 1971	5.0	0.1
	Oct. 5, 1971, to Sept. 28, 1972	5.8	0.6
4	Oct. 5, 1964, to Sept. 29, 1965	3.7	-0.4
	Oct. 5, 1967, to Sept. 28, 1968	3.2	-0.2
	Oct. 5, 1970, to Sept. 29, 1971	4.4	0.5
	Oct. 5, 1971, to Sept. 28, 1972	3.4	-0.2

1/ Divided reach
2/ Undivided reach

Reach 2b - Susquehanna River (Site A to Wilkes-Barre).--The simulated daily streamflows at site A were added to observed flows from Tunkhannock Creek and routed 29.9 mi to Wilkes-Barre. Observed flows from the Lackawanna River were then added to the routed flows to simulate the flows at Wilkes-Barre.

Reach 3a - Susquehanna River (Wilkes-Barre to Site B).--The simulated flows at Wilkes-Barre were added to observed flows from Toby and Solomon Creeks and then routed 21.8 mi to site B (immediately upstream from Wapwallopen Creek). Reach 3 was divided at this point to provide low-flow frequency data at a second ungaged site.

Reach 3b - Susquehanna River (Site B to Danville).--Simulated flows from site B were added to observed flows from Wapwallopen Creek and routed 30.3 mi to Danville, where observed flows from Fishing Creek were added to provide simulated flows at Danville.

Reach 4 - Susquehanna River (Danville to Sunbury).--Simulated flows at Danville were routed 15.0 mi to Sunbury where observed flows from the West Branch at Lewisburg were added to provide simulated flows at Sunbury.

The adequacy of each model may be judged by comparing simulated and observed flows for the entire simulation period, October 1, 1941, to September 30, 1973 (see table 4). Errors in daily flows ranged from 5.1 percent to 8.5 percent. Flow-volume errors were between 0.0 percent in reaches 2a + 2b and 0.9 percent in reaches 3a + 3b. (The 0.0 value was a result of rounding to the nearest tenth of a percent).

Low-flow characteristics are of primary interest. Comparisons of low-flow frequency curves for simulated versus observed data provide a valuable means for evaluating adequacy of the models. Low-flow analyses are generally based on the climatic year (April 1 to March 31), thus low-flow frequency comparisons are based on 31 years of data, since only 31 climatic years of data can be obtained from 32 water years.

Seven-day low-flow frequency curves computed from the simulated and observed data, at each of the four gaged sites are presented in figures 6-9. Visual comparison of the curves indicates very good agreement between observed and simulated data. Furthermore, figure 7 also indicates that the frequency curve of simulated flows at Wilkes-Barre using one model for reach 2 compares favorably with simulated flows using models for reaches 2a and 2b. Similarly, figure 8 also indicates good agreement between the simulated flows using one model for reach 3 and the simulated flows using models for reaches 3a and 3b. Thus, the models of the divided reaches, which are necessary for simulation of streamflows at sites A and B, are implicitly verified. Table 5 presents the average absolute errors between observed and simulated annual minimum flows at the gaged sites for one-, three-, and seven-day periods.

Table 4.--Errors, in percent, between simulated and observed flows for the period October 5, 1941, to September 30, 1973

Reach number	Daily flows	Flow volume
1	5.1	0.3
2a + 2b	7.7	0.0[a/]
3a + 3b	8.5	0.9
4	5.7	0.4

a/ Rounded to tenths

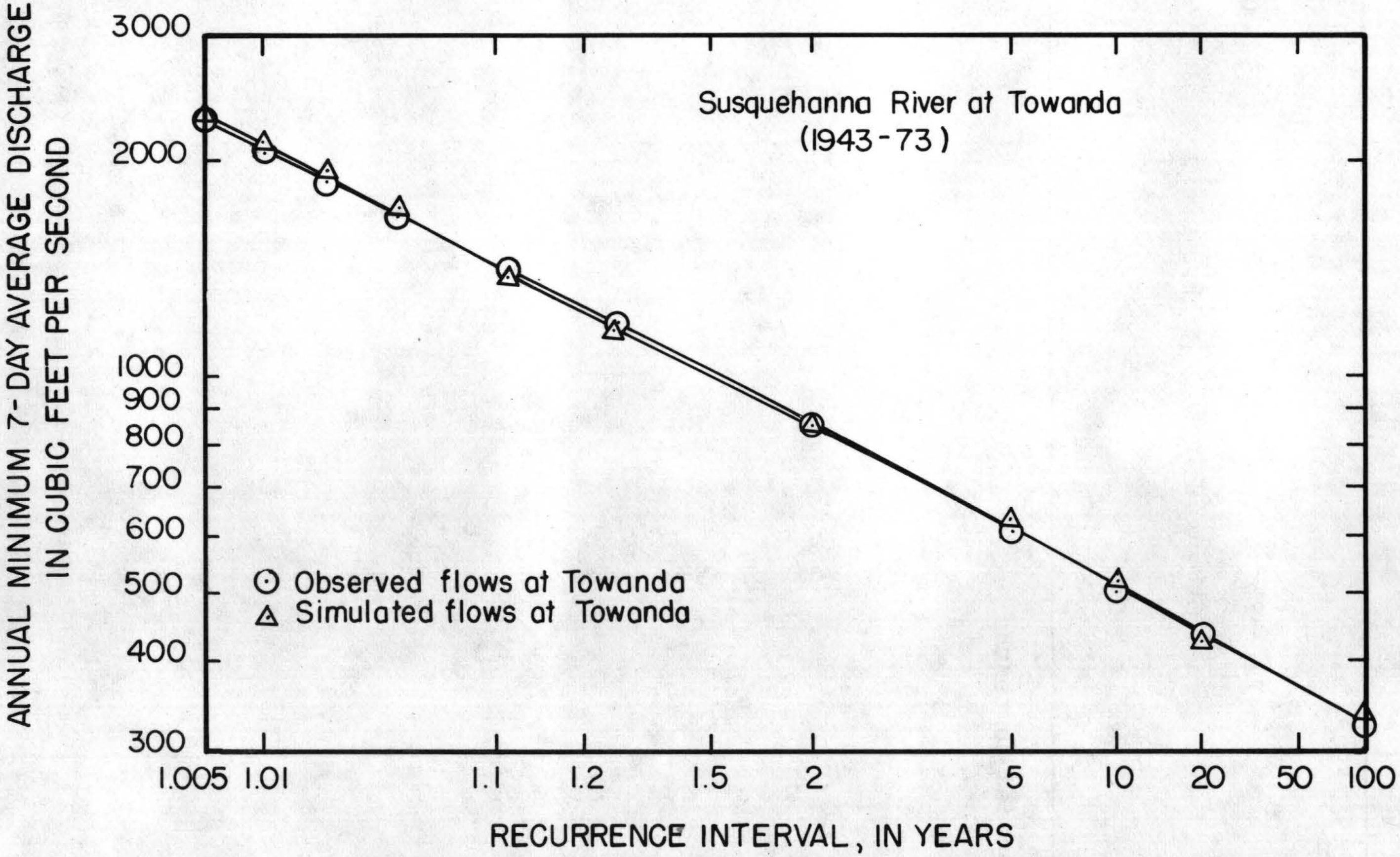


Figure 6.--Seven-day low-flow frequency curves computed from observed and simulated daily flows for station 01531500.

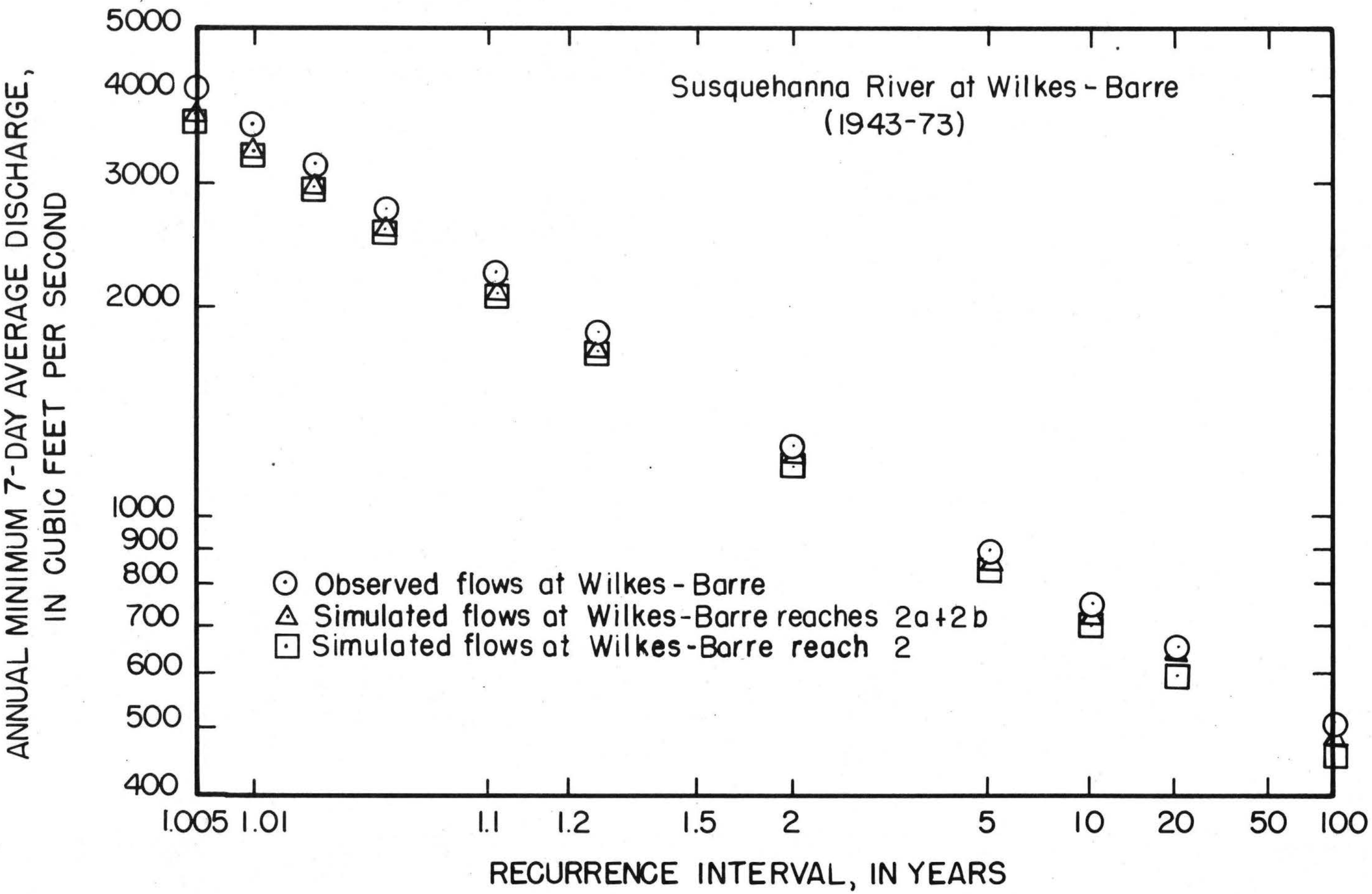


Figure 7.--Seven-day low-flow frequency curves computed from observed and simulated daily flows for station 01536500.

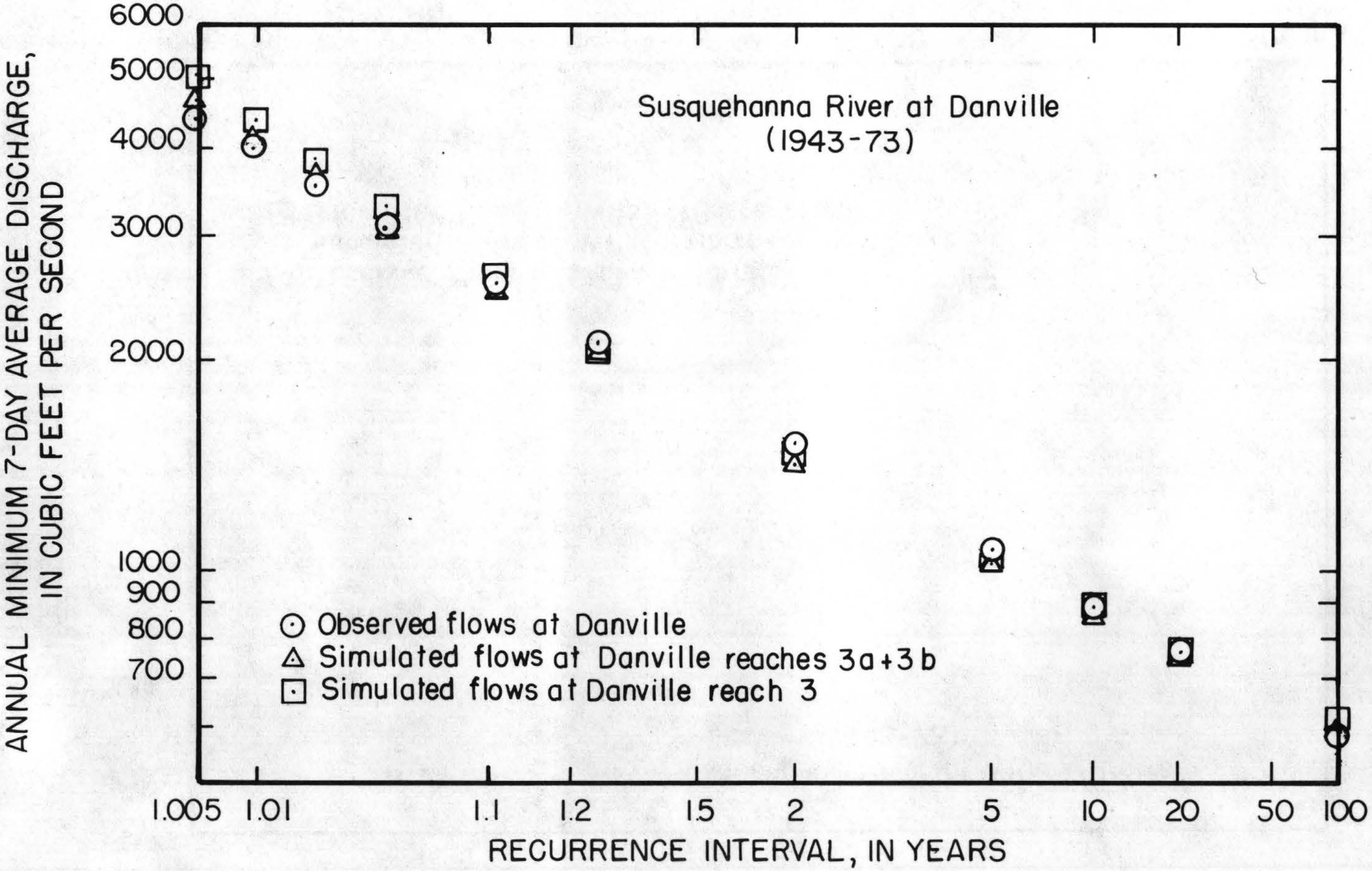


Figure 8.--Seven-day low-flow frequency curves computed from observed and simulated daily flows for station 01540500.

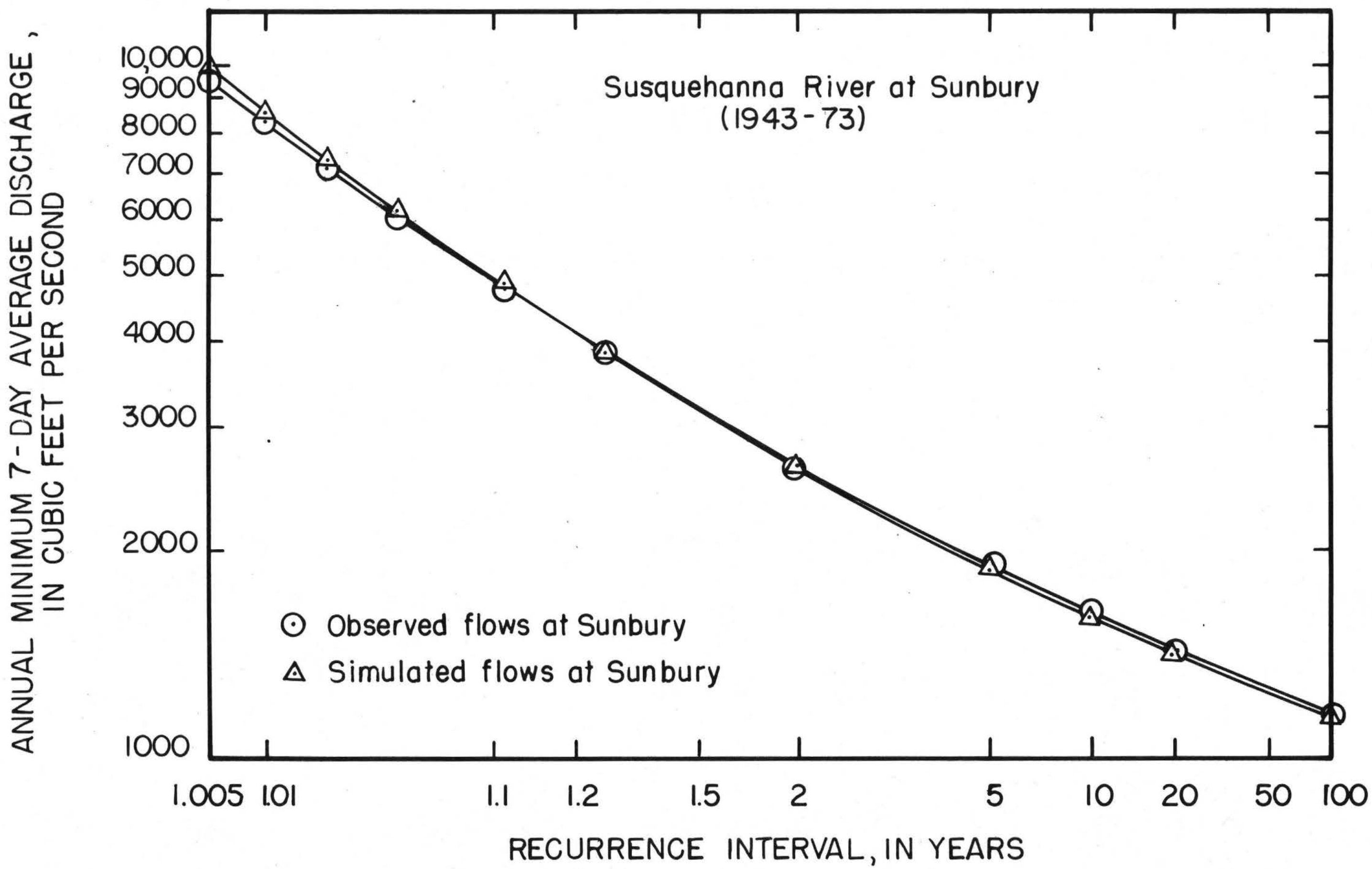


Figure 9.--Seven-day low-flow frequency curves computed from observed and simulated daily flows for station 01554000.

Table 5.--Summary of average absolute errors between observed and simulated annual minimum flows

Station	Average absolute error of annual minimum flows, in percent		
	1 day	3 day	7 day
Towanda 01531500	5.87	5.55	5.38
Wilkes-Barre 01536500	9.64	9.21	9.01
Danville 01540500	7.36	7.21	6.83
Sunbury 01554000	4.61	4.50	4.25

Without observed flow data, low-flow frequency curves for sites A and B cannot be verified. However, the curves may still be useful for estimating the 7-day low-flow at the 10-year recurrence interval ($Q_{7,10}$). Figures 10 and 11 present the 7-day low-flow frequency curves computed from streamflow data simulated for sites A and B. These relations yield estimates for $Q_{7,10}$ as shown in table 6. Also shown in table 6 are estimates of $Q_{7,10}$ for the four gaged sites, based on observed data for 1942-1973. Armbruster (1976) presents a method for estimating low-flow frequency characteristics that is based on multiple regression techniques. Use of his method yields the estimates of $Q_{7,10}$ for sites A and B as well as the four gaged sites that are also shown in table 6. Armbruster indicated that the average length of record for major stream stations was 55 years. The shorter period (1942-1973) used in this report puts more emphasis on the drought of the 1960's, resulting in lower estimates for $Q_{7,10}$.

Figures 12-15 present flow-duration curves of observed and simulated data for stations 01531500, 01536500, 01540500, and 01554000. It can be seen that good agreement exists between the observed and simulated flows for the entire flow range at all four stations. Therefore, the models are judged adequate at the four gaged sites over the entire range of flows.

APPLICATION OF MODELS

The model development, calibration, and verification procedure yielded a 32-year record of simulated flows at ungaged sites A and B that can be put to immediate application. For example, the low-flow frequency characteristics curves at sites A and B (fig. 10 and 11) can be used to estimate, at the 10-year recurrence interval, 7-day low-flow values of 540 and 770 ft^3/s, respectively. Other analyses of the simulated streamflows such as flow duration curves (fig. 16 and 17) can be made to estimate additional flow characteristics. Also, additional frequency analyses could be made to estimate high-flow and low-flow characteristics for time periods other than seven days. The reader must assess the applicability of any such estimates giving consideration to the fact that model results at sites A and B cannot be verified by observed flow data.

In the future, modified streamflows at Waverly (for example, by an upstream reservoir whose effects on flow at Waverly are known) can be routed downstream to assess effects of the water resource development on streamflows at downstream locations.

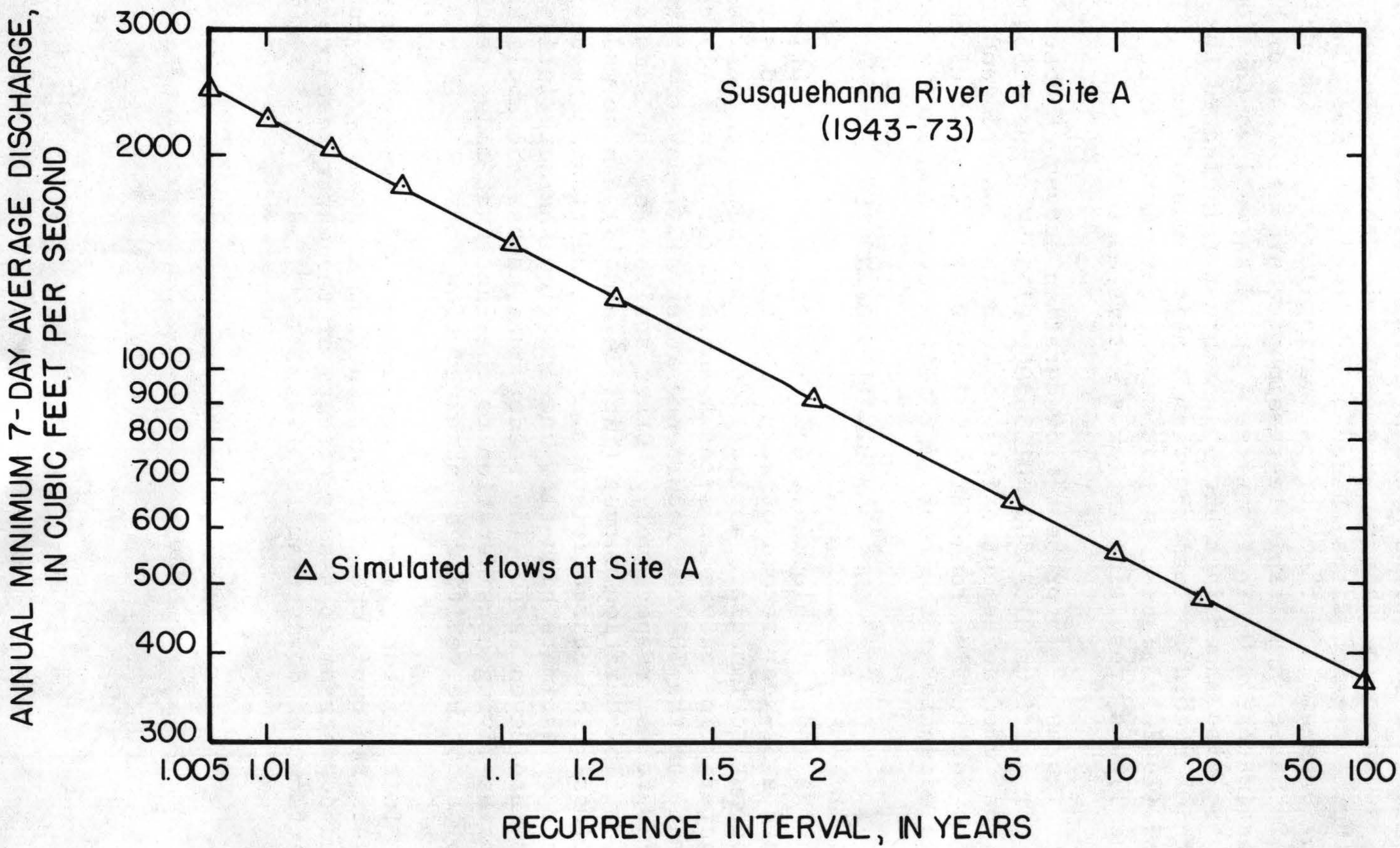


Figure 10.--Seven-day low-flow frequency curve computed from simulated daily flows at Site A.

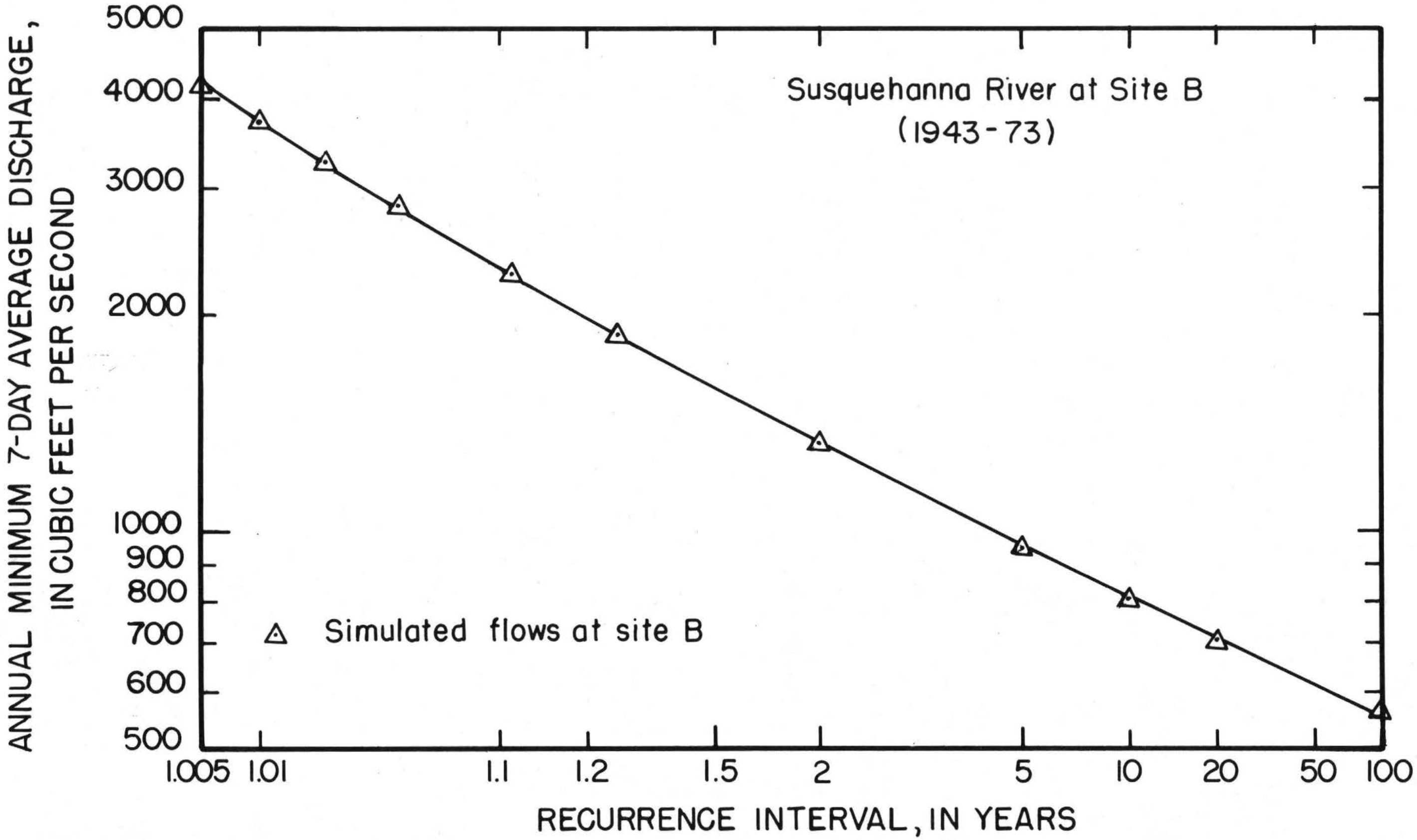


Figure 11.--Seven-day low-flow frequency curve computed from simulated daily flows at Site B.

Table 6.--Comparison of computed 7-day low-flows at the 10-year recurrence interval

Station	$Q_{7,10}$ in cubic feet per second: from 1942-73 data	$Q_{7,10}$ in cubic feet per second: from Armbruster (1976)
Towanda (01531500)	508 2/	638
Site A	540 1/	730
Wilkes-Barre (01536500)	752 2/	832
Site B	770 1/	860
Danville (01540500)	894 2/	945
Sunbury (01554000)	1630 2/	1609

1/ From frequency curves of simulated daily flows.

2/ From frequency curves of observed daily flows.

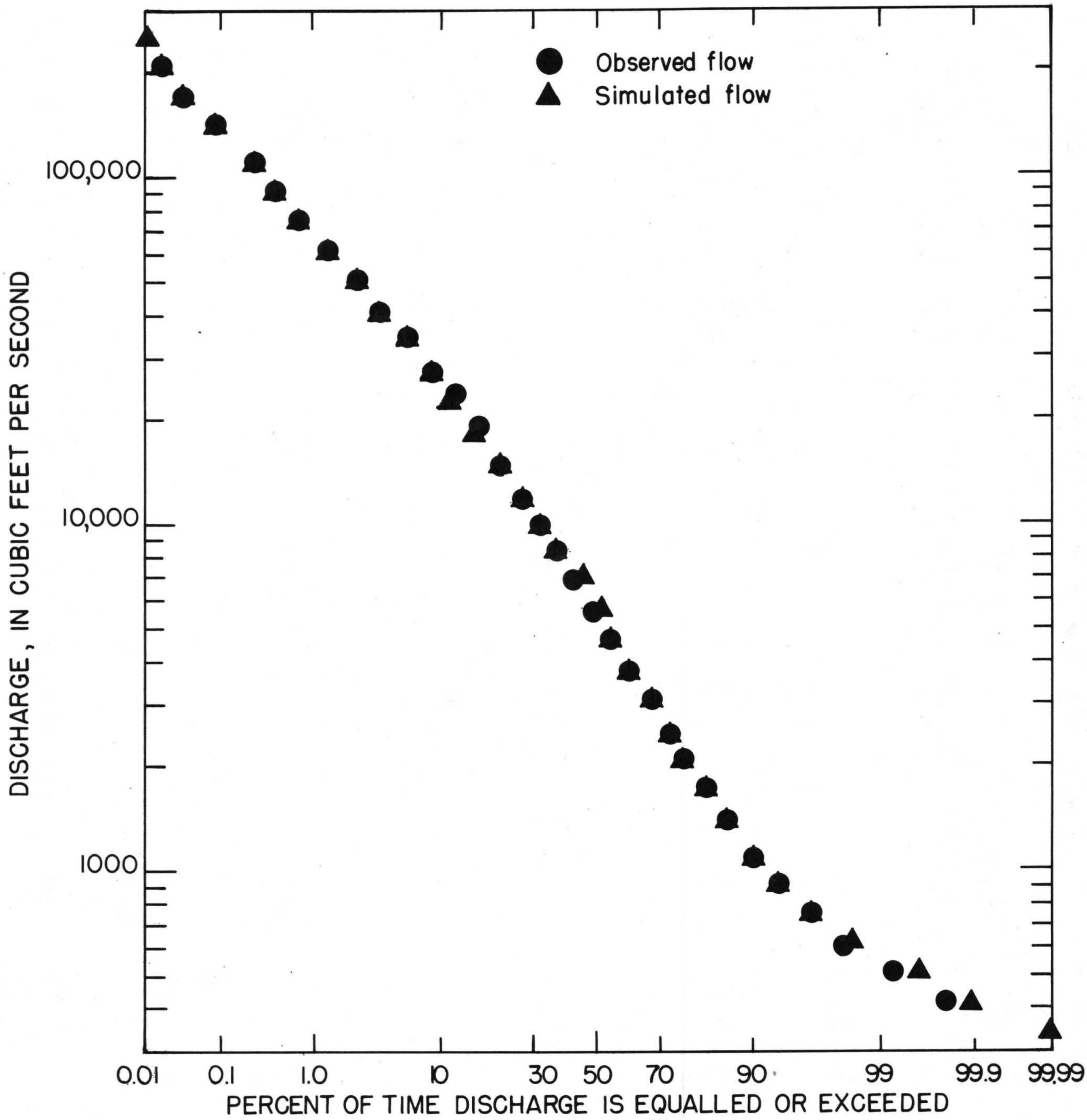


Figure 12.--Flow-duration curves of observed and simulated daily flows for station 01531500.

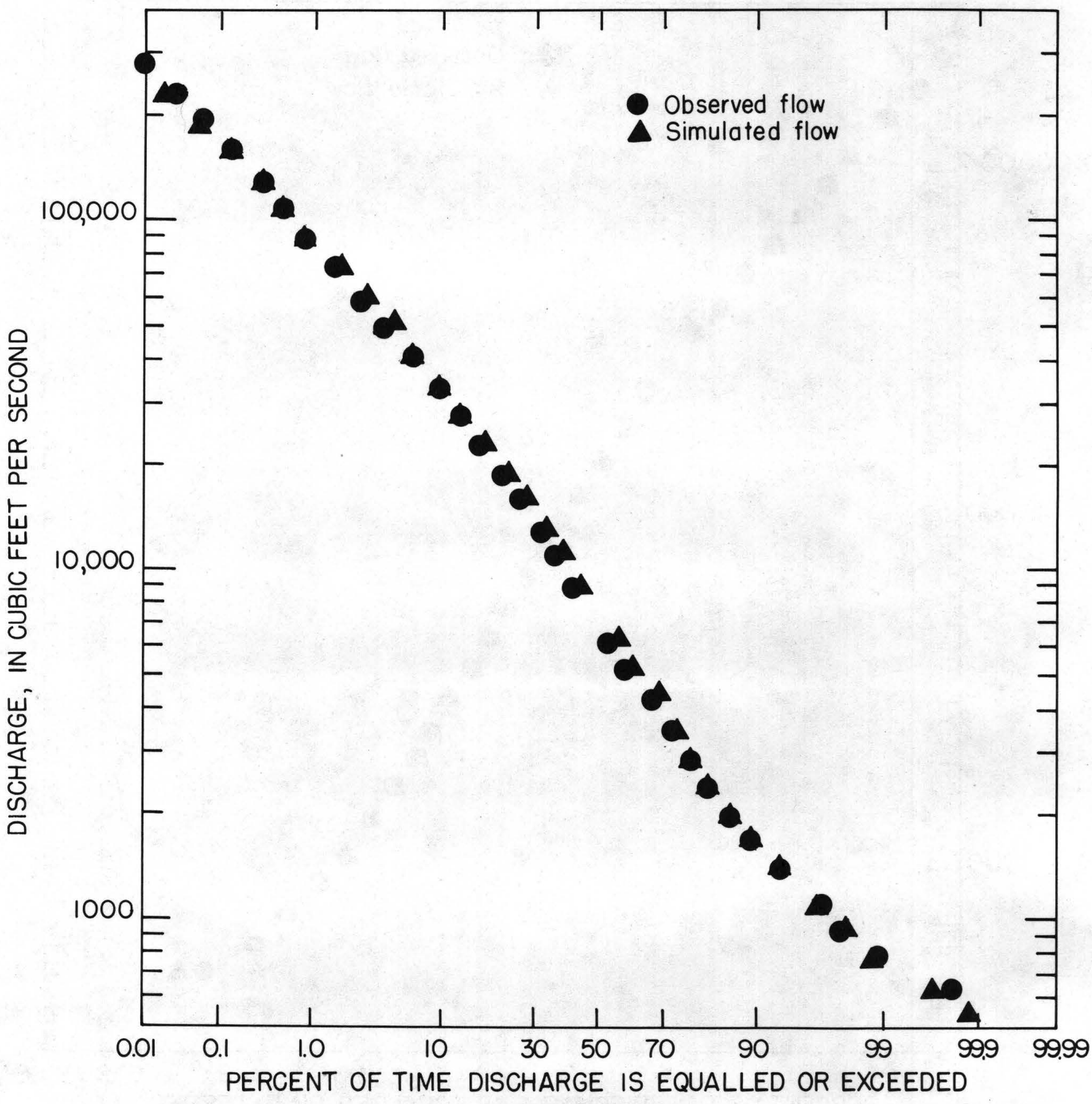


Figure 13.--Flow-duration curves of observed and simulated daily flows for station 01536500.

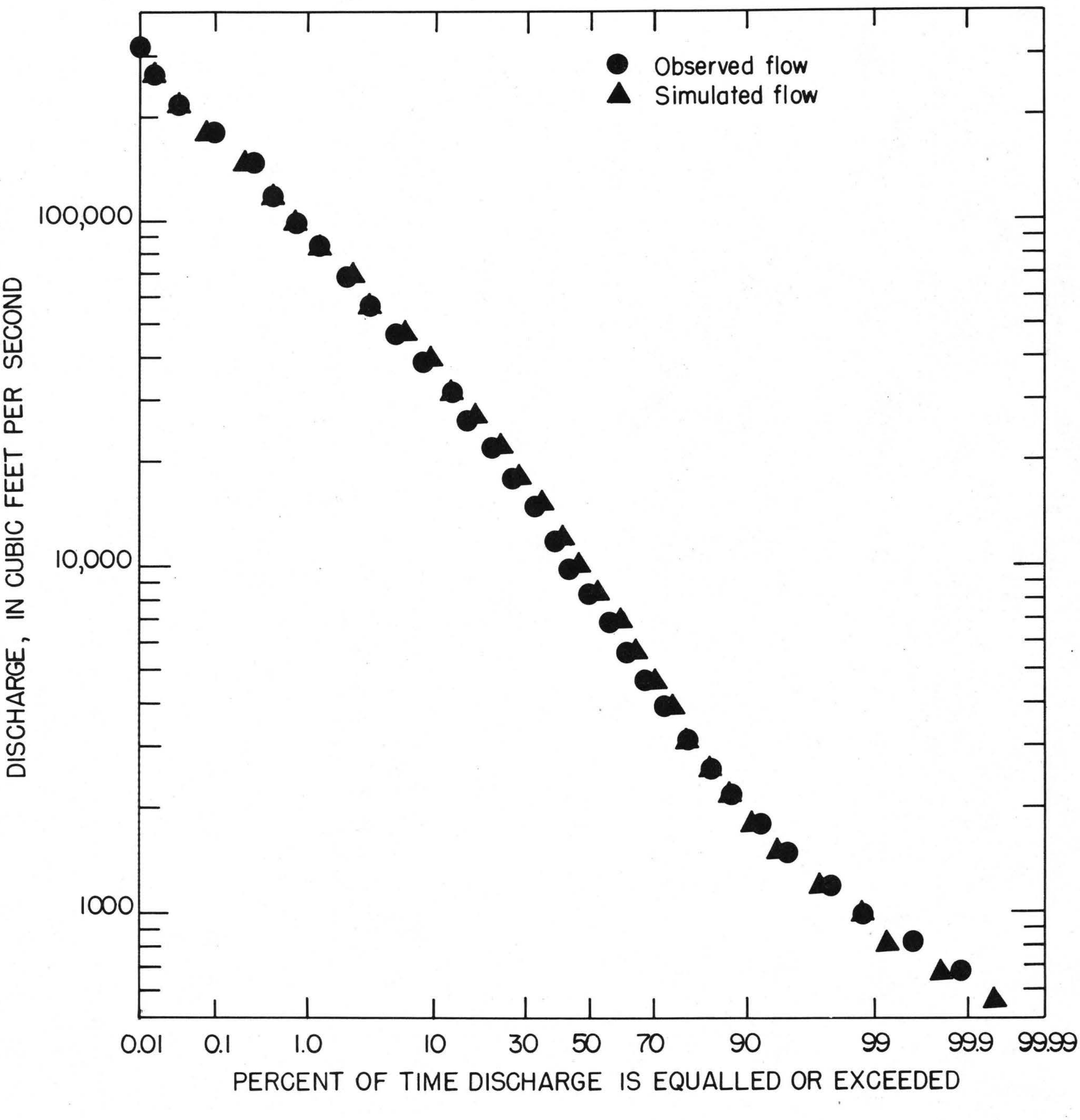


Figure 14.--Flow-duration curves of observed and simulated daily flows for station 01540500.

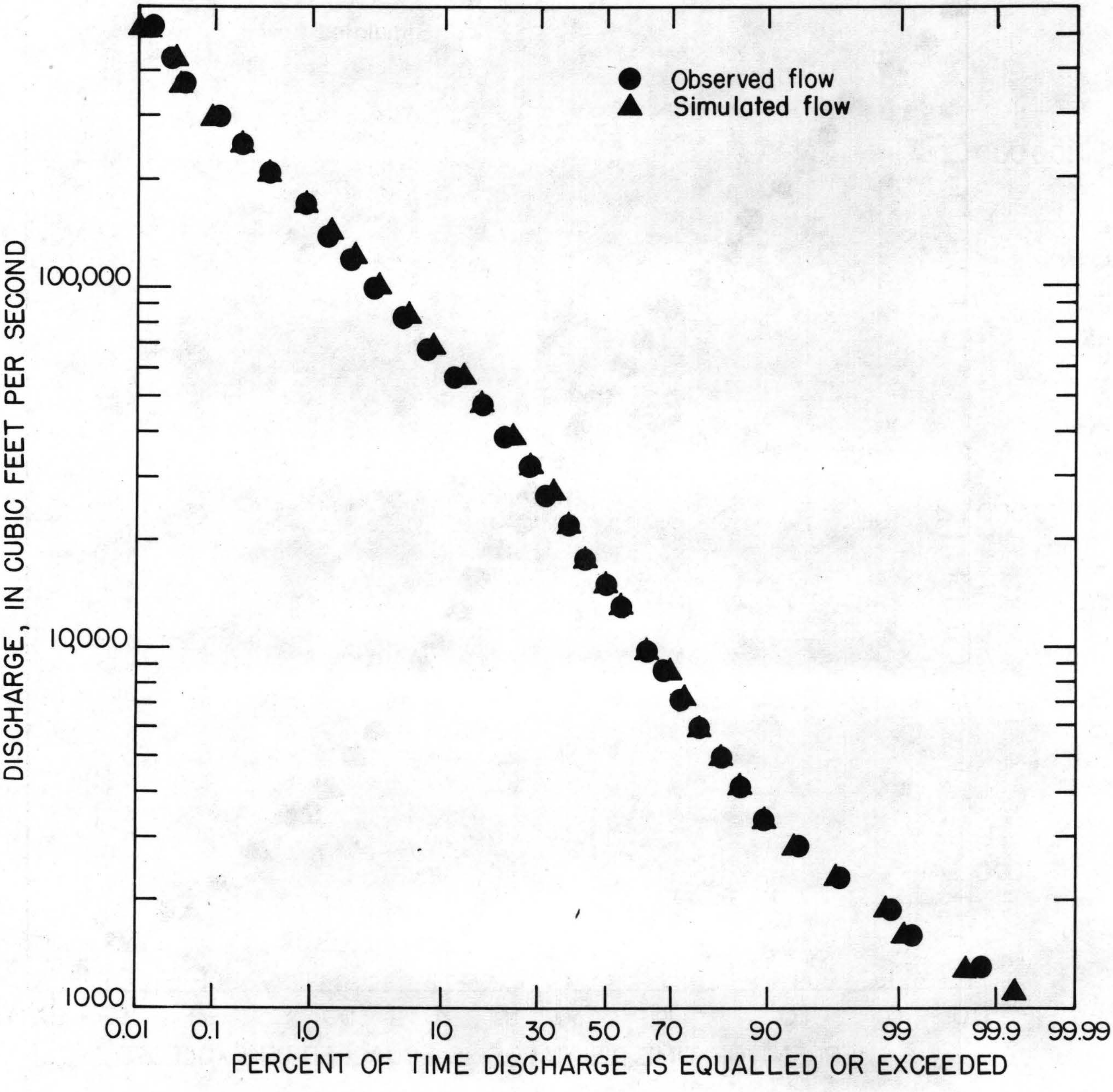


Figure 15.--Flow-duration curves of observed and simulated daily flows for station 01554000.

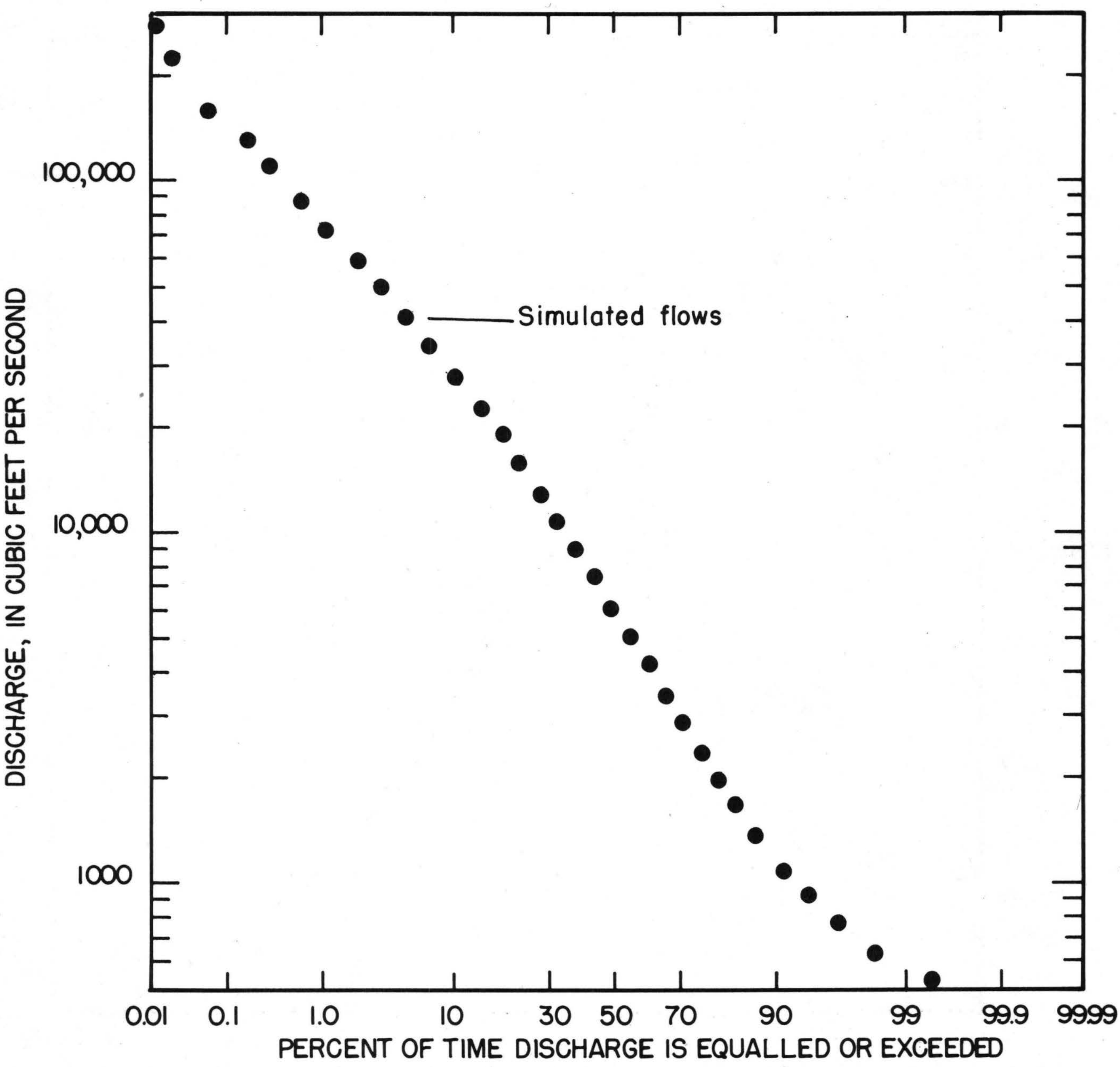


Figure 16.--Duration curve of simulated daily flows at Site A.

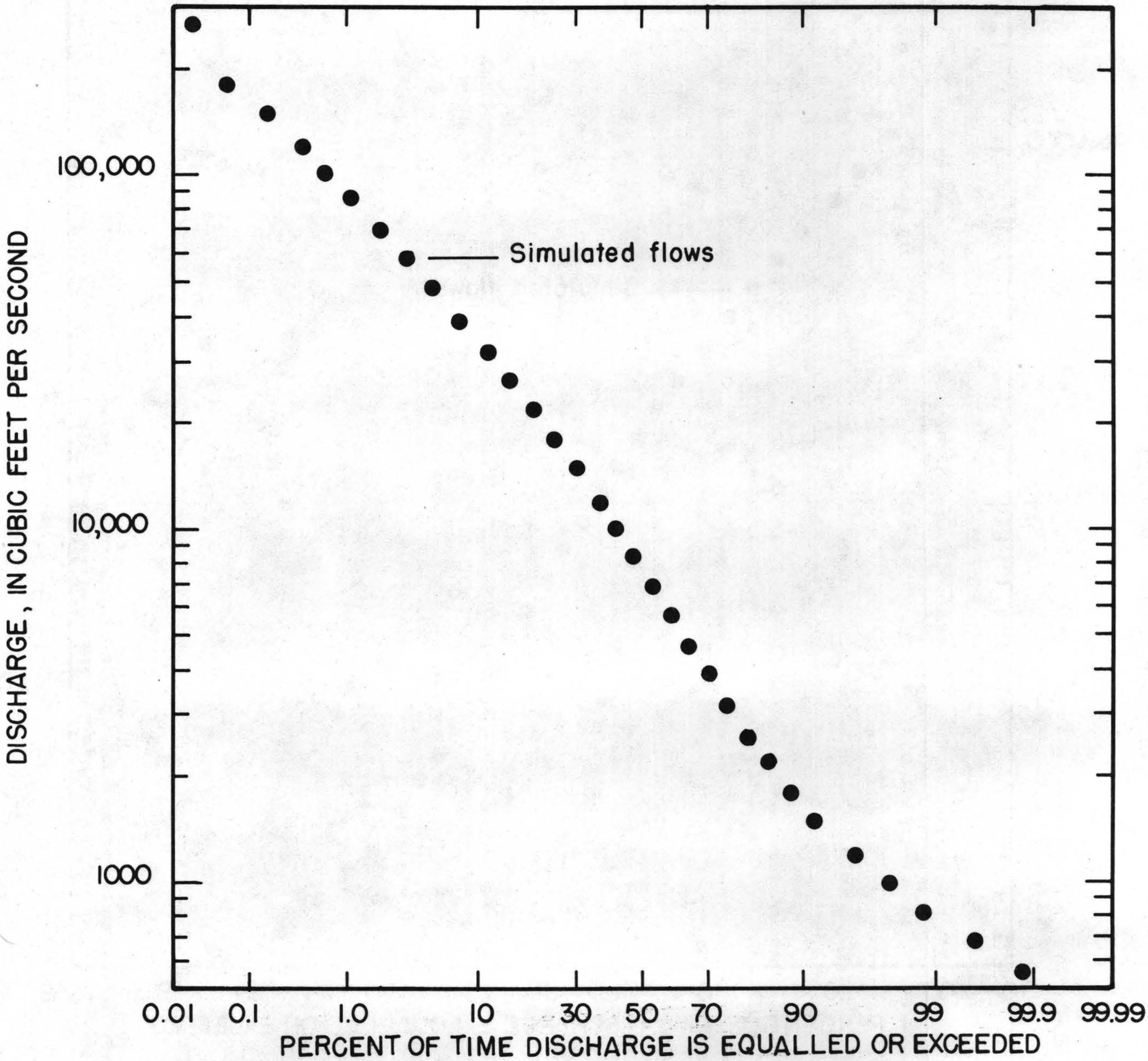


Figure 17.--Duration curve of simulated daily flows at Site B.

SUMMARY

Flow-routing models for six reaches of the Susquehanna River between Waverly, New York, and Sunbury, Pennsylvania, have been developed, calibrated, and verified. These models can be used to translate the effects of proposed water-resource developments upstream from Waverly to six sites within the study area. The models have already been used to simulate 32 years of flow data, for existing conditions, at two ungaged sites. These simulated data were used to estimate the low-flow characteristics at the two ungaged sites. At the 10-year recurrence interval, the 7-day low-flow at site A is estimated to be 540 cubic feet per second and at site B it is estimated to be 770 cubic feet per second. Low-flow frequency curves of simulated and observed data at the four gaged sites are in good agreement.

All flow-routing models contain some inherent errors, but these errors are within acceptable limits, indicating that the models are useful.

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