CALIBRATION AND VERIFICATION OF A STREAMFLOW SIMULATION MODEL FOR THE KENTUCKY RIVER NEAR LEXINGTON AND FRANKFORT, KENTUCKY

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ILLUSTRATIONS

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METRIC CONVERSIONS

Inch-pound units used in this report may be converted to International System of Units (SI) of measurements by the following conversion factors:

Multiply Inch-pound units	By	To obtain SI units
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second-day [$(ft^3/s)d$]	2,447	cubic meter (m^3)
foot (ft)	0.3048	meter (m)
mile (mi)	1.6093	kilometer (km)
square foot (ft^2)	0.0929	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)

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ABSTRACT

A streamflow-routing model was developed to simulate flows that could be used to evaluate stresses on the streamflow characteristics of the Kentucky River near Lexington and Frankfort, Kentucky. The river in the study area was divided into four reaches, and the model simulated daily streamflows at the downstream end of each reach.

Statistical analyses on the observed and simulated flows between October 1, 1940, and September 30, 1981, were compared to evaluate the model. Observed and simulated annual minimum 7-day average discharges compared satisfactorily. Frequency analyses showed the 7-day, 10-year simulated low flow values to be about 7 to 29 percent less than the observed flows. Flow duration curves showed very close comparison between observed and simulated discharges. These statistical results indicate the model was calibrated sufficiently to give reasonable simulated values.

INTRODUCTION

The Kentucky River is the source of water for Lexington and Frankfort, Ky., and existing problems with water quality and quantity will increase as these cities continue to grow. Decisions with regard to water-resources planning and management require sufficient information about the characteristics of the streamflow in these areas. A management tool to evaluate stresses on water supplies would be particularly valuable. Thus, a cooperative study between the U.S. Geological Survey and the Kentucky Geological Survey was initiated to develop a model that could be used to simulate flows on the Kentucky River between Lock 10 near Winchester and Lock 2 at Lockport.

Purpose and Scope

The purpose of this study was to simulate flows for that part of the Kentucky River near Lexington and Frankfort that could be used to evaluate stresses on the total flow characteristics of the stream.

The scope of this study was to adapt and calibrate an existing flow-routing model in order to simulate flows between October 1, 1940, and September 30, 1981, at four sites on the Kentucky River, downstream of Lock 10 near Winchester, Kentucky. These sites were:

1. Kentucky River at Lock 8, near Camp Nelson

2. Kentucky River at Lock 6, near Salvisa

3. Kentucky River at Lock 4, near Frankfort

4. Kentucky River at Lock 2, at Lockport

The daily streamflows simulated at these sites were analyzed statistically. These statistics were compared with statistics of observed records for the same time periods to provide an assessment of the model.

Acknowledgment

The author wishes to thank the Kentucky Utilities Company for providing information on Herrington Lake used in the study.

DESCRIPTION OF STUDY AREA

The Kentucky River basin is located entirely within Kentucky (fig. 1). The river originates in the mountainous terrain of southeastern Kentucky and flows northwesterly through the central part of the State to its junction with the Ohio River at Carrollton, Kentucky. The modeled reach of the river is in the lower part of the basin in the Bluegrass physiographic region (fig. 2). Surface elevations in the region are generally between 800 and 1,000 feet above sea level. The region is divided into the Inner Bluegrass, Eden Shale Belt, and Outer Bluegrass physiographic subdivisions. The Inner Bluegrass is in the central part of the region and is a gently rolling peneplain that is underlain by thick-bedded limestone. The Kentucky River and some of its tributaries are deeply entrenched in the limestone. Karst areas in the Inner Bluegrass have numerous sinkholes and extensive subsurface drainage systems. The Eden Shale Belt surrounds the Inner Bluegrass and is characterized by sharp ridges and narrow valleys. The Outer Bluegrass lies outside of the Eden Shale. These latter two areas are underlain by interbedded shale and limestone, have few sinkholes, and very little subsurface drainage.

Figure 1.--Location of study area and streamflow stations.

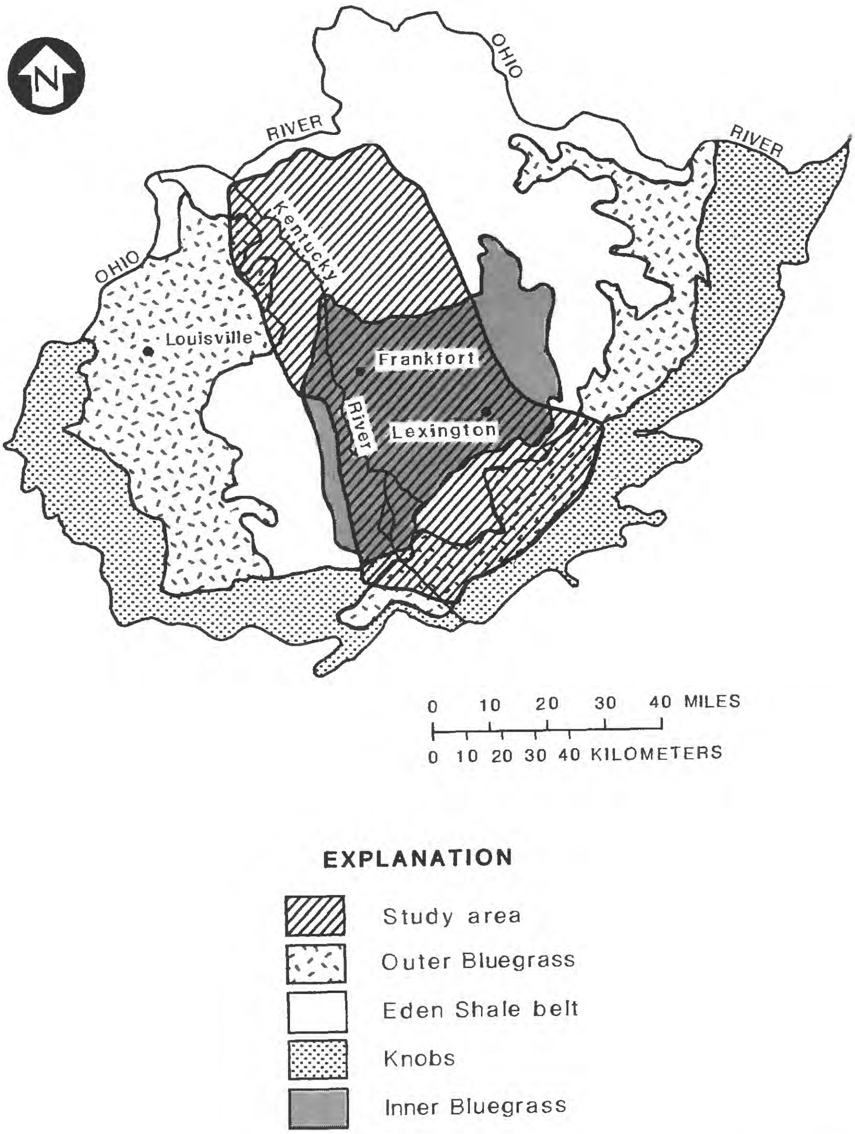

Figure 2.--Subdivisions of the Bluegrass physiographic region (modified from Karan, 1973).

DATA BASE

A large amount of streamflow information, for both regulated and non-regulated conditions, is available for the basin. Streamflow records used in the study were obtained from seven U.S. Geological Survey streamflow stations. The U.S. Geological Survey downstream order station numbers, station names, abbreviated site names, drainage areas, and periods of record are summarized in table 1 for these stations. The site locations are shown in figure 1, and also in a schematic diagram in figure 3.

Table 1.--Drainage areas and surface-water records used in the model

Station number	Station name	Name used in text	Drainage area (mi^2)	Water years of record
03283500	Red River at Clay City	Red River	362	1938-81
03284000	Kentucky River at Lock 10, near Winchester.	Lock 10	3,955	1907-81
03284500	Kentucky River at Lock 8, near Camp Nelson.	Lock 8	4,414	1939-71
03287000	Kentucky River at Lock 6, near Salvisa.	Lock 6	5,102	1925-81
03287500	Kentucky River at Lock 4, at Frankfort.	Lock 4	5,412	1932-81
03289500	Elkhorn Creek near Frankfort.	Elkhorn Creek	473	1941-81
03290500	Kentucky River at Lock 2, at Lockport.	Lock 2	6,180	1925-81

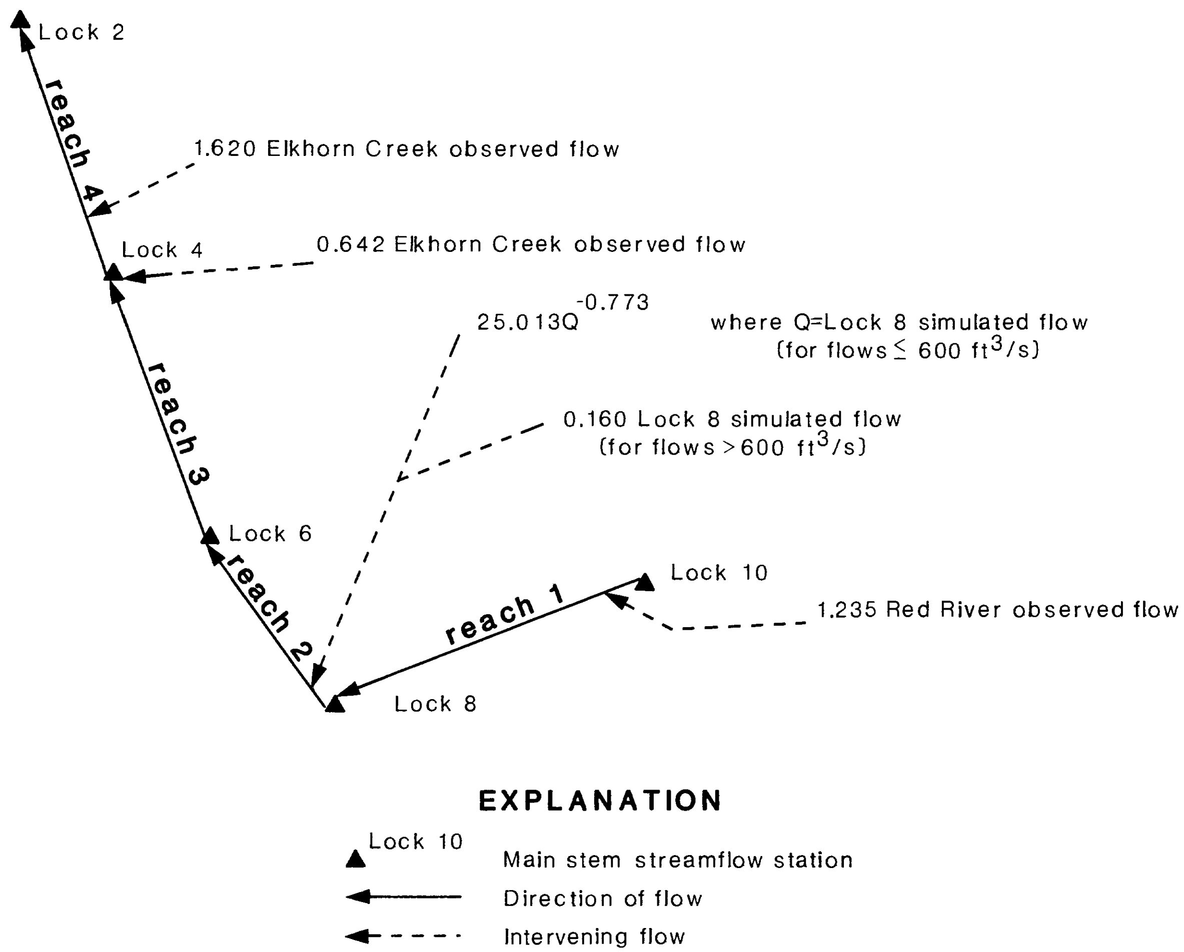

Figure 3.--Stream reaches and intervening flows used in model.

MODELING APPROACH

A U.S. Geological Survey computer model, CONROUT, was chosen for this study. The computer program was documented by Doyle and others (1983) and is based on the unit-response concept and convolution technique described by Sauer (1973). The unit-response functions are computed by the diffusion-analogy method developed by Keefer and McQuivey (1974). A unit-response function as determined by the diffusion-analogy method depends upon the reach length, the flood wave celerity (C_0), and the wave dispersion coefficient (K_0). Daily streamflow discharge data were used in computations for the model.

The unit-response function defines the discharge at the downstream end of a modeling reach as a function of present and prior discharges at the upstream end. The model computes an instantaneous unit-response function, which is a continuous function representing the time-distribution of downstream discharge resulting from an instantaneous upstream flow pulse. 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 ordinates 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 contributions of discharge at the upstream end from that day and each preceding day.

The diffusion-analogy method uses either single linearization or multiple linearization as the means of computing system response. The single linearization method was used to determine system response for this study. This method applies only one flood wave celerity and wave dispersion coefficient to each segment, thereby ignoring possible variation of these parameters with changing discharge. Resultant errors between observed and simulated flows obtained with the single linearization method were less than those errors obtained with the multiple linearization method.

Calibration and Verification of Model

The river in the study area was divided into four separate reaches for purposes of calibration, verification, and operation of the model. Figure 3 shows a diagram of these reaches and the intervening flow adjustments that were used within the reaches during the modeling.

Concurrent observed streamflow records are required at both the upstream and downstream ends of a reach for model calibration and verification. These concurrent records are necessary because simulated model output and observed daily streamflow values are compared to determine the validity of model results. Calibration and verification were performed with the most recent concurrent observed streamflow records to more accurately reflect the present-day stream conditions. The 1968 and 1969 water years were selected for calibration, and the 1970 and 1971 water years were chosen for verification of the four modeled reaches, because the Lock 8 gaging station was discontinued after 1971.

During the calibration and verification process, observed daily discharges were used in each reach for model input. Reach lengths were determined from differences in river mile locations of stream gages at both ends of each reach. These river mile locations were obtained from streamflow station records. Wave celerities were computed for both ends of the reaches and then averaged. Wave dispersion coefficients for each reach were computed on the basis of average reach width and slope (see Doyle and others, 1983, for computation procedures). These computed values were adjusted during model calibration to obtain the best possible agreement between simulated and observed daily discharges.

The intervening flows were estimated simultaneously with the calibration of C_0 and K_0. Intervening flows are defined as that volume of water entering the stream system between the upper and lower ends of the reach. Where possible, nearby tributary gaging stations were used as index stations. Index station flows were multiplied by a factor to estimate intervening flows. Using tributary stations (rather than main stem stations) as index stations is generally preferable because they are more likely to reflect the effects of the localized hydrologic conditions such as precipitation, runoff, and ground-water contribution. The initial value used for the multiplying factor was a straight drainage-area ratio of intervening ungaged drainage area to the drainage area of the index station. The multiplying factors were generally adjusted during the calibration process as necessary to improve the simulated results.

The Red River streamflow record was used to estimate intervening flows in reach 1. The best fit was obtained when a factor of 1.235 times the Red River daily discharge was added to Lock 10 observed flows, then the sum routed to Lock 8. This resulted in an 8.4 percent daily flow error when observed and simulated flows were compared at Lock 8.

Initial calibration in reach 2 showed the model underestimating flows of less than 600 ft^3/s when using a straight ratio of Lock 6 to Lock 8 drainage areas to estimate intervening flows. This was attributed mostly to the effects of Herrington Lake which discharges into this reach. The lake is used for peak power generation, and low flows are augmented by discharge from powerplant operations. During low flow, a greater percentage of the total volume of water is contributed to the main channel of the Kentucky River from Herrington Lake than during average and high flows. In addition, surface-storage problems associated with leakage and storage at the locks and dams are also a factor at low flows. Similar problems were noted by Shearman and Swisshlem (1973) in an upper Kentucky River basin study. The best results in reach 2 were achieved when the intervening flows between Locks 6 and 8 were computed by the following equation to adjust for a larger percentage of water being contributed from Herrington Lake at discharges less than or equal to 600 ft^3/s:

$$25.013(Q)^{-0.776}$$

where Q equals the Lock 8 simulated daily discharge.

A straight factor of 0.160 times the Lock 8 simulated daily flows was used for discharges greater than 600 ft^3/s. Lock 8 simulated flows were used to compute intervening flows in reach 2 to allow use of the model past the 1971 water year, and because initial calibration indicated insignificant differences between observed and simulated flows at Lock 8. These intervening flows were added to Lock 8 observed daily flows, then routed to Lock 6. A daily flow error of 15 percent was achieved for the calibration period.

During the calibration of reaches 3 and 4, Elkhorn Creek observed daily streamflow record was used to estimate intervening flows in both reaches. In reach 3 a factor of 0.624 times the Elkhorn Creek observed daily streamflows was added to Lock 6 observed flows that had been routed to Lock 4. A 9.6 percent daily flow error was obtained for the calibration period. A factor of 1.620 times the Elkhorn Creek daily discharge ratio added to Lock 4 observed flows then routed to Lock 2 resulted in a 9.7 percent daily flow error for reach 4. Table 2 summarizes the calibrated parameters determined for all reaches. Comparison of observed and simulated flows for the verification period agreed favorably with those of the calibration period.

Table 2.--Calibrated parameters determined for model

Reach	Begin (B) End (E)	Length (mi)	C_o (ft/s)	K_o (ft^2/s)	Intervening flows
1	(B) Lock 10 (E) Lock 8	36.5	7.250	49,800	1.235 times Red River observed daily discharge.
2	(B) Lock 8 (E) Lock 6	43.7	7.150	79,800	[a]$25.013(Q)^{-0.776}$, where Q equals the Lock 8 simulated daily discharge. [b]0.160 times Lock 8 simulated daily discharge.
3	(B) Lock 6 (E) Lock 4	30.4	9.750	76,400	0.624 times Elkhorn Creek observed daily discharge.
4	(B) Lock 4 (E) Lock 2	34.8	7.350	88,600	1.620 times Elkhorn Creek observed daily discharge.

[a]For flows less than or equal to 600 ft^3/s.
[b]For flows greater than 600 ft^3/s.

SIMULATION OF STREAMFLOW RECORDS AND MODEL EVALUATION

Flows were routed through the entire system after model calibration of the individual reaches. Observed flows were input at Lock 10, then the resulting simulated flows were routed through each subsequent reach for model operation. Table 3 summarizes both the model errors for the calibration phase (observed discharges input to each individual reach) and the model errors obtained when combining the four reaches into a system model (simulated input in all but the initial reach). Model errors usually tend to be cumulative when simulated flows are routed through consecutive reaches. Such is the case with this system. However, the cumulative model errors are not so large that the model is not applicable in the system mode of operation.

Table 3.--Comparison of calibration and model errors for the 1968-69 water years

Reach	Calibration error[1] (percent)		Model error[2] (percent)	
	Daily flow	Volume	Daily flow	Volume
1	8.4	-0.7	8.4	-0.7
2	15	1.5	16	.9
3	9.6	.1	17	.9
4	9.7	1.1	16	1.9

[1]Observed daily flow input at each reach for model calibration.
[2]Observed daily flow input at reach 1 and resulting simulated flow input at each consecutive reach for model operation.

Model summaries from October 1 to December 31, 1967, are given in table 4. This short period shows adequate model operation for a wide range of flows. Hydrographs in figures 4 to 7 show favorable comparisons between observed and simulated flows for this same period. Model summaries for the 1968-69 and 1970-71 water years are given in tables 5 and 6 to demonstrate results of model operation for longer periods.

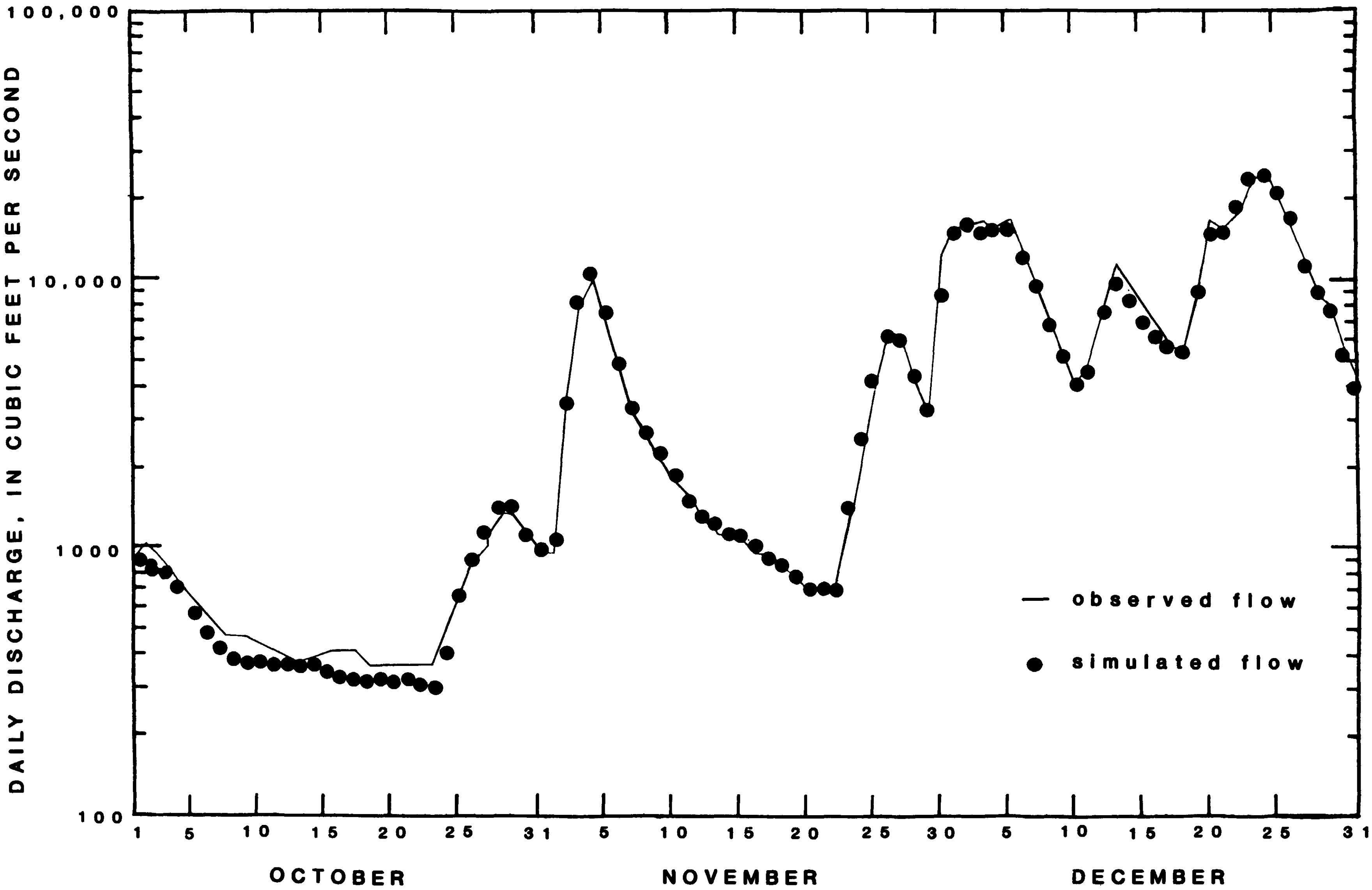

Figure 4.--Comparison of observed and simulated flows at Lock 8 from October 1 to December 31, 1967.

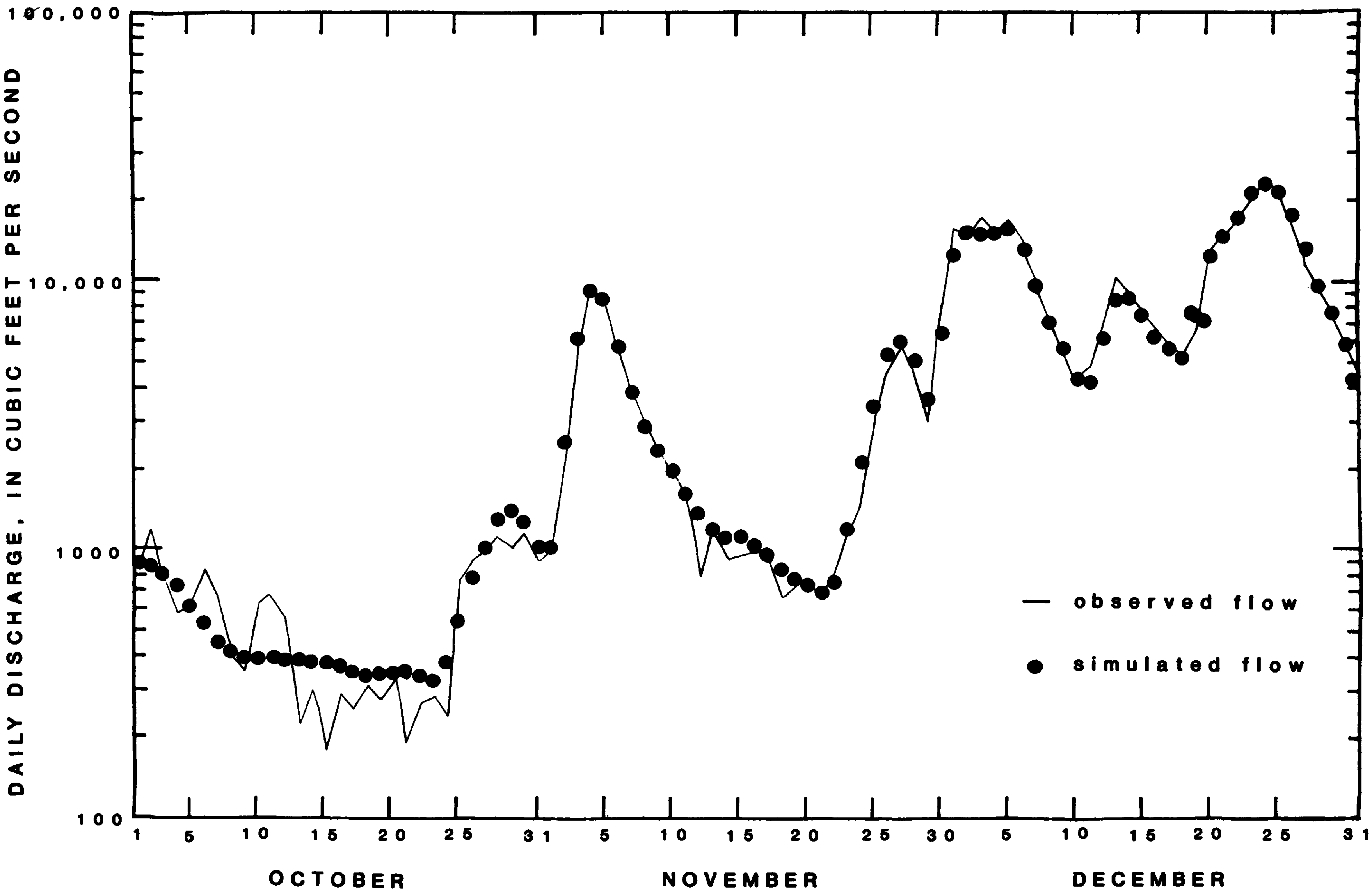

Figure 5.--Comparison of observed and simulated flows at Lock 6 from October 1 to December 31, 1967.

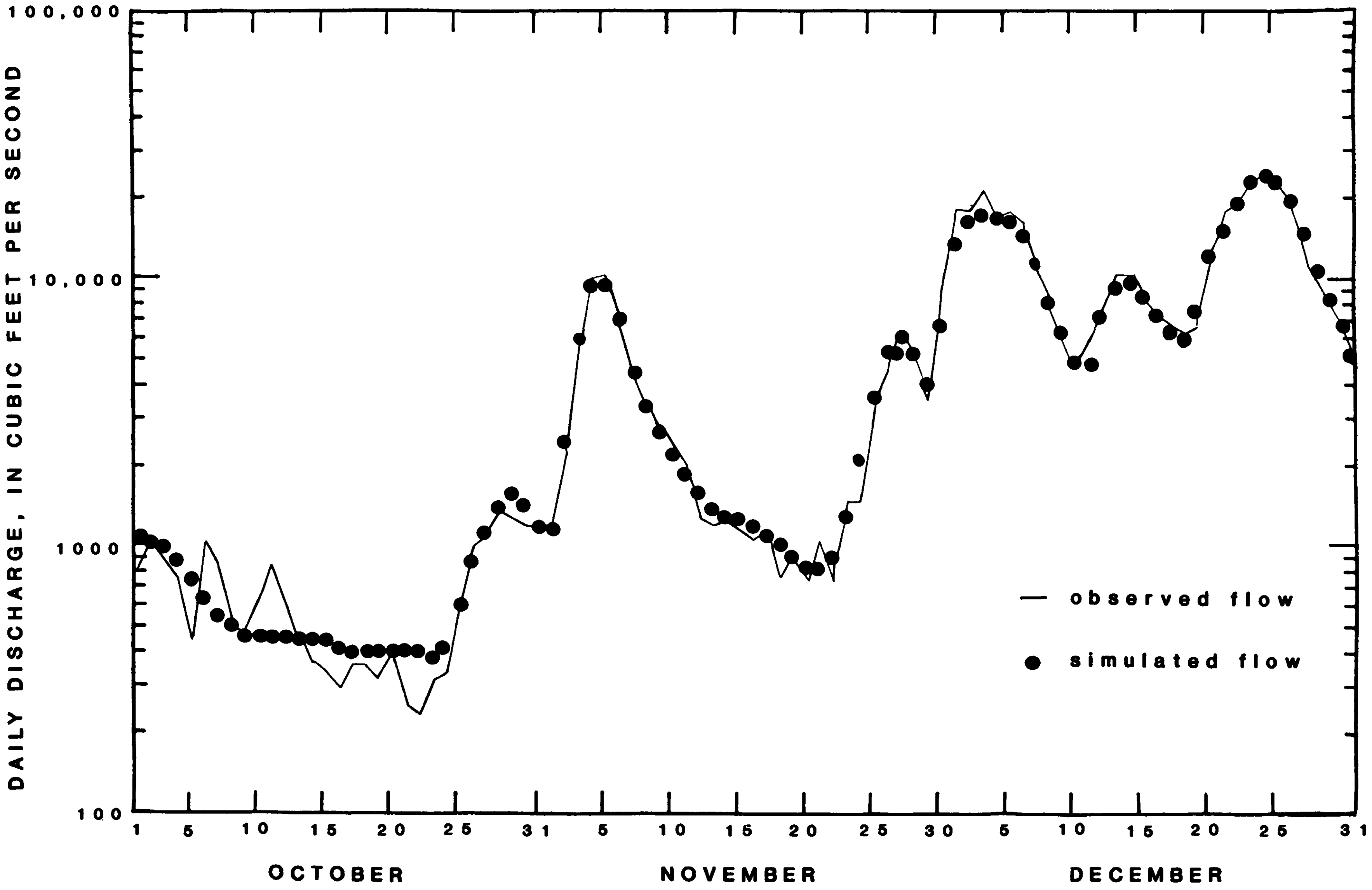

Figure 6.--Comparison of observed and simulated flows at Lock 4 from October 1 to December 31, 1967.

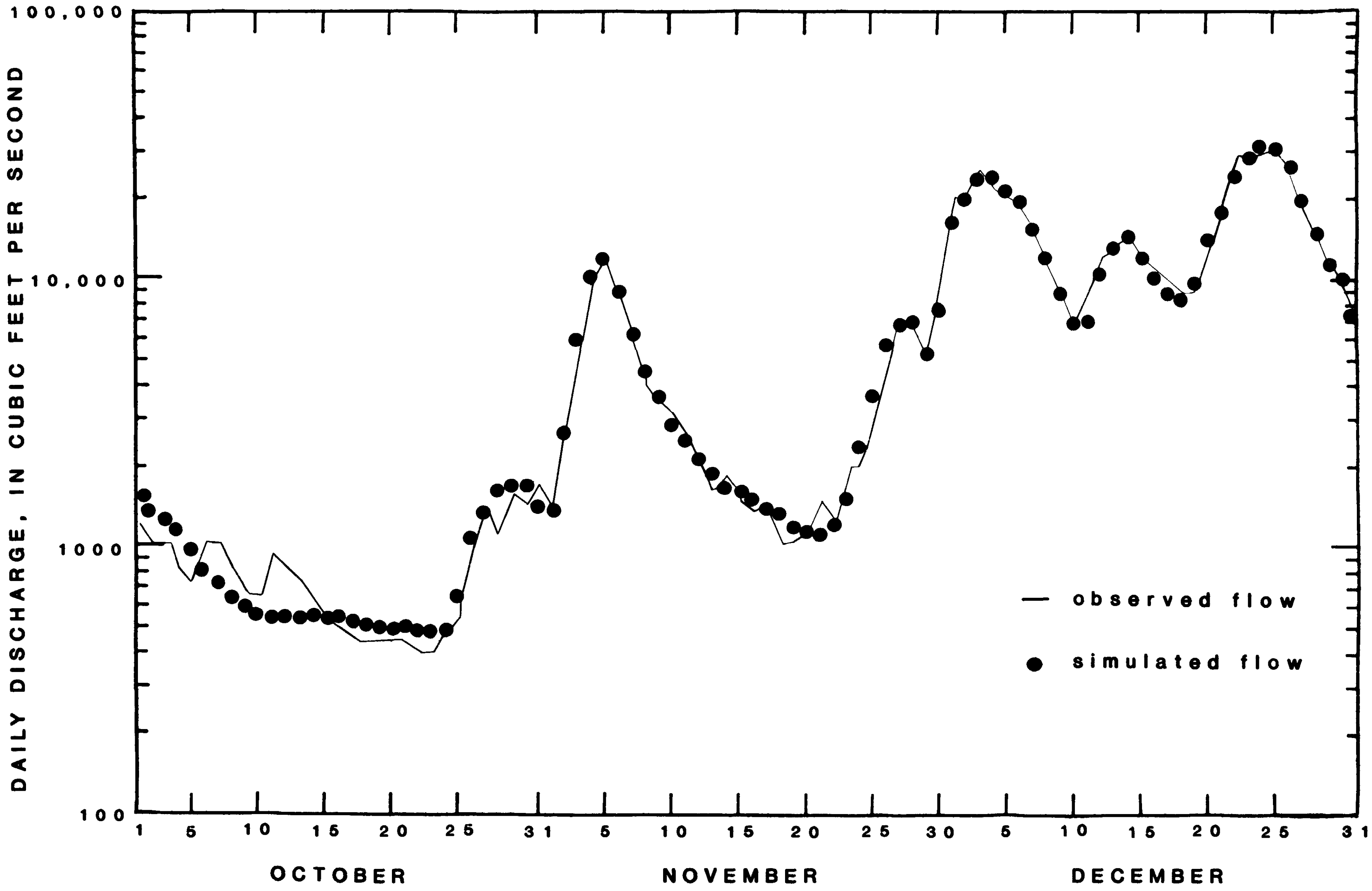

Figure 7.--Comparison of observed and simulated flows at Lock 2 from October 1 to December 31, 1967.

Table 4.--Model results for all reaches, October 1 to December 31, 1967

	Reach 1 (Lock 8)	Reach 2 (Lock 6)	Reach 3 (Lock 4)	Reach 4 (Lock 2)
Simulation period (days)	92	92	92	92
Mean error (percent)	7.7	16	14	13
Negative error days	54	39	45	43
Mean negative error (percent)	-9.0	-11	-11	-11
Positive error days	38	53	47	49
Mean positive error (percent)	5.8	19	18	14
Simulated volume [1,000 $(ft^3/s)d$]	431	500	529	606
Observed volume [1,000 $(ft^3/s)d$]	442	504	546	608
Volume error (percent)	-2.5	-.8	-3.1	-.4
Root mean square error (percent)	10	25	20	17
Errors in indicated range (percent)				
<5	44	36	32	25
5-10	24	16	15	25
10-15	20	12	17	16
15-25	6	6	9	10
20-25	3	8	9	9
>25	3	22	18	15

Table 5.--Model results for all reaches, 1968-69 water years

	Reach 1 (Lock 8)	Reach 2 (Lock 6)	Reach 3 (Lock 4)	Reach 4 (Lock 2)
Simulation period (days)	731	731	731	731
Mean error (percent)	8.4	16	17	16
Negative error days	299	297	273	284
Mean negative error (percent)	-7.3	-14	-15	-15
Positive error days	432	434	458	447
Mean positive error (percent)	9.2	18	19	17
Simulated volume [1,000 $(ft^3/s)d$]	3,102	3,604	3,843	4,461
Observed volume [1,000 $(ft^3/s)d$]	3,125	3,572	3,808	4,379
Volume error (percent)	-.7	.9	.9	1.9
Root mean square error (percent)	12	24	25	22
Errors in indicated range (percent)				
<5	45	22	21	20
5-10	25	22	19	19
10-15	14	20	18	19
15-25	7	11	13	15
20-25	4	7	8	8
>25	5	18	21	19

Table 6.--Model results for all reaches, 1970-71 water years

	Reach 1 (Lock 8)	Reach 2 (Lock 6)	Reach 3 (Lock 4)	Reach 4 (Lock 2)
Simulation period (days)	730	730	730	730
Mean error (percent)	9.8	17	18	18
Negative error days	264	364	373	344
Mean negative error (percent)	-8.1	-18	-18	-20
Positive error days	466	366	357	386
Mean positive error (percent)	11	16	18	16
Simulated volume [1,000 (ft^3/s)d]	4,200	4,875	5,149	5,862
Observed volume [1,000 (ft^3/s)d]	4,176	4,832	5,134	5,944
Volume error (percent)	1.6	1.9	.3	-1.4
Root mean square error (percent)	16	25	27	26
Errors in indicated range (percent)				
<5	41	24	24	24
5-10	27	20	19	17
10-15	14	15	14	13
15-25	6	11	10	12
20-25	4	8	9	9
>25	8	22	24	25

The model was operated for the 1940-81 water years and statistics were computed at Locks 8, 6, 4, and 2. Statistics on the observed and simulated flows at these sites were compared to evaluate the model. Comparisons could not be made at Lock 8 past the 1971 water year because observed flows were not available, but favorable comparisons at Locks 6, 4, and 2 indicate that the simulated flows at Lock 8 were adequate for the 1972-81 water years. Plots of the observed versus the simulated annual minimum 7-day average discharges are given in figures 8 to 11 and show satisfactory agreement. Frequency curves of the observed and simulated annual minimum 7-day discharges are in figures 12 to 15. At the 10-year recurrence interval the minimum 7-day average discharges computed from the simulated flows are about 7 to 29 percent less than the values computed from the observed flows. Flow-duration curves in figures 16 to 19 also show a reasonable agreement between the observed and simulated daily flows. These comparisons indicate that the model, as calibrated, adequately represents the stream system.

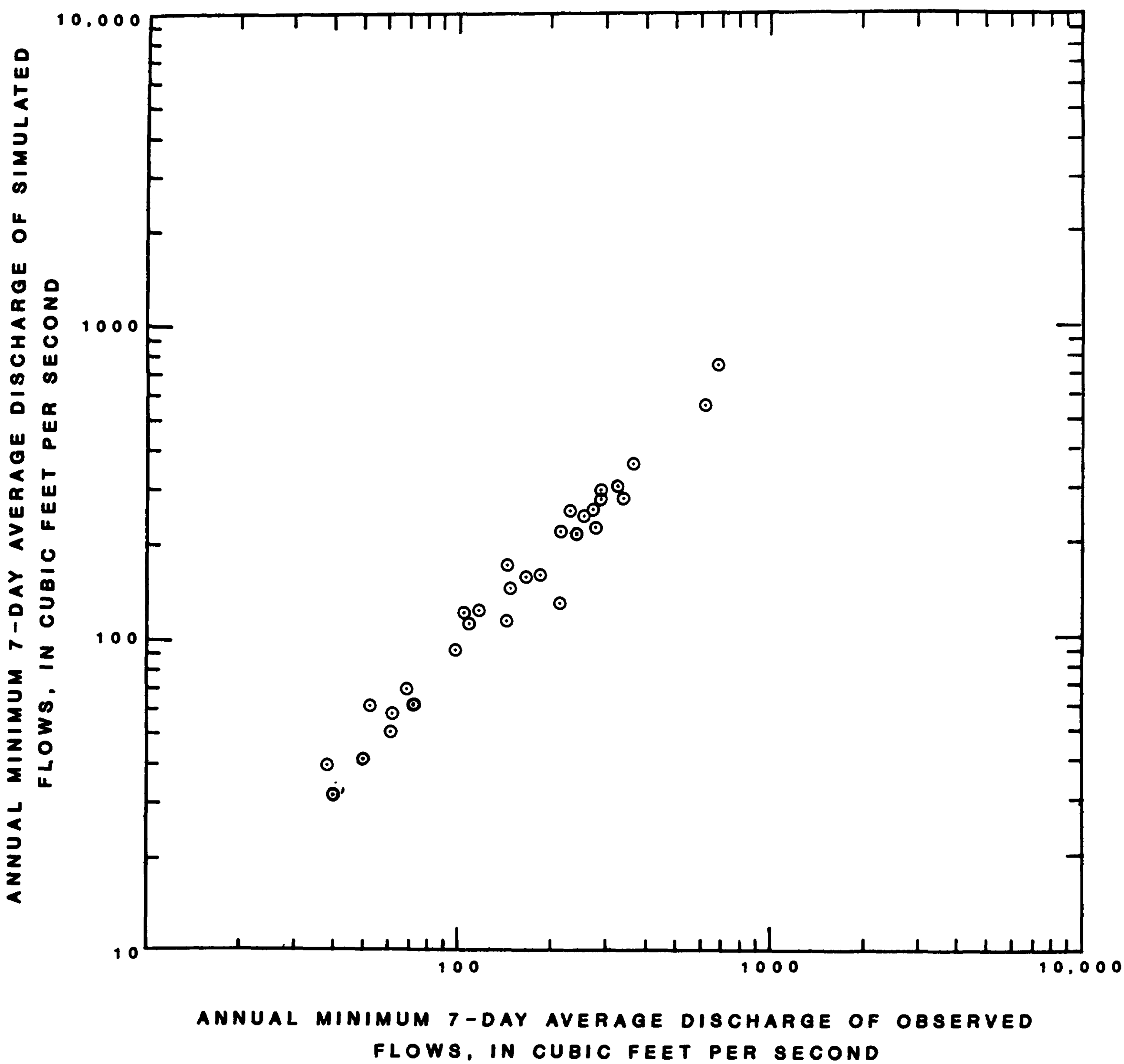

Figure 8.--Comparison of 7-day low flows at Lock 8, observed versus simulated flow, for the period 1941-71.

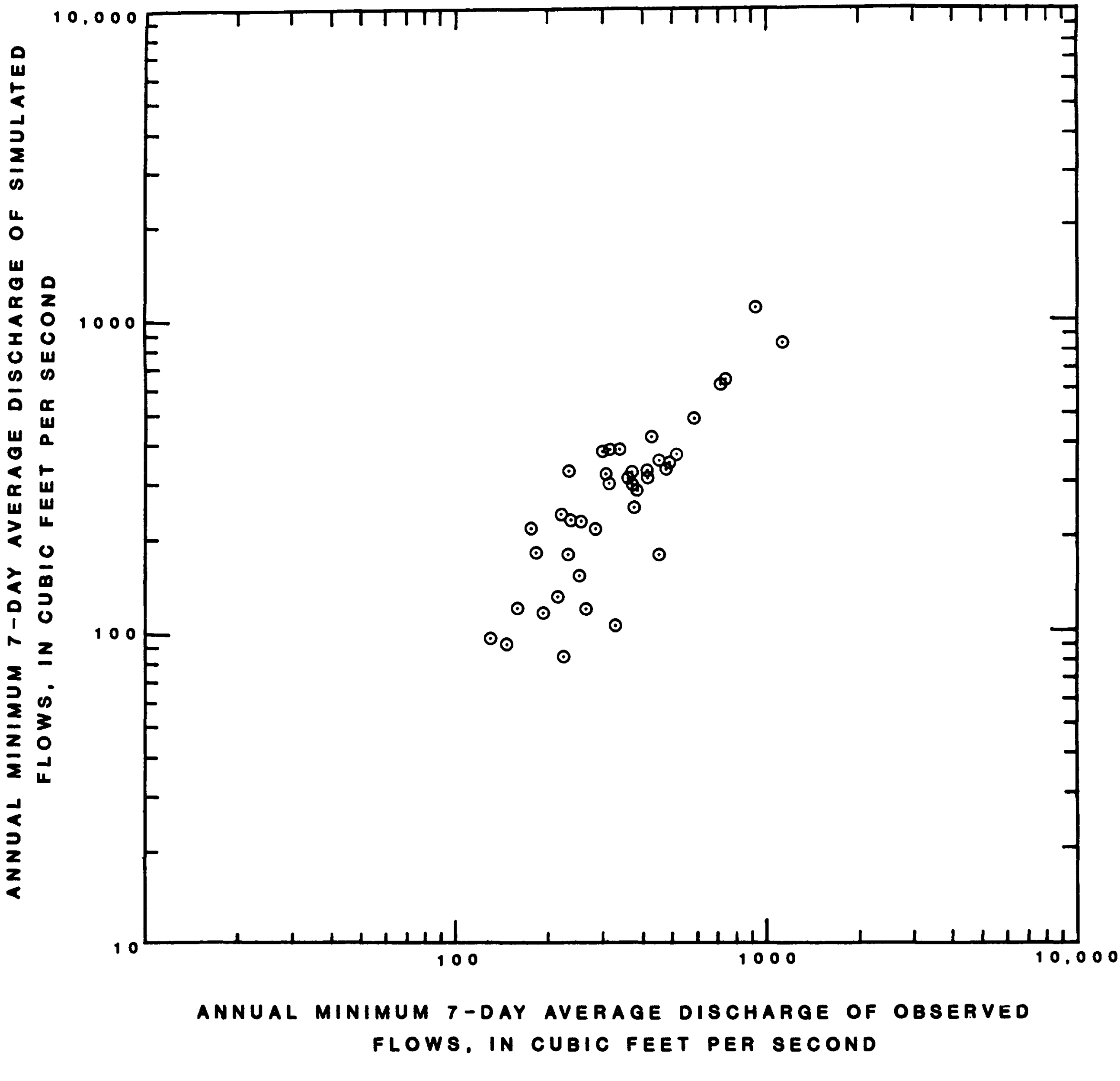

Figure 9.--Comparison of 7-day low flows at Lock 6, observed versus simulated flow, for the period 1941-81.

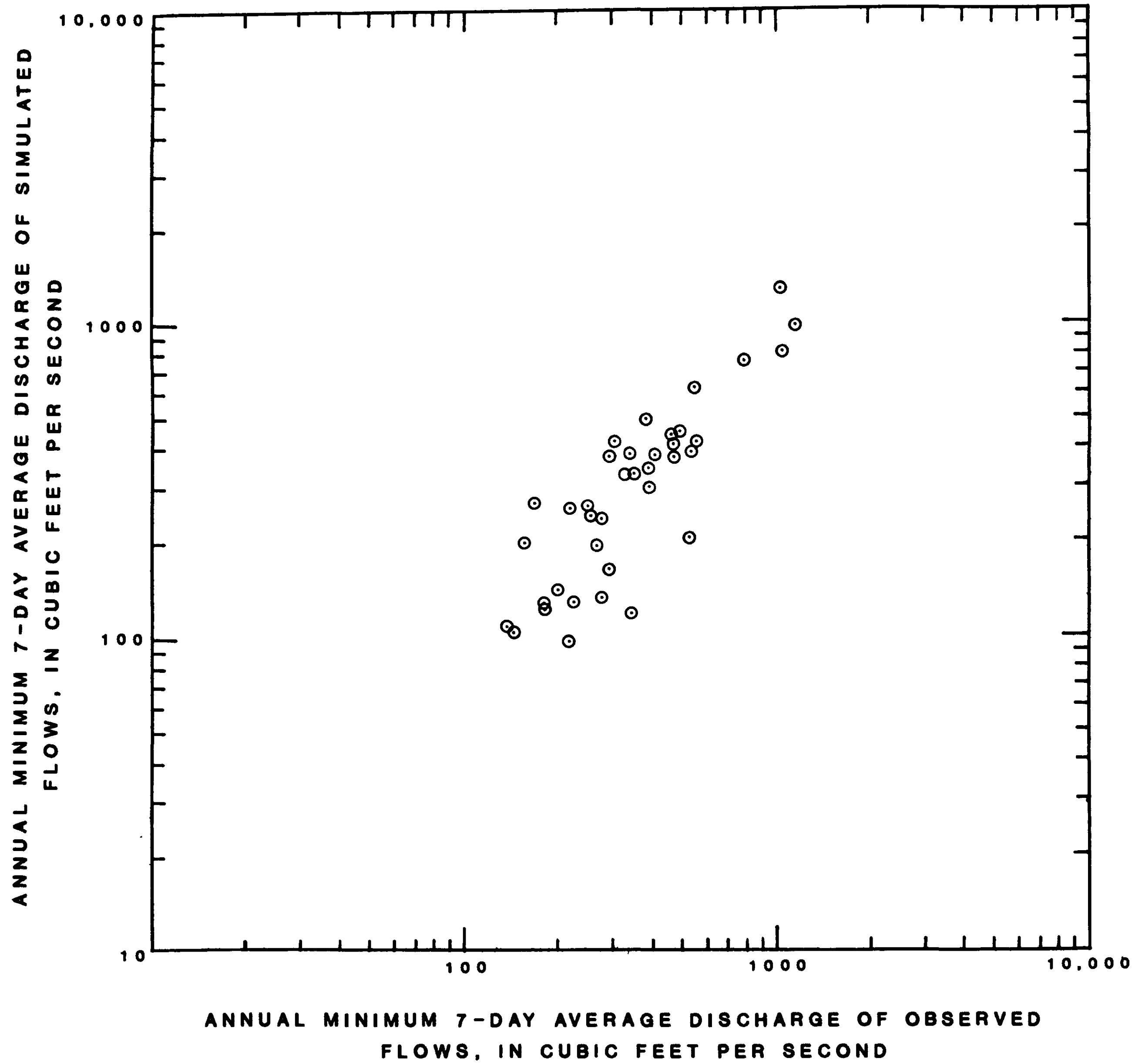

Figure 10.--Comparison of 7-day low flows at Lock 4, observed versus simulated flow, for the period 1941-81.

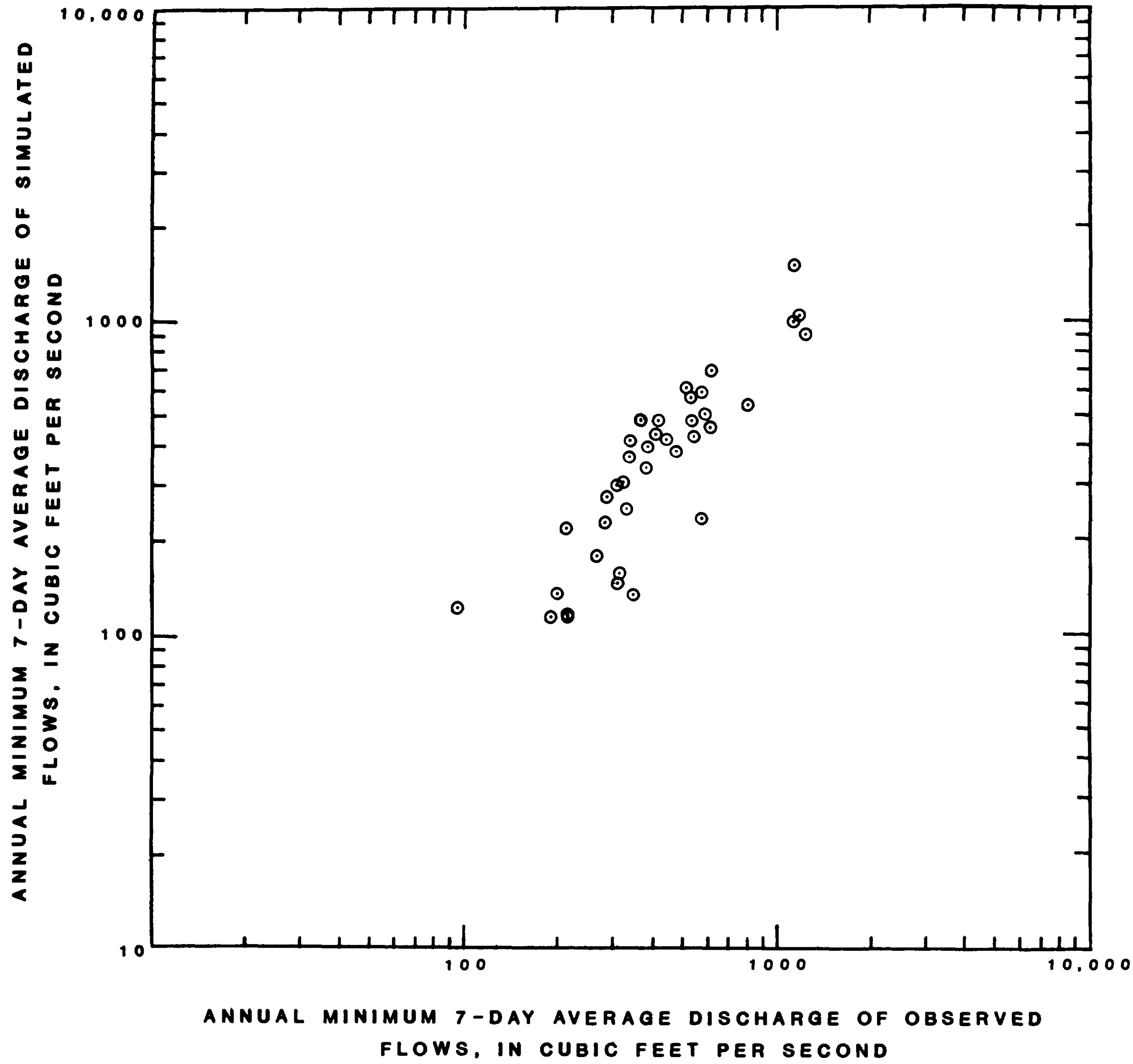

Figure 11.--Comparison of 7-day low flows at Lock 2, observed versus simulated flow, for the period 1941-81.

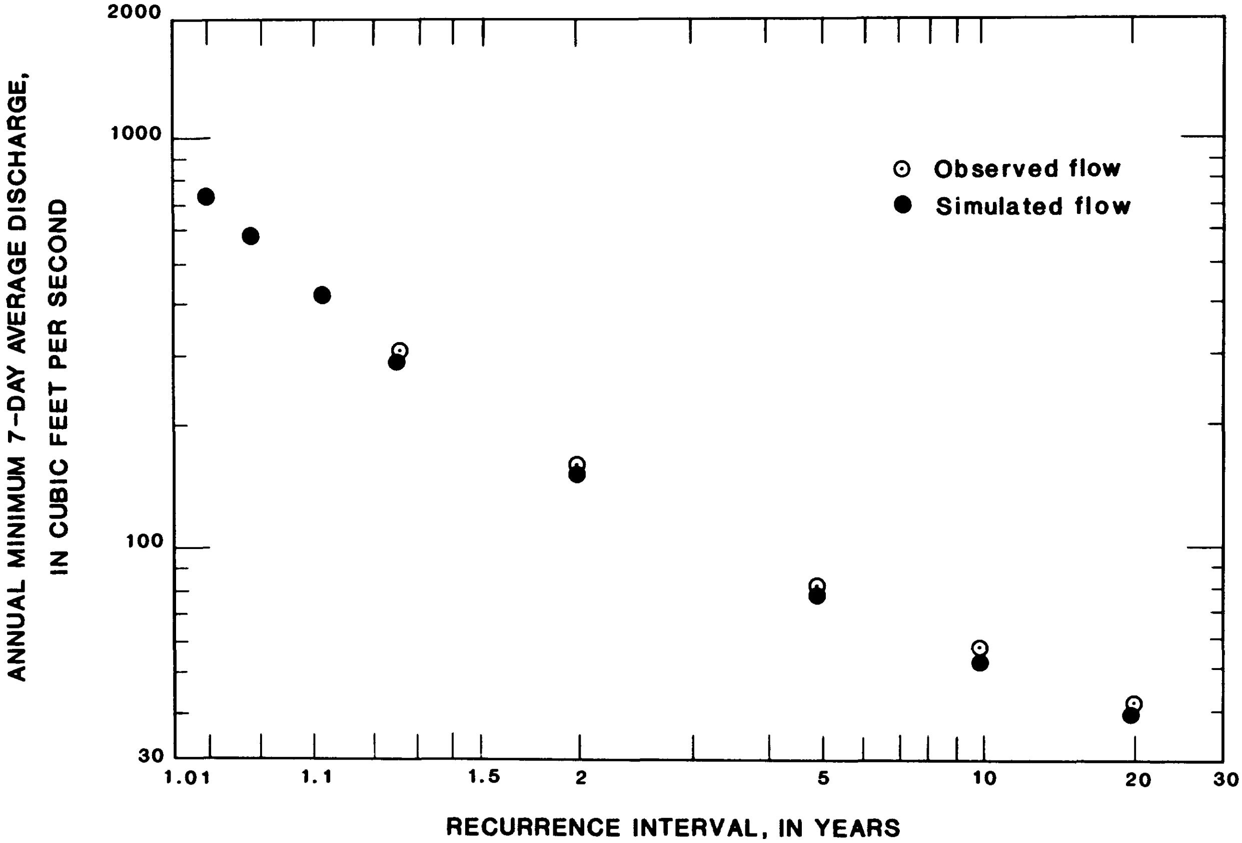

Figure 12.--Comparison of frequency curves of 7-day low flows at Lock 8, observed versus simulated, for the period 1941-71.

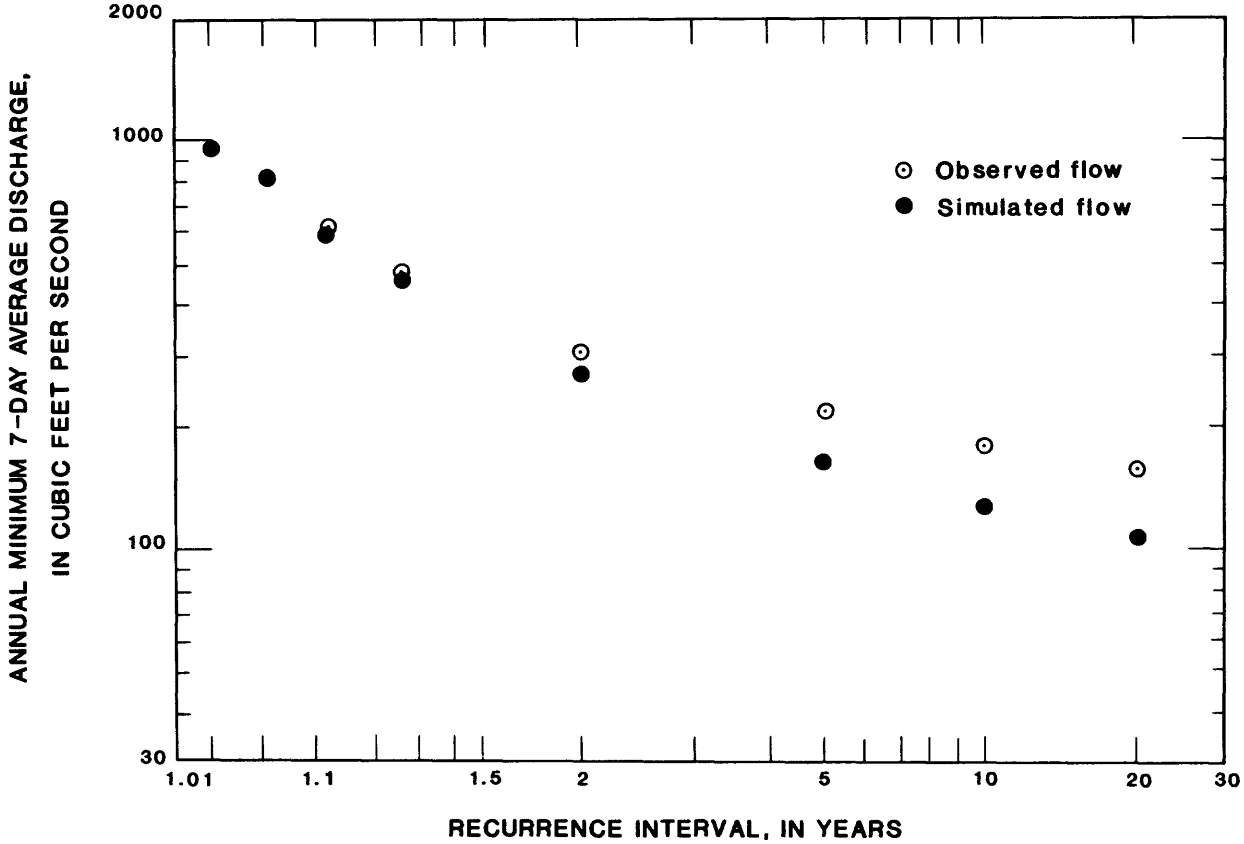

Figure 13.--Comparison of frequency curves of 7-day low flows at Lock 6, observed versus simulated, for the period 1941-81.

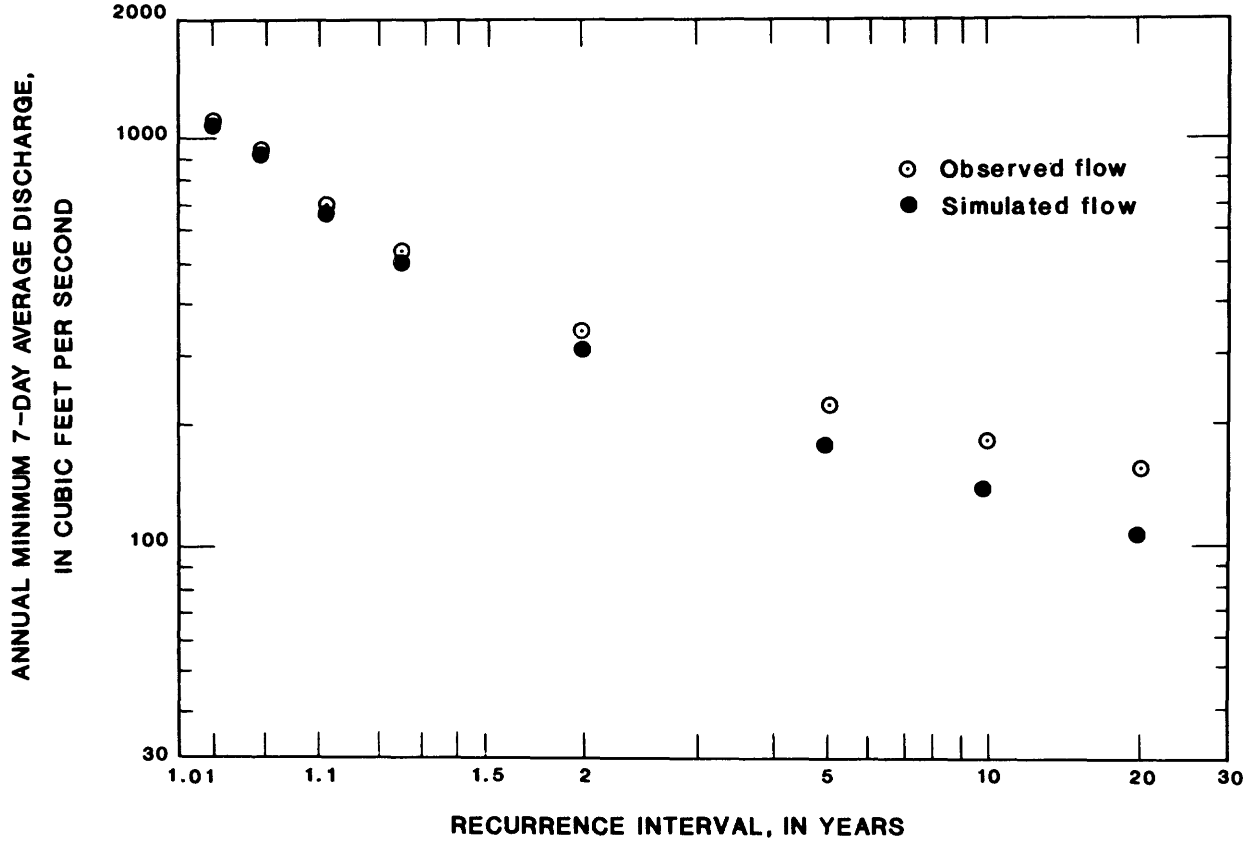

Figure 14.--Comparison of frequency curves of 7-day low flows at Lock 4, observed versus simulated, for the period 1941-81.

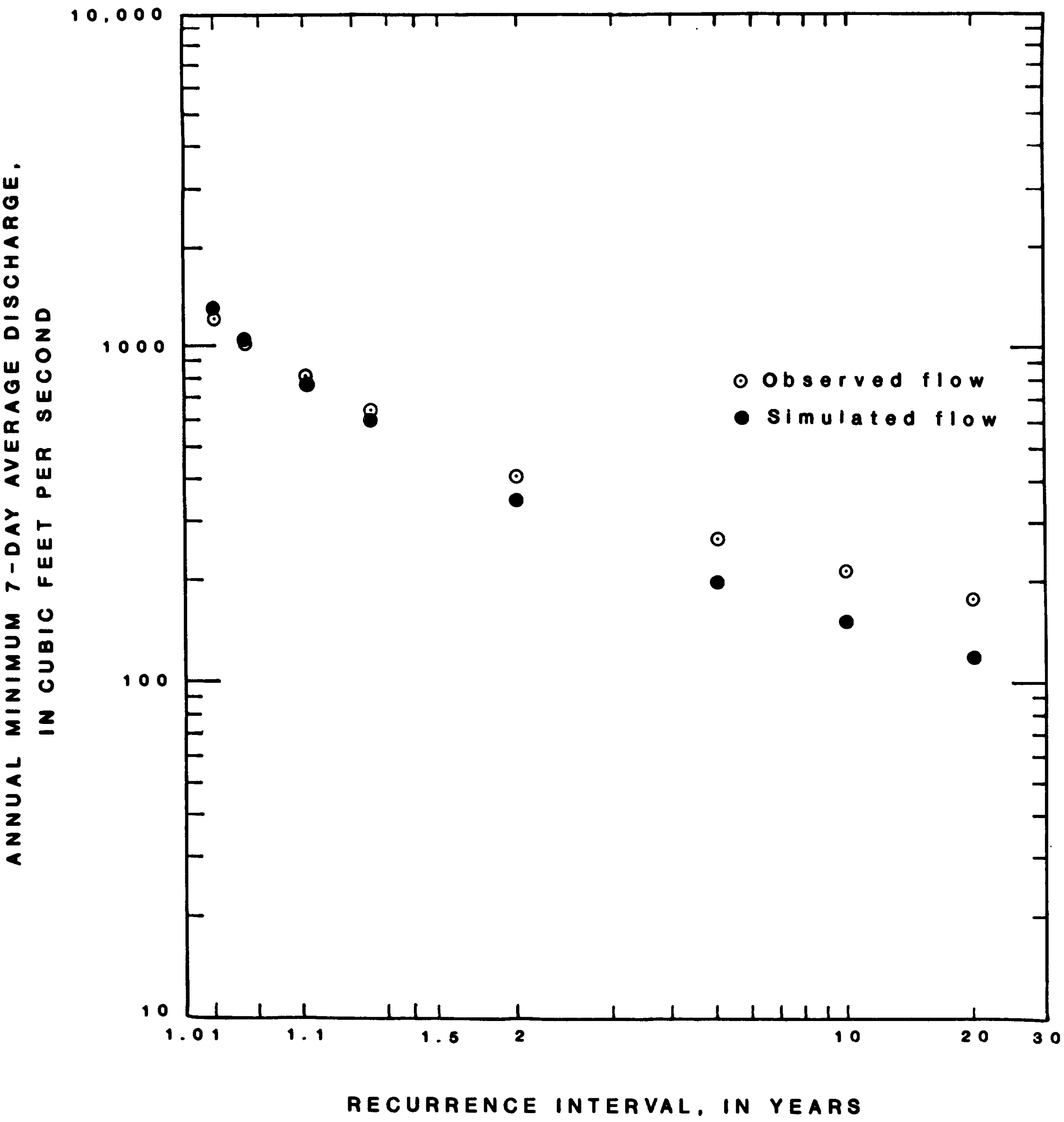

Figure 15.--Comparison of frequency curves of 7-day low flows at Lock 2, observed versus simulated, for the period 1941-81.

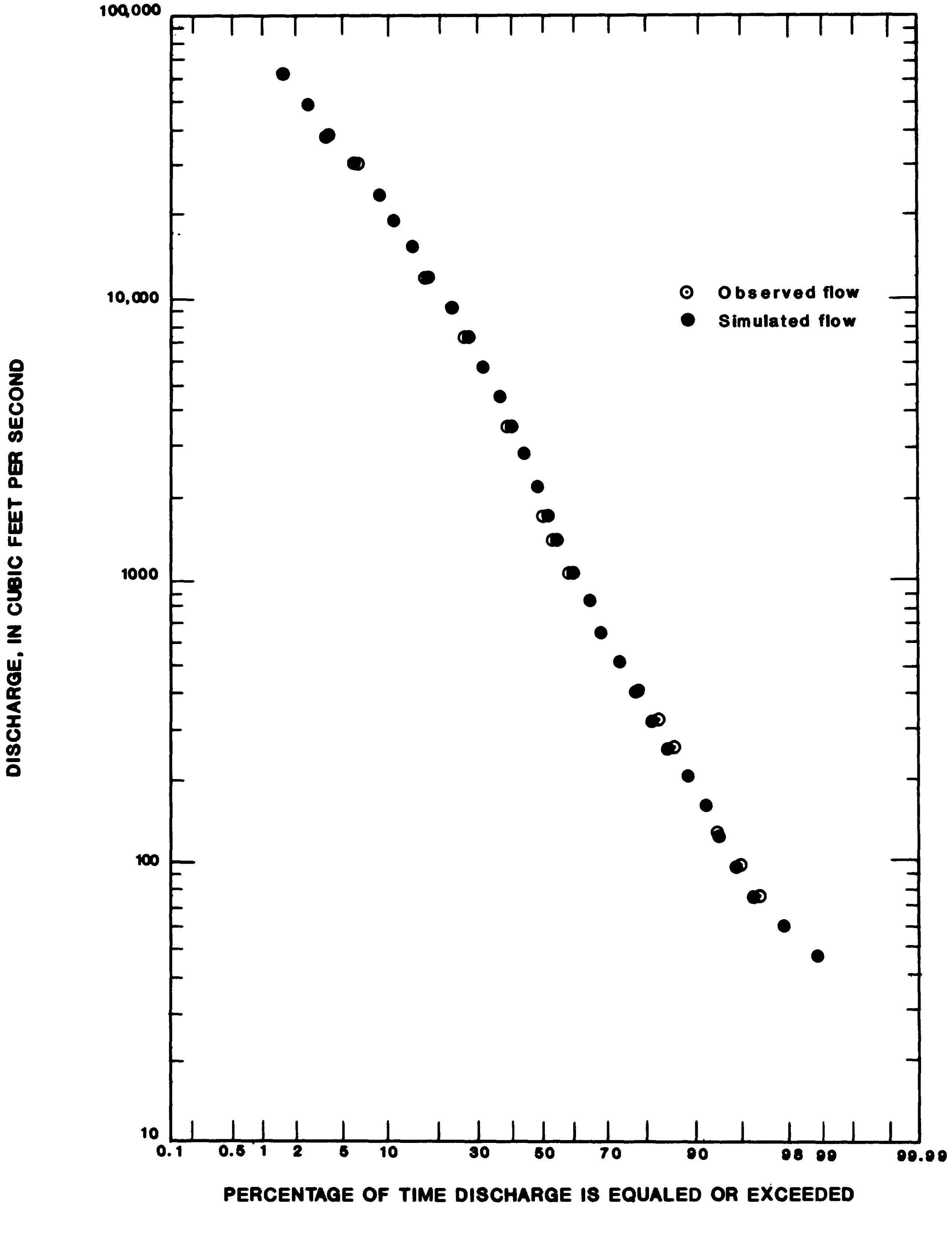

Figure 16.--Comparison of duration curves of daily flows at Lock 8, observed versus simulated, for the period 1941-71.

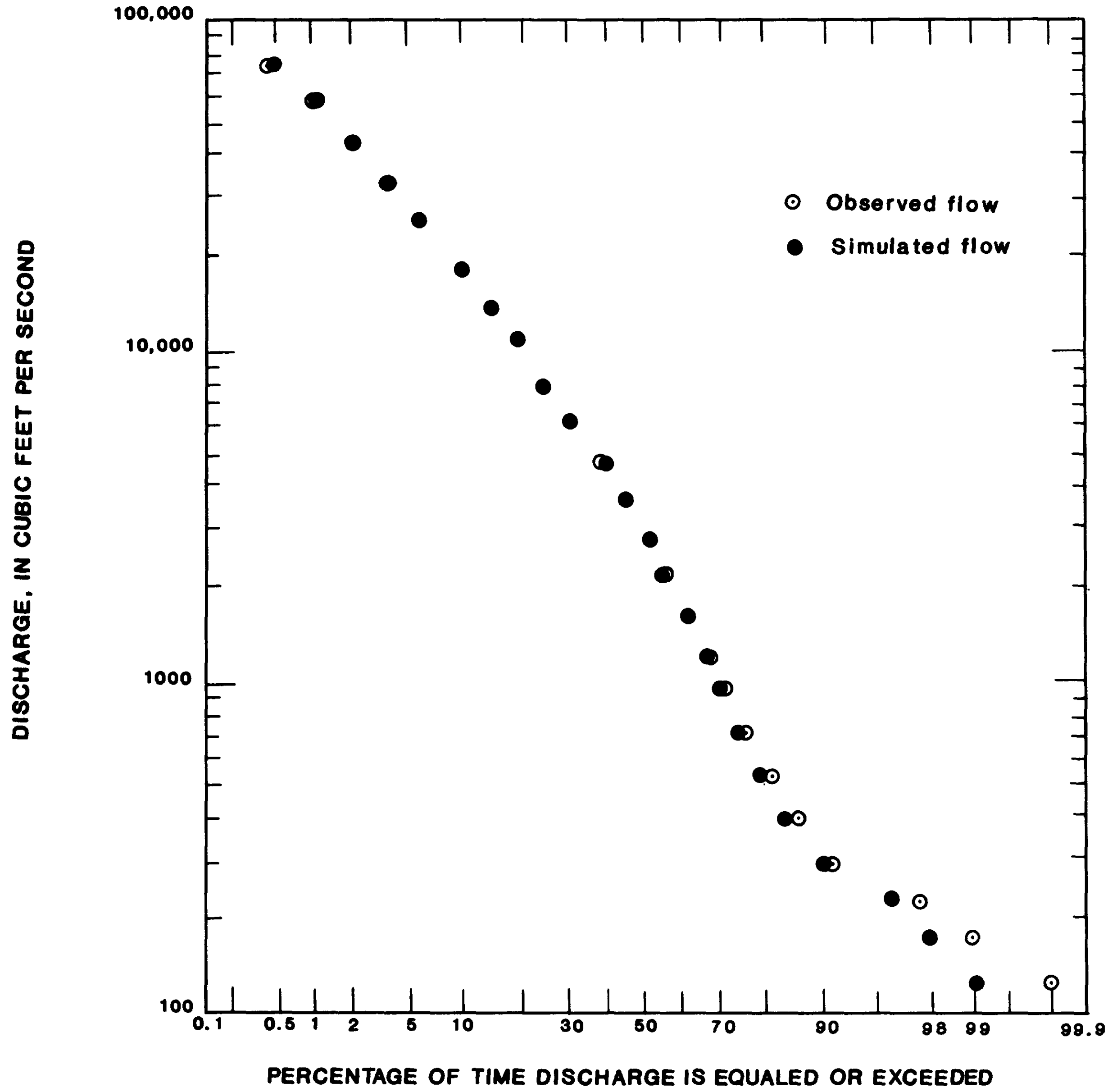

Figure 17.--Comparison of duration curves of daily flows at Lock 6, observed versus simulated, for the period 1941-81.

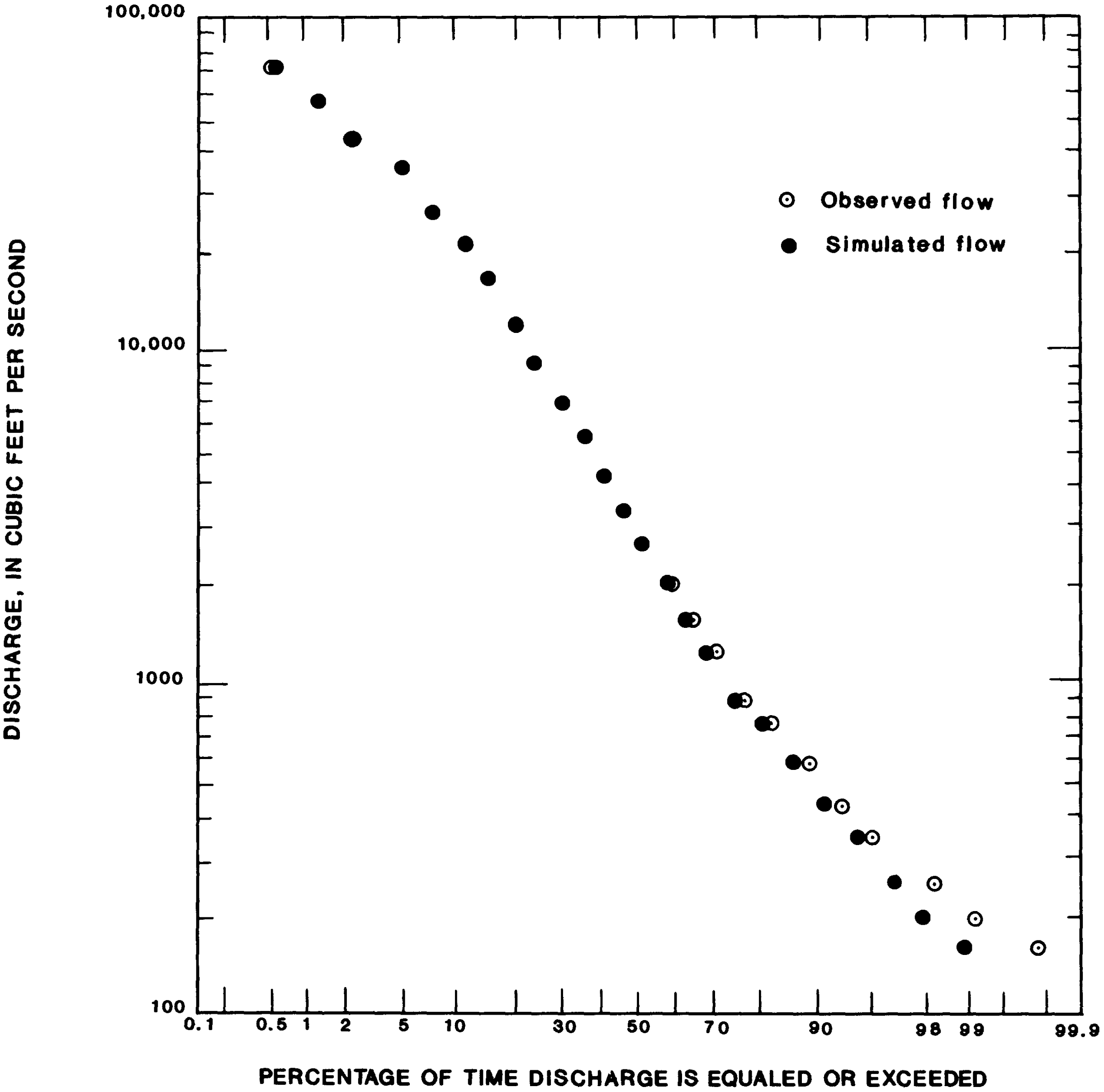

Figure 18.--Comparison of duration curves of daily flows at Lock 4, observed versus simulated, for the period 1941-81.

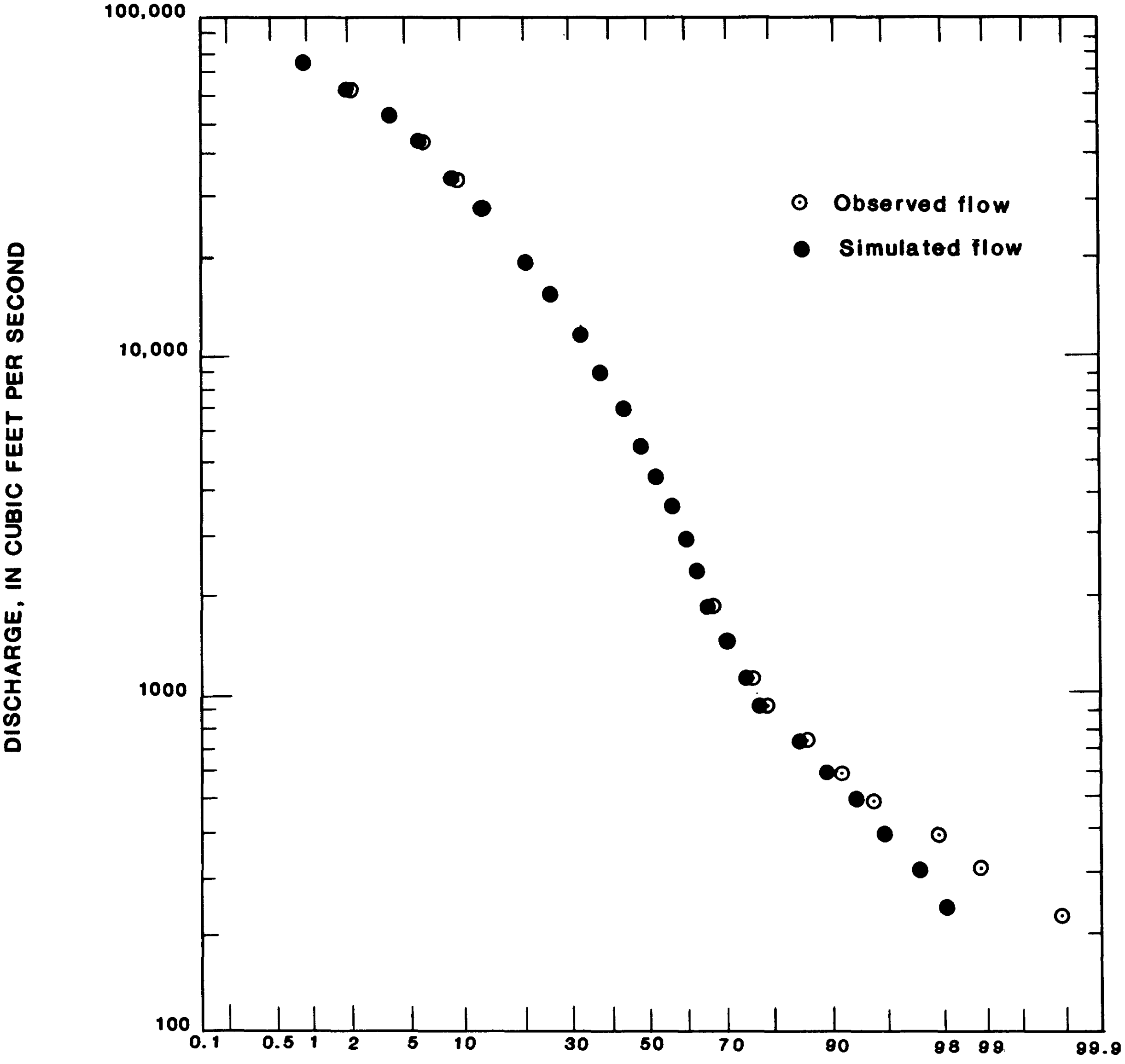

Figure 19.--Comparison of duration curves of daily flows at Lock 2, observed versus simulated, for the period 1941-81.

Table 7.--Computational expressions for model operation

[obs, observed flow at referenced location; rt, routed; sim, simulated flow at referenced location]

Flow-routing scheme 1
[Lock 10_{obs} + 1.235 Red $River_{obs}]_{rt}$ = Lock 8_{sim}
[Lock 8_{sim} + [1]reach 2 intervening $flow]_{rt}$ = Lock 6_{sim}
[Lock $6_{sim}]_{rt}$ + 0.624 Elkhorn $Creek_{obs}$ = Lock 4_{sim}
[Lock 4_{sim} + 1.620 Elkhorn $Creek_{obs}]_{rt}$ = Lock 2_{sim}
Flow-routing scheme 2
[Lock 8_{obs} + [1]reach 2 intervening $flow]_{rt}$ = Lock 6_{sim}
[Lock $6_{sim}]_{rt}$ + 0.624 Elkhorn $Creek_{obs}$ = Lock 4_{sim}
[Lock 4_{sim} + 1.620 Elkhorn $Creek_{obs}]_{rt}$ = Lock 2_{sim}
Flow-routing scheme 3
[Lock $6_{sim}]_{rt}$ + 0.624 Elkhorn $Creek_{obs}$ = Lock 4_{sim}
[Lock 4_{sim} + 1.620 Elkhorn $Creek_{obs}]_{rt}$ = Lock 2_{sim}
Flow-routing scheme 4
[Lock 4_{obs} + 1.620 Elkhorn $Creek_{obs}]_{rt}$ = Lock 2_{sim}

[1]Flows $\leq$ 600 ft^3/s: $25.013(Q)^{-0.776}$, where Q=Lock 8 simulated daily discharge.
Flows > 600 ft^3/s: 0.160 Lock 8 simulated daily discharge.

MODEL APPLICATION

Computational expressions for model operation are listed in table 7. Four flow-routing schemes are derived which vary according to startup location. The model can be started at any reach where streamflow data are available for input. The additive impact of modeling error is significantly reduced when flow routing begins in a reach nearest the site where system evaluation is to be performed. For example, if an evaluation of Lock 2 is to be made when a withdrawal is made at Lock 4, then flow-routing scheme 4 should be used with a stress file reflecting this withdrawal. Modeling errors from reaches 1 to 3 will be bypassed which will result in more accurate simulations.

Because evaluations of water-supply stresses are a primary concern for the study area, a multiyear file could be built for withdrawals and returns. This file could be created from monthly or seasonal "demand" curves from past water use records and return flow data from sewage treatment plants. This multiyear file could be incorporated into the model by the same method the tributary index stations were used to estimate intervening flows during model calibration. For additional informtion and instructions on model application, input preparations, and execution/operation of this model, refer to Doyle and others (1983).

SUMMARY AND CONCLUSIONS

A system model for the Kentucky River was developed to simulate flows on that part of the river near Lexington and Frankfort, Ky. The stream was divided into four reaches to aid in model calibration, and flows were simulated at the downstream end of each reach.

Observed flows for the 1968-69 water years were input at each reach for model calibration. Daily flow errors ranged from 8.4 to 15 percent for individual reaches during the calibration period. After calibration, the model was operated for the same time period with simulated flows input at each reach except the first. Daily flow errors ranged from 8.4 to 17 percent indicating adequate model operation.

Statistics of the observed and simulated flows for the 1941-81 water years showed close agreement. Plots of annual minimum 7-day average discharges computed from observed and simulated data showed satisfactory agreement. At the 10-year recurrence interval, the minimum 7-day average discharges computed from the simulated flows were about 7 to 29 percent less than values computed from the observed flows. Hydrograph comparisons indicated a good fit throughout a wide range of flows. These comparisons show the model can simulate flows adequately.

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