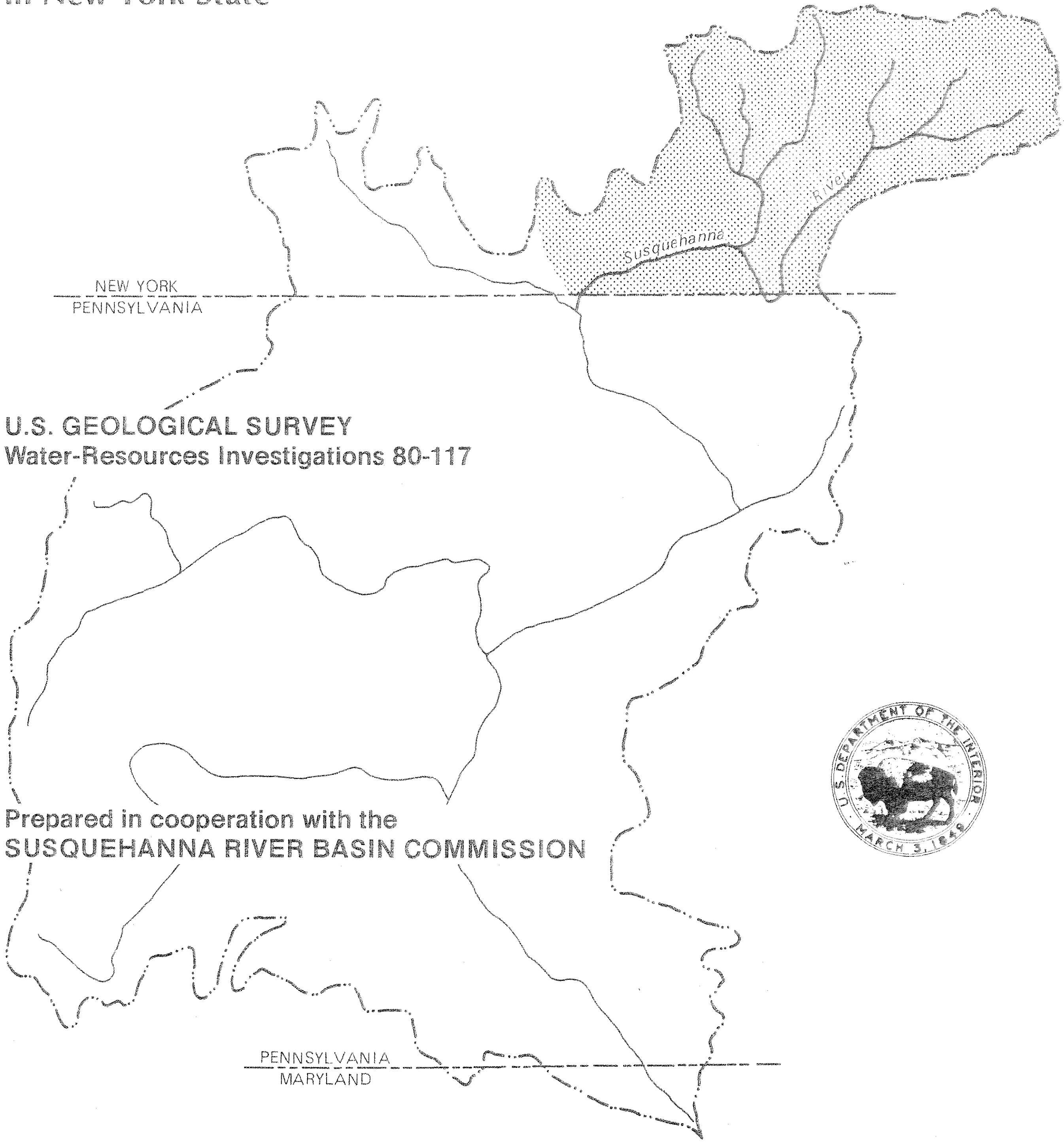
# FLOW ROUTING IN THE SUSQUEHANNA RIVER BASIN: PART IV

## Routing Reservoir Releases in the Eastern Susquehanna River Basin in New York State

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Flow-routing models were developed for six reaches of major streams in the eastern Susquehanna River basin in New York State and were used to trace releases of water from East Sidney Lake and Whitney Point Lake to gaged points downstream. Daily streamflow from 1942-77 was modeled for the following reaches: Susquehanna River--Unadilla to Conklin, Conklin to Vestal, and Vestal to Waverly; Chenango River--Sherburne to Greene and Greene to Chenango Forks; Tioughnioga River--Cortland to Itaska. The models were developed with convolution techniques and were based on the unit-response method of flow routing, assuming the diffusion analogy and using multilinearization. Overall accuracy of the models, as measured by the average difference between observed and simulated daily flows over the base period was within the stated accuracy of published gaging-station records used. As an example of one application of the models, hypothetical releases from East Sidney Lake and Whitney Point Lake during low flow were traced downstream to the Waverly gaging station at the lower end of the area studied. The leading edge of the East Sidney release arrived in 5 days, and the full release arrived in 6 days. The leading edge of the Whitney Point release arrived in 1 day, and the full release arrived in 3 days.

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# FLOW ROUTING IN THE SUSQUEHANNA RIVER BASIN:

# PART IV--ROUTING RESERVOIR RELEASES IN THE EASTERN SUSQUEHANNA RIVER BASIN IN NEW YORK STATE

By Thomas J. Zembrzuski, Jr.

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1981

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## CONVERSION FACTORS AND ABBREVIATIONS

The following factors may be used to convert the inch-pound units given herein to the International System (SI) units.

| Multiply inch-pound units | By | To obtain SI units |
|---|---|---|
| inch (in) | 25.40 | millimeter (mm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| cubic foot per second-day ($(ft^3/s) \cdot d$) | 2447. | cubic meter ($m^3$) |
| foot per second (ft/s) | 0.3048 | meter per second (m/s) |
| square foot per second ($ft^2/s$) | 0.09290 | square meter per second ($m^2/s$) |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second ($m^3/s$) |

# FLOW ROUTING IN THE SUSQUEHANNA RIVER BASIN:

# PART IV--ROUTING RESERVOIR RELEASES IN THE EASTERN SUSQUEHANNA RIVER BASIN IN NEW YORK STATE

by

Thomas J. Zembrzuski, Jr.

## ABSTRACT

Flow-routing models for six reaches of major streams in the eastern Susquehanna River basin in New York were developed and used to trace releases of water from East Sidney Lake and Whitney Point Lake to gaged points downstream. Daily streamflow during 1942-77 was modeled for the following reaches: Susquehanna River--Unadilla to Conklin, Conklin to Vestal, and Vestal to Waverly; Chenango River--Sherburne to Greene, and Greene to Chenango Forks; Tioughnioga River--Cortland to Itaska. The models were developed with convolution techniques and were based on the unit-response method of flow routing, assuming the diffusion analogy and using multilinearization. Overall accuracy of the models, as measured by the average difference between observed and simulated daily flows over the base period, was within the stated accuracy of published gaging-station records.

As an example of one application of the models, hypothetical releases from East Sidney Lake and Whitney Point Lake during low flow were traced downstream to the Waverly gaging station at the lower end of the area studied. The leading edge of the East Sidney release arrived in 4 days, and the full release arrived in 6 days. The leading edge of the Whitney Point release arrived in 1 day, and the full release arrived in 3 days.

# INTRODUCTION

One of the challenges facing water-resource managers is to ensure adequate streamflow quantity and acceptable standards of water quality during drought. This requires the capability to evaluate the effects that water-resource development would have at downstream locations. One type of development may be the use of reservoirs to augment streamflow during abnormally low flows.

When a reservoir is designed, or the feasibility of using a reservoir to augment low flows is considered, it is necessary to evaluate what effects the release of water will have on streamflow downstream and how long it will take that water to reach a given point.

The Susquehanna River Basin Commission (SRBC) is responsible for managing the water resources of the Susquehanna River basin and evaluating the effects that proposed water-resources developments within the basin would have at points downstream. One of their requirements is that new water consumers replace their withdrawals by the amount of their consumption whenever streamflow declines to or below the 7-day, 10-year low flow.

In 1975, the U.S. Geological Survey and SRBC began a series of jointly funded studies to develop computerized flow-routing models of all major streams in the Susquehanna River basin. The models will be used by SRBC to evaluate effects of water-resource development. The first study (Armbruster, 1977), which involved the Juniata River downstream from Raystown Lake, Pa., and the Susquehanna River from Sunbury, Pa., to Conowingo, Md, evaluated the effects of water-level control at Raystown Lake on low-flow frequency characteristics downstream. The models developed for that study were subsequently modified (Karplus and Dickey, 1980). The second study (Bingham, 1979) developed flow-routing models for the Susquehanna River between Waverly, N.Y., and Sunbury, Pa., and simulated long-term daily streamflow records at two ungaged sites on the Susquehanna River. The third study (Armbruster, 1979) covered the Chemung River basin, N.Y., from the Tioga-Hammond and Cowanesque Reservoirs on the Tioga River to the gaging station on the Chemung River at Chemung, N.Y. The models developed for that study were used to evaluate the effects of hypothetical reservoir-release patterns on downstream reaches during periods of low flow. Stratified drift and alluvial deposits underlying and bordering some reaches of the Chemung River have a significant effect on streamflow, and models developed for those reaches took into account the interaction between surface water and ground water near the stream.

## Purpose and Scope

This study, the fourth in the series, involves the eastern part of the Susquehanna River basin in New York State. Six flow-routing models were developed and used to trace hypothetical releases of water from both East Sidney Lake on Ouleout Creek and Whitney Point Lake on the Otselic River to Waverly, N.Y. on the Susquehanna River. The models represent approximately 112 river miles of the Susquehanna River from Unadilla to Waverly, 60 miles of the Chenango River from Sherburne to its mouth, and 34 miles of the Tioughnioga River from Cortland to its mouth. Locations are shown in figure 1. The models are compatible with those developed in the other studies and can be linked together to route flows in the Susquehanna River downstream from Waverly to Conowingo, Md.

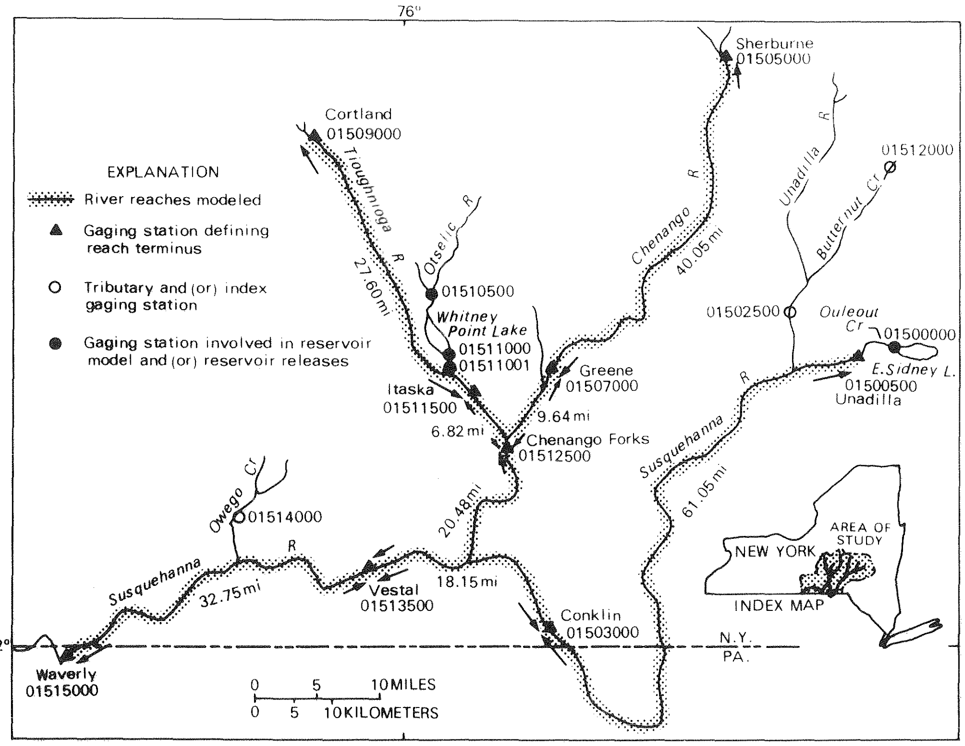


*Figure 1.--Location of gaging stations used in study.*

As in the three previous studies, the flow-routing models described herein were developed through convolution techniques and were based on the unit-response method of flow routing, assuming the diffusion analogy and using multilinearization. The models simulated the daily streamflow record of 1942-77[1] at six gaging stations upstream from (and including) the gage on the Susquehanna River near Waverly. The models were verified through comparisons of (1) observed and simulated daily streamflow records, and (2) low-flow statistics generated from the observed and simulated records.

Ground-water discharge to streams was not treated separately in this study. Consideration was given to including the ground-water component by using computer program J351 (Land, 1977), which is a streamflow-routing model capable of accounting for the interaction between ground water and surface water in an alluvial channel. The reaches modeled in this study all have appreciable intervening tributary inflow between the upstream and downstream ends, however, and the program is not intended for application to this particular hydrologic situation. Data modifications and assumptions to simplify the problem would generate errors that would be difficult to evaluate. Preliminary investigations indicated that streamflow could be adequately modeled without specifically accounting for the interaction between ground water and surface water. Errors caused by neglecting this component are probably overshadowed by other errors that are discussed later.

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[1] Unless otherwise noted, references to period of record in this report are in water years (October 1 to September 30).

# DESCRIPTION OF AREA

The flow-routing models developed for this study represent streams in the eastern part of the Susquehanna River basin that are upstream from the gaging station on the Susquehanna River near Waverly (fig. 1). The drainage area at the Waverly gaging station is 4,773 $mi^2$.

Mean annual precipitation in the basin ranges from 37 inches in the southwest to 43 inches in the north. Precipitation is fairly evenly distributed throughout the year. The areal variation of mean annual runoff follows the same pattern as mean annual precipitation and ranges from 17 to 25 inches.

## Reservoirs

The area studied contains two Corps of Engineers reservoirs, which were constructed primarily for flood control. Water is stored during high flows and released when downstream conditions permit. Since 1964, a secondary purpose has been maintenance of fairly constant pool elevations for recreation from about May 15 to September 30 of each year. When the reservoirs are being filled to recreation-pool levels each spring, the Corps requires that minimum outflows of 10 $ft^3/s$ be maintained to ensure adequate flows for aquatic life and to prevent stagnation in the channels downstream.

The dam impounding East Sidney Lake is 4.4 mi upstream from the mouth of Ouleout Creek (fig. 1). The drainage area of Ouleout Creek at the dam is 102 $mi^2$. The usable capacity (between the sill of the conduits and the crest of the spillway) is 16,900 $(ft^3/s)\cdot d$ (6.16 inches of runoff). Storage at the recreation (summer) pool level is 1,650 $(ft^3/s)\cdot d$ (0.60 inches of runoff) and, at the conservation (winter) pool level, is 820 $(ft^3/s)\cdot d$ (0.31 inches of runoff).

The dam impounding Whitney Point Lake is 0.9 mi upstream from the mouth of the Otselic River. The drainage area at the dam is 257 $mi^2$. The usable capacity (between the sill of the gates and the crest of the spillway) is 43,600 $(ft^3/s)\cdot d$ (6.31 inches of runoff). Storage at the recreation (summer) pool level is 6,380 $(ft^3/s)\cdot d$ (0.92 inches of runoff) and, at the conservation (winter) pool, is 2,570 $(ft^3/s)\cdot d$ (0.37 inches of runoff).

## Reaches Studied

Models were developed for six reaches on three major rivers. All reach termini are defined by gaging stations (fig. 1). Three of the reaches are on the main stem of the Susquehanna River: Unadilla (01500500) to Conklin (01503000); Conklin to Vestal (01513500); and Vestal to Waverly (01515000). Two reaches are on the Chenango River: Sherburne (01505000) to Greene (01507000) and Greene to Chenango Forks (01512500). The sixth reach is on the Tioughnioga River from Cortland (01509000) to Itaska (01511500). Distances between gaging stations in each reach are shown in figure 1.

## DATA USED IN MODELING

Several factors were considered in determining the number of reaches to be modeled and the gaging-station records to be used. First, the models must extend far enough upstream to use reservoir outflows as input data, and second, the records of the stations farthest upstream, and any other stations whose data were required as direct input to any model, must be complete for the base period, 1942-77. The base period was selected for continuity with the first three studies in the series.

Models were developed for reaches between all gaging stations in the study area along the main stem of the Susquehanna, Chenango, and Tioughnioga Rivers that had daily streamflow records for at least 10 years during 1942-77. Main-stem stations having short records were included to shorten the model reaches and increase model accuracy and to provide more stations at which subsequent hydrologic studies would be improved by use of simulated streamflow. (Records missing from short-record stations during this period were simulated later.)

In addition to the daily streamflow data from the gaging stations mentioned previously, records from additional stations were used to represent

*Table 1.--Gaging stations from which records were used.*

| Station number | Station name | Use of record[1] | Drainage area ($mi^2$) | Period of record (water years) |
|---|---|---|---|---|
| 01500000 | Ouleout Creek at East Sidney | R | 102 | 1941-77 |
| 01500500 | Susquehanna River at Unadilla | C | 980 | 1939-77 |
| 01502000 | Butternut Creek at Morris | T | 59.7 | 1939-77 |
| 01502500 | Unadilla River at Rockdale | T | 520 | 1938-77 |
| 01503000 | Susquehanna River at Conklin | C | 2232 | 1914-77 |
| 01505000 | Chenango River at Sherburne | C | 263 | 1939-77 |
| 01507000 | Chenango River at Greene | C | 593 | 1938-70 |
| 01509000 | Tioughnioga River at Cortland | C | 292 | 1939-77 |
| 01510500 | Otselic River near Upper Lisle | R | 217 | 1938-69 |
| 01511000 | Whitney Point Lake at Whitney Point | R | 257 | 1942-77 |
| 01511001 | Otselic River below Whitney Dam at Whitney Point | T, R | 257 | [2]1965-77 |
| 01511500 | Tioughnioga River at Itaska | C | 735 | 1929-66 |
| 01512500 | Chenango River near Chenango Forks | C | 1483 | 1913-77 |
| 01513500 | Susquehanna River at Vestal | C | 3941 | 1938-66 |
| 01514000 | Owego Creek at Owego | T | 185 | 1931-77 |
| 01515000 | Susquehanna River near Waverly | C | 4773 | 1938-77 |

[1]C = Stations defining channel-routing models.
R = Stations defining reservoir outflow or reservoir-routing models.
T = Stations defining tributary flow and (or) serving as index stations for ungaged drainage area.

[2]Unpublished gate-operation records.

tributary flow into a reach. Table 1 lists the stations used in the study and indicates their drainage area and period of record.

Daily outflow data from Whitney Point Lake (station 01511001) were needed to model the reach of the Tioughnioga River between Cortland and Itaska. Records of gate operations at the reservoir were provided by the Corps of Engineers, and daily flow values for April 1, 1964 to September 30, 1977 were computed and compiled by SRBC for digital computer use.

To derive the rest of the period of record (1942 to March 31, 1964) for Whitney Point Lake, a reservoir outflow model was developed. The input data were the inflows (station 01510500, Otselic River at Upper Lisle), the reservoir elevation record (station 01511000, Whitney Point Lake at Whitney Point), and an elevation-capacity table, which was furnished by the Corps.

Outflows derived from the gate-operation records from before March 31, 1964 were not used because they were not consistent with the inflow records and reservoir elevation records. In addition, gate-operation data were unavailable for some periods.

## DESCRIPTION OF MODELS

### Channel-Routing Models

The U.S. Geological Survey computer program J351 (Shearman and others, written commun., 1979) was used to model streamflow in the six study reaches. This program can both route and combine hydrographs. The procedure is to develop a daily streamflow hydrograph for the downstream gaging station of each reach by routing and (or) adding together the hydrograph values of the upstream gaging stations.

The streamflow-routing component of the program uses convolution techniques, whereby the stream is treated as a linear, one-dimensional system in which the downstream hydrograph is computed by convoluting the system unit response with the upstream hydrograph. A 1-day routing interval was used.

The system unit-response function is based on the diffusion analogy (Keefer, 1974), whereby the diffusion of a wave or slug of water is mathematically likened to the diffusion of an unsteady flow of particles. The timing and shape of the response of a stream to a given inflow depends upon characteristics unique to the particular stream reach and is defined by two flow characteristics--celerity (wave speed), and dispersion (dampening of the wave through channel storage).

Both celerity and dispersion vary with discharge. Over small ranges in discharge, a single unit-response function with fixed values of celerity and dispersion is adequate. For streams having a wide range of flows, however, linearization about a high discharge would result in underestimated low flows that arrive too soon, and linearization about a low discharge would result in overestimated high flows that arrive too late.

To simulate the actual system more accurately, the multilinearization concept of Keefer and McQuivey (1974) was used. A family of unit-response functions, linearized about several discharge levels, accounts for the variation in celerity and dispersion with discharge. Figure 2 illustrates how model inflows are divided (multilinearized), routed, and recombined (convoluted) to form the reach outflow.

The routing component of the model does not account for inflow from tributaries entering between the upstream and downstream ends of a reach. This inflow must be estimated and added to a routed hydrograph. In some of the reaches studied, part of the intervening tributary flow was gaged. Depending on the proportionate distance of the gaged tributary stream from the downstream station, its flow was either added directly, or first routed and then added, to the simulated downstream hydrograph.

Initial estimates of intervening ungaged tributary flow were made from data from index gaging stations. These stations were selected for hydrologic characteristics similar to those of the ungaged area. Gaged flows were then multiplied by a ratio of the ungaged-to-gaged drainage areas. Ideally, the index gaging station would be a tributary that enters the reach being modeled, but, if no tributary streams in the model reach were gaged, a nearby gaged stream was selected.

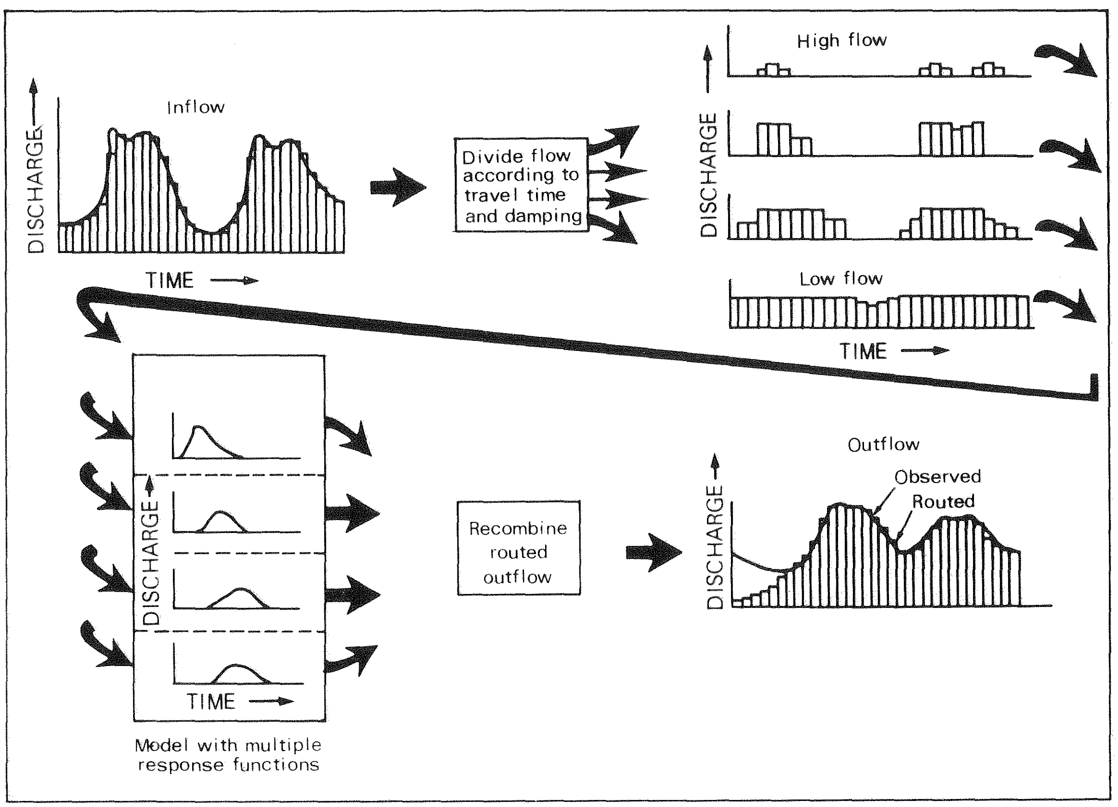



*Figure 2.--Schematic diagram of multiple linearization flow-routing model. (From Keefer and McQuivey, 1974.)*

## Reservoir-Routing Model

The outflow of Whitney Point Lake is a necessary component for simulating the flows of Tioughnioga River at Itaska. Outflows since April 1, 1964, were obtained from records of gate operations; outflow records before this date were simulated by a simple reservoir-routing model:

$$O_i = I_i - (S_i - S_{i-1})$$

where: $O_i$ is outflow volume for $i$th day

$I_i$ is inflow volume for $i$th day

$S_i - S_{i-1}$ is net change in storage from the $i$th -1 day to the $i$th day.

A continuous record of the reservoir pool level (station 01511000) has been collected since May 7, 1943. From an elevation-contents table provided by the Corps of Engineers, a record of net daily change in contents was computed for May 7, 1943 to March 31, 1964.

Daily inflow to the reservoir was estimated from the daily flow record of Otselic River at Upper Lisle (station 01510500). To account for the difference between drainage area of the reservoir and that of Upper Lisle, the flows at Upper Lisle were multiplied by a drainage-area adjustment factor of 1.15.

The period preceding May 7, 1943 (when the reservoir became fully operational and a continuous stage record was begun) was simulated from the Upper Lisle flows multiplied by the drainage-area adjustment factor.

The outflow of East Sidney Lake is gaged (station 01500000), and no reservoir routing model was required.

# MODEL CALIBRATION

The three variables used to calibrate the streamflow routing models are celerity, dispersion coefficient, and intervening tributary inflow. The calibration procedure is outlined below.

1. Four to six segments of concurrent streamflow-record intervals at the upstream and downstream ends of each reach were selected. The foremost concern was to choose those periods in which the stated accuracy of published streamflow records was the best available. Winter periods of record were generally excluded because ice in the stream channels tends to diminish the accuracy of the records. Summer and fall periods were

excluded if the accuracy of the record at one or more of the gaging stations was downgraded more than usual because of aquatic growth in the stream channel. Other requirements were that the period have several rises and recessions; additional emphasis was placed on periods that had relatively low flows.

2. Estimates of average celerity and dispersion coefficients for each reach were made according to procedures given by Keefer and McQuivey (1974).

3. Index stations were selected, and initial adjustment factors based on drainage area were computed for use in estimating the ungaged flow contribution. These first estimates, expressed in an equation of flow for the downstream gaging station of each reach, are given in table 2. The ratios presented in these equations represent the true proportion of ungaged area to gaged area in a reach.

4. Outflows were simulated through the use of observed inflows and were then evaluated by comparison with observed flows on the basis of (1) average absolute deviations of daily flow, (2) total flow volume for the calibration period, and (3) plots of the station hydrographs.

*Table 2.--Equations of daily streamflow showing first estimates of drainage-area adjustment factors.*

[Q is flow; subscript numbers 5030 are the third through sixth digits of station 01503000.]

| Reach | Equation |
|---|---|
| Unadilla to Conklin | $Q_{5030} = \underbrace{(Q_{5005} + Q_{5025})}_{\text{ROUTED}} + 0.49\ (Q_{5005} + Q_{5025})$ |
| Sherburne to Greene | $Q_{5070} = \underbrace{Q_{5050}}_{\text{ROUTED}} + 1.25\ Q_{5050}$ |
| Cortland to Itaska | $Q_{5115} = \underbrace{Q_{5090}}_{\text{ROUTED}} = 0.62\ Q_{5090} + Q_{511001}$ |
| Greene to Chenango Forks | $Q_{5125} = Q_{5115} + 1.26\ Q_{5070}$ |
| Conklin to Vestal | $Q_{5135} = \underbrace{Q_{5030}}_{\text{ROUTED}} + \underbrace{Q_{5125}}_{\text{ROUTED}} + 1.22\ Q_{5140}$ |
| Vestal to Waverly | $Q_{5150} = \underbrace{Q_{5135}}_{\text{ROUTED}} + 4.50\ Q_{5140}$ |

5. Drainage-area factors and(or) values of celerity and dispersion were adjusted and step 4 repeated until the differences (errors) in step 4 seemed to be at a minimum. For reaches lacking a suitable index station (as defined in a previous section, "Data Used in Modeling"), other index stations were selected in an effort to improve the simulation results. The errors mentioned in step 4 were computed as follows:

$$\text{Average absolute daily flow error (in percent)} = \left( \frac{\sum_{i=1}^{N} \left| \frac{Q_{sim_i} - Q_{obs_i}}{Q_{obs_i}} \right|}{N} \right) \times 100$$

where: $Q_{obs}$ and $Q_{sim}$ are the observed and simulated flows, respectively, for the $i$th day, and

N is the number of days in the calibration period.

$$\text{Total volume error (in percent)} = \left( \frac{V_{sim} - V_{obs}}{V_{obs}} \right) \times 100$$

where: $V_{obs}$ and $V_{sim}$ are the observed and simulated flow volumes, respectively, in the calibration period.

The calibration errors for each reach and calibration period are given in table 3; the last entry for each reach is for the entire period of concurrent record within the base period. Examples of good and poor fits of the simulated hydrograph to the observed flow data are illustrated in figure 3. Final values of celerity and dispersion coefficient for each reach are presented in table 4. The final equations for each model and schematic diagrams of the reaches are given in figure 4.

During calibration, errors in simulated flow for short time periods were found to be large compared to the average error during the entire calibration period. (See fig. 3B.) Most of these errors were in model reaches having a large proportion of ungaged drainage area. These occurred during and after rises in the hydrograph and could be attributed to a different amount and intensity of precipitation on the index-station basin(s) than on the area the index station is being used to represent. No attempt was made to reduce errors of this type at the expense of accuracy of the low-flow periods.

The following paragraphs describe how each model reach was calibrated:

*Susquehanna River from Unadilla to Conklin*.--The observed flows of Susquehanna River at Unadilla and Unadilla River at Rockdale were added together and routed to Conklin. Because this reach is relatively long, the

Unadilla River flows were increased by a drainage-area adjustment factor to take into account some of the ungaged area in the upper part of the reach before being added to and routed with the Susquehanna River flows. The rest of the ungaged area along the reach was accounted for by using as index stations both Unadilla River at Rockdale and Owego Creek at Owego. The ungaged intervening drainage area in this reach is 33 percent of the total area at Conklin. Calibration data were available for the entire period, 1942-77.

*Chenango River from Sherburne to Greene*.--The observed flows of Chenango River at Sherburne were adjusted to account for some of the ungaged area at the upper part of the reach and were then routed to Greene. The rest of the ungaged area in the reach was accounted for by using adjusted flows from the index stations at Sherburne and Butternut Creek at Morris. The ungaged intervening drainage area in this reach is 56 percent of the total area at Greene. The period of concurrent record available for calibrating this reach was 1942-70.

*Tioughnioga River from Cortland to Itaska*.--The observed flows of the Tioughnioga River at Cortland were routed to Itaska. Outflows of Whitney Point Lake were translated directly over the 5-mile distance to Itaska. The ungaged area between Cortland and Itaska was accounted for by using Tioughnioga River at Cortland as an index station. No tributaries in the reach between Cortland and Itaska are gaged. In this reach, the ungaged intervening drainage area is 25 percent of the total drainage area at Itaska. The concurrent period, 1942-66, was available for calibration.

*Chenango River from Greene to Chenango Forks*.--Because the distance from the gaging stations at both Greene and Itaska to Chenango Forks is relatively short, simple translation and addition of the observed Itaska and Greene records produced acceptable results. Ungaged area was accounted for by multiplying flows of Chenango River at Greene by a drainage-area adjustment factor. In this reach, the ungaged intervening drainage area is 10 percent of the total area at Chenango Forks. The period of concurrent record available for calibration of this model was 1942-66.

*Susquehanna River, Conklin to Vestal*.--The observed flows of Susquehanna River at Conklin and of Chenango River at Chenango Forks were routed separately to Vestal. Neither reach contains gaged tributaries; therefore, adjusted flows of Owego Creek at Owego were used to account for the ungaged area. The ungaged intervening drainage area is 6 percent of the total drainage area at Vestal. The period of concurrent record available for calibration was 1942-66.

*Susquehanna River, Vestal to Waverly*.--Observed flows of Susquehanna River at Vestal were routed to Waverly. The flows of Owego Creek, a gaged tributary to the reach, were added directly to flow at Waverly and were also used to estimate flow from the ungaged tributaries. The ungaged intervening drainage area in this reach is 14 percent of the total area at Waverly. The period of concurrent record available for calibration was 1942-66.

*Table 3.--Model calibration errors.*

[Errors are computed from observed inflows at all upstream stations.]

| Reach | Calibration period | Errors (percent) | |
|---|---|---|---|
| | | Daily flows | Flow volume |
| Unadilla to Conklin | 4-1-1946 to 10-31-1946 | 11.0 | -9.8 |
| | 4-1-1958 to 12-31-1958 | 11.4 | -3.1 |
| | 4-1-1960 to 9-30-1960 | 11.8 | -7.6 |
| | 4-1-1977 to 9-30-1977 | 9.8 | -5.7 |
| | 10-1-1941 to 9-30-1977 | 10.2 | -4.7 |
| Sherburne to Greene | 4-1-1952 to 11-30-1952 | 18.6 | 0.0 |
| | 4-1-1954 to 8-30-1954 | 16.7 | 9.8 |
| | 4-1-1964 to 11-30-1964 | 14.1 | -12.4 |
| | 4-1-1969 to 11-30-1969 | 16.4 | 1.2 |
| | 10-1-1941 to 9-30-1970 | 14.4 | -2.3 |
| Cortland to Itaska | 6-15-1944 to 9-30-1944 | 5.8 | 0.9 |
| | 7-1-1951 to 10-31-1951 | 5.8 | -4.6 |
| | 5-1-1953 to 9-30-1953 | 6.0 | -0.8 |
| | 5-1-1959 to 9-30-1959 | 6.4 | -3.5 |
| | 5-1-1962 to 9-30-1962 | 9.1 | 0.0 |
| | 10-1-1965 to 9-30-1966 | 9.6 | 1.8 |
| | 10-1-1941 to 9-30-1966 | 9.1 | -4.3 |
| Greene to Chenango Forks | 4-1-1942 to 10-31-1942 | 3.9 | 0.5 |
| | 4-1-1947 to 10-31-1947 | 3.1 | -0.9 |
| | 4-1-1950 to 10-31-1950 | 2.9 | -0.7 |
| | 4-1-1955 to 10-31-1955 | 3.4 | 0.9 |
| | 4-1-1965 to 10-31-1965 | 4.2 | -0.3 |
| | 10-1-1941 to 9-30-1966 | 3.8 | -0.3 |
| Conklin to Vestal | 4-1-1945 to 10-30-1945 | 3.1 | -0.3 |
| | 4-1-1948 to 10-30-1948 | 2.9 | -1.4 |
| | 4-1-1951 to 10-30-1951 | 3.9 | -0.3 |
| | 4-1-1957 to 9-30-1957 | 3.6 | -1.3 |
| | 4-1-1964 to 10-31-1964 | 3.3 | -0.1 |
| | 10-1-1941 to 9-30-1966 | 4.0 | -0.2 |
| Vestal to Waverly | 4-1-1942 to 9-30-1942 | 4.4 | -1.6 |
| | 4-1-1948 to 10-31-1948 | 4.2 | -3.7 |
| | 4-1-1953 to 10-31-1953 | 3.7 | -2.3 |
| | 4-1-1963 to 10-31-1963 | 3.8 | -0.1 |
| | 4-1-1966 to 9-30-1966 | 5.0 | -2.5 |
| | 10-1-1941 to 9-30-1966 | 5.1 | -2.4 |

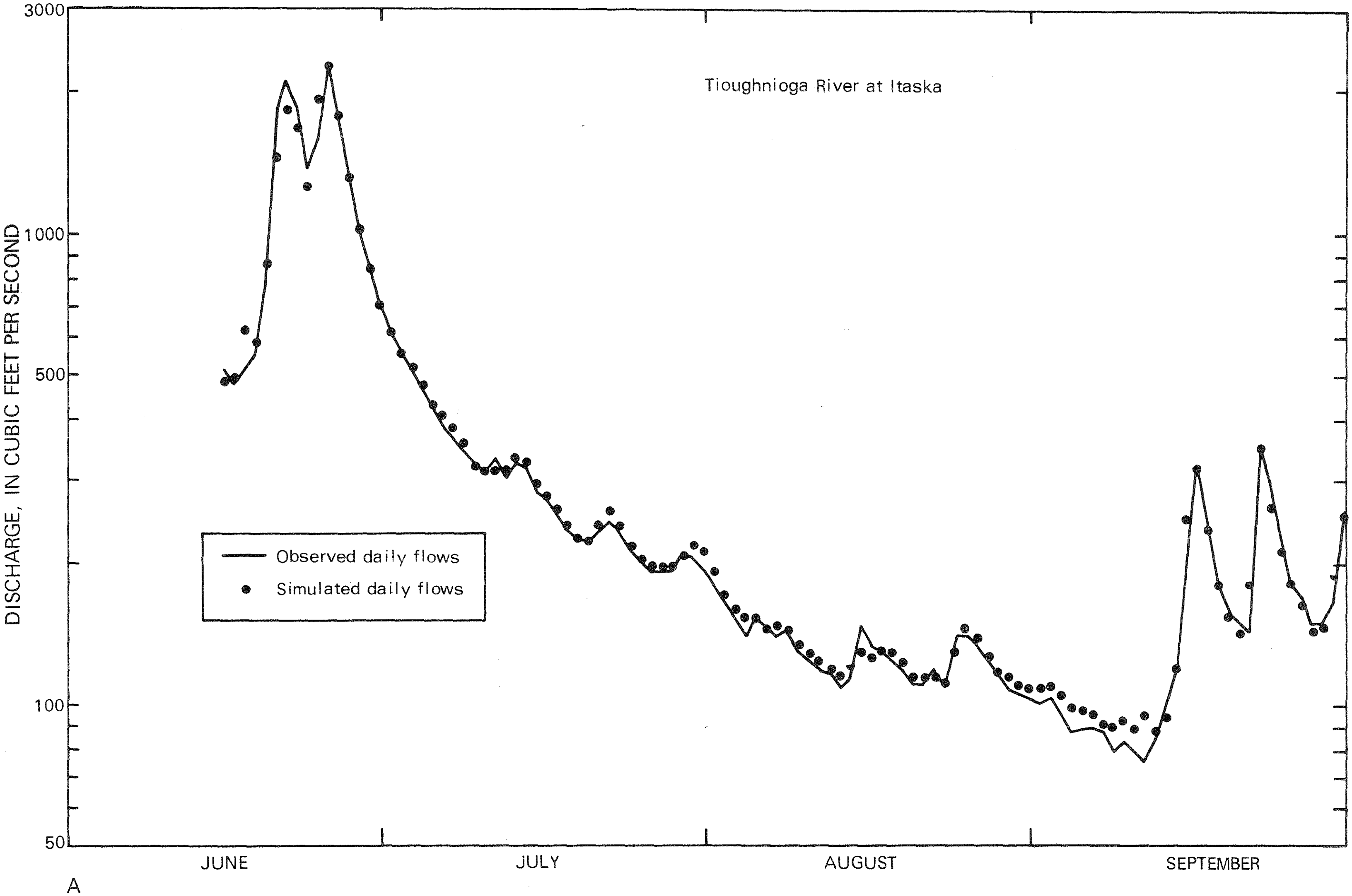
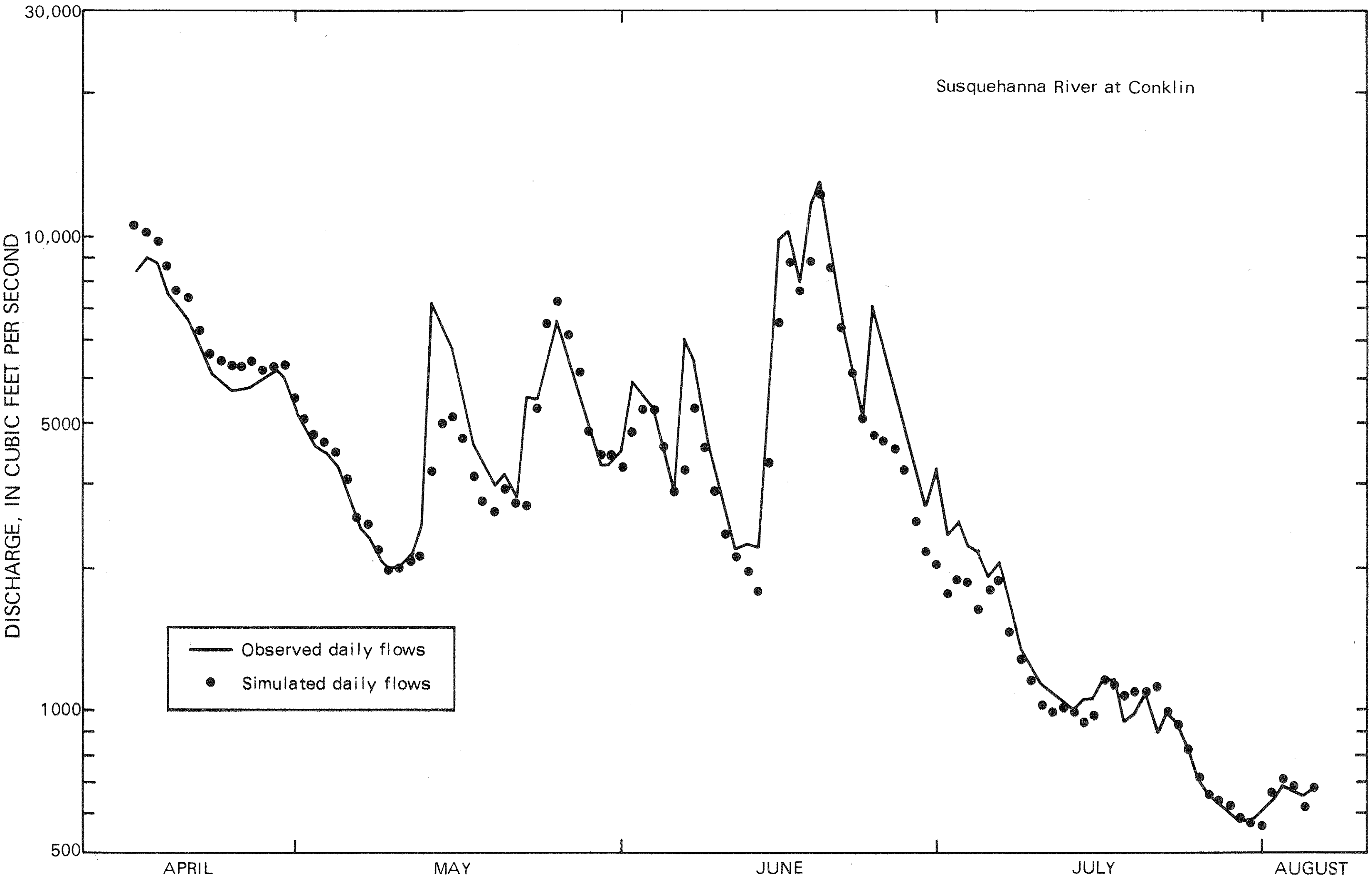



*Figure 3A.--Comparison of simulated and observed flows during calibration period: example of close match for Tioughnioga River at Itaska, June 15 to September 30, 1964.*



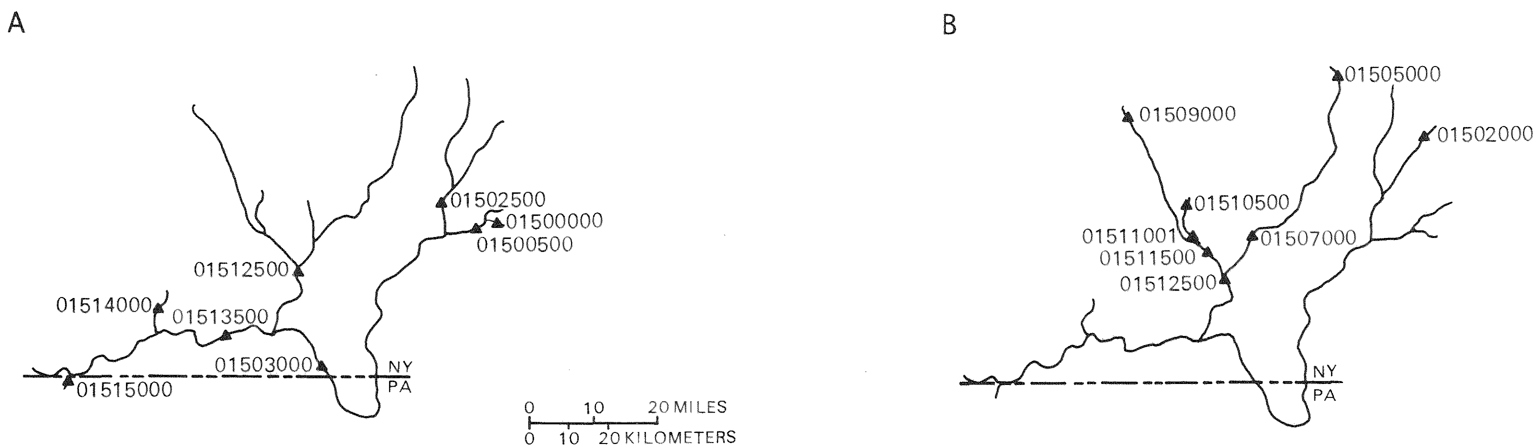

B

*Figure 3B.--Comparison of simulated and observed flows during calibration period: example of poor match for Susquehanna River at Conklin, April 15 to August 5, 1960.*

*Table 4.--Routing coefficients used in final flow-routing models.*

[C = celerity, in feet per second; K = dispersion coefficient, in square feet per second]

| Discharge (cubic feet per second) | Unadilla to Conklin | | Sherburne to Greene | | Cortland to Itaska | |
|---|---|---|---|---|---|---|
| | C | K | C | K | C | K |
| 100 | 1.4 | 500 | 2.5 | 570 | 3.6 | 270 |
| 200 | 1.6 | 770 | 2.8 | 1000 | 4.0 | 510 |
| 400 | 2.0 | 1500 | 3.3 | 1800 | 4.6 | 960 |
| 1000 | 2.8 | 3100 | 4.2 | 4300 | 5.9 | 2200 |
| 2000 | 3.4 | 6500 | 5.4 | 8700 | 7.2 | 4100 |
| 4000 | 3.9 | 12,000 | 7.2 | 13,000 | 8.9 | 7700 |
| 10,000 | 4.7 | 26,000 | 11.0 | 24,000 | 11.5 | 17,000 |
| 20,000 | 6.0 | 47,000 | -- | -- | -- | -- |
| 40,000 | 7.8 | 62,000 | -- | -- | -- | -- |
| | Conklin to Vestal | | Greene to Chenango Forks | | Vestal to Waverly | |
| | C | K | C | K | C | K |
| 200 | 1.2 | 630 | 2.2 | 500 | 1.3 | 500 |
| 800 | 1.9 | 2200 | 3.5 | 1700 | 2.2 | 2000 |
| 2000 | 2.6 | 4800 | 4.8 | 3500 | 3.0 | 3000 |
| 4000 | 3.4 | 9300 | 6.0 | 6800 | 3.8 | 8000 |
| 8000 | 4.5 | 18,000 | 8.2 | 13,000 | 4.7 | 18,000 |
| 16,000 | 5.8 | 30,000 | 10.4 | 24,000 | 5.8 | 30,000 |
| 25,000 | 6.7 | 38,000 | 12.0 | 32,000 | 6.8 | 41,000 |
| 50,000 | 8.4 | 54,000 | 14.4 | 45,000 | 7.7 | 67,000 |
| 100,000 | 10.4 | 83,000 | 17.0 | 70,000 | 9.0 | 90,000 |




$$QS_{5030} = \underbrace{(QO_{5005} + 1.3(QO_{5025}))}_{\text{ROUTED}} + 0.35(QO_{5025}) + 1.5(QO_{5140})$$

$$QS_{5135} = \underbrace{QS_{5030}}_{\text{ROUTED}} + \underbrace{QS_{5125}}_{\text{ROUTED}} + 1.27(QO_{5140})$$

$$QS_{5150} = \underbrace{QS_{5135}}_{\text{ROUTED}} + 3.5(QO_{5140})$$

$$QS_{5070} = \underbrace{1.2(QO_{5050})}_{\text{ROUTED}} + 0.2(QO_{5050}) + 3.2(QO_{5020})$$

$$QS_{5115} = \underbrace{QO_{5090}}_{\text{ROUTED}} + 0.55(QO_{5090}) + QO_{511001}$$

$$QS_{5125} = QS_{5115} + 1.25(QS_{5070})$$

EXPLANATION

| | |
|---|---|
| ▲01512500 | Gaging station and number |
| $QO_{5140}$ | Observed flow at station 01514000 |
| $QS_{5125}$ | Simulated flow at station 01512500 |

*Figure 4.--Schematic diagram of rivers showing location of gaging stations and mathematical relationships used in flow-routing models: A, Susquehanna River; B, Chenango and Tioughnioga Rivers.*

## VERIFICATION OF MODELS

After all reaches had been calibrated, the models were operated to simulate daily flows of 1942–77, starting at the reaches farthest upstream. Rather than use observed inflows from the upstream gaging station in each reach to generate the simulated downstream hydrograph, as was done in calibration, simulated inflows were used. Observed inflow data were used only from the main-stem stations farthest upstream and from index stations and tributary stations.

The models were verified in two ways. The first method was to obtain the average absolute errors in simulated daily flow and in flow volume for the entire post-1942 period of record of the downstream gaging station in a given reach. If these errors were comparable to the general stated accuracy of the stations' published streamflow records, the model was considered acceptable. Although some water years were simulated better than others in each model, all six models were judged acceptable by this first verification criterion. (The errors for each model are given in table 5.) Because inflow data used were the observed rather than simulated values, the errors tabulated for the three upstream reaches (Unadilla to Conklin, Sherburne to Greene, and Cortland to Itaska) are identical with those given in table 3 for the stated period of record.

The second verification method was to compare daily flow-duration curves and mean annual 7-day low-flow frequency curves generated from observed and simulated flow data at the downstream gaging station in each reach. These comparisons are presented in figures 5–6.

Climatic year data (April 1 to March 31) were used in log-Pearson type III analyses to compute the low-flow frequency curves. The low-flow frequency curves differed by less than 10 percent with few exceptions. The differences between observed and computed curves at the higher recurrence intervals for Chenango River at Greene and Tioughnioga River at Itaska were relatively large (between 15 and 20 percent). The same magnitude of error was present in the frequency curve at the lower recurrence intervals for Chenango River near Chenango Forks. These errors indicate some weakness in the models for these particular reaches in reproducing historical low-flow periods. The errors were not transferred with the same order of magnitude to the reaches downstream from Chenango Forks, however.

The observed and simulated flow-duration curves also compared closely. The models were calibrated to obtain the best simulation of low-flow periods; however, the simulation of flows in the middle range was also favorable. The poorer duplication in the higher range of the curve is attributed to the tendency of index stations and drainage-area adjustment factors to be less representative of the response of the ungaged areas during high flows as during low flows. Data on a water-year basis was used to compute the duration curves.

It was found that the ratio of ungaged drainage area between the reach termini to the drainage area of the downstream gaging station is a major factor in how accurately flows can be simulated. Figure 7 summarizes this relationship for the six models and suggests a direct relationship between model accuracy and percentage of ungaged area. Values for average error in daily flow for all data points in figure 7 are those shown in table 3 as the last entry for each reach. These errors were based on flows computed from only observed inflows and the longest period of concurrent record. The three upstream models (Unadilla to Conklin, Sherburne to Greene, and Cortland to Itaska) showed the greatest amount of error. When the simulated flow values generated by these models are used as inflow values for downstream models, the errors tend to be passed along. This becomes evident by comparing daily-flow errors in the record produced from observed inflows (table 3) with errors in the same record produced from simulated inflows (table 5).

*Table 5.--Model verification errors.*

[Errors are computed from simulated inflow at three upstream stations of the three lower reaches.]

| Reach | Period (water years) | Difference (percent) Daily flows | Flow volume |
|---|---|---|---|
| Unadilla to Conklin | 1942-77 | 10.2 | -4.7 |
| Sherburne to Greene | 1942-70 | 14.4 | -2.3 |
| Cortland to Itaska | 1942-66 | 9.1 | -4.3 |
| Greene to Chenango Forks | 1942-77 | 11.2 | -1.4 |
| | *1942-66 | 10.6 | -3.2 |
| Conklin to Vestal | 1942-66 | 8.8 | -3.9 |
| Vestal to Waverly | 1942-77 | 9.9 | -6.2 |
| | *1942-66 | 9.5 | -5.7 |

* Represents concurrent period of record of gaging stations in the reach.

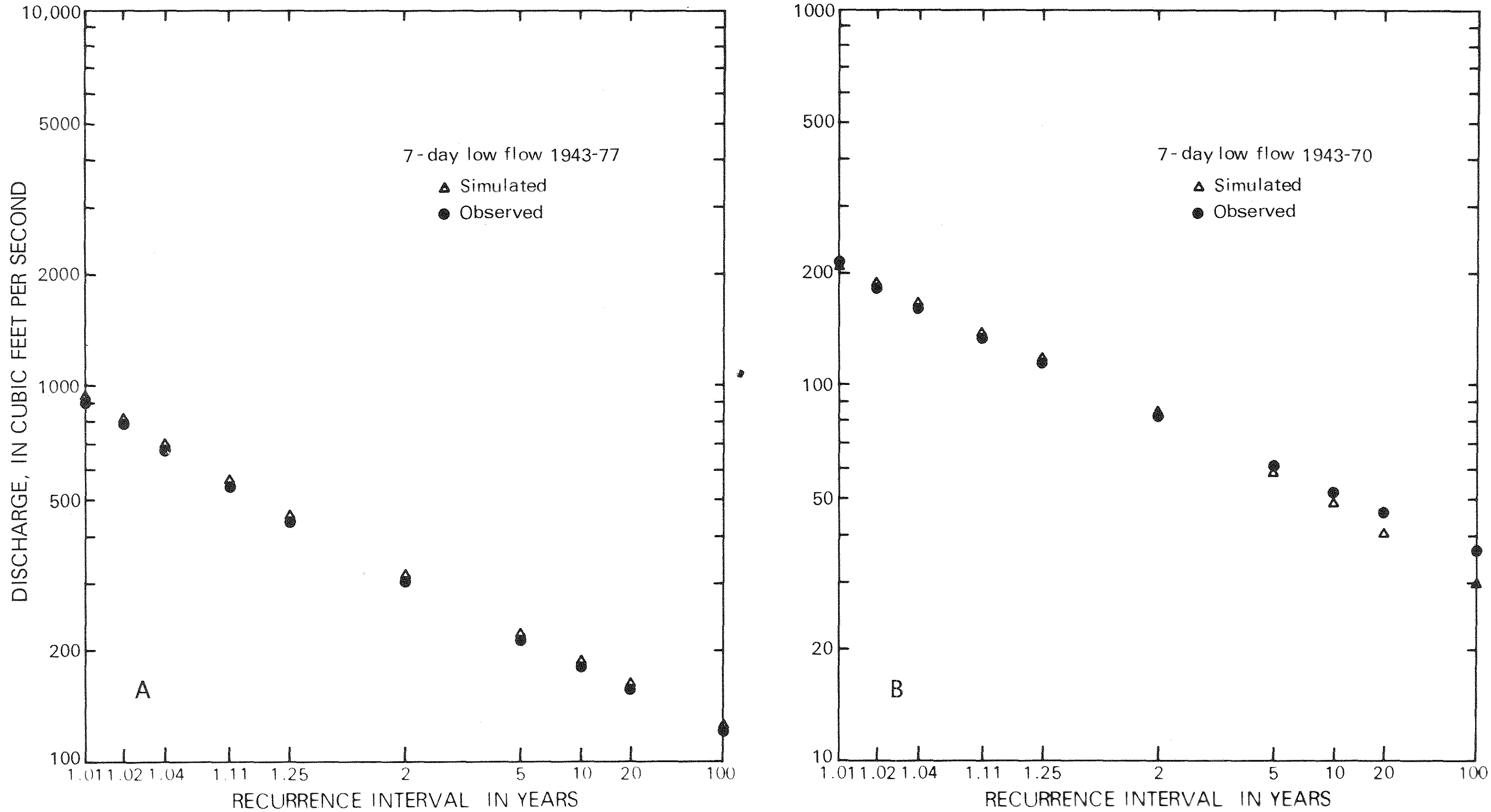



*Figure 5.--Seven-day low-flow frequency curves computed from observed and simulated daily flows: A, station 01503000, Susquehanna River at Conklin, 1943-77 climatic years; B, station 01507000, Chenango River at Greene, 1943-70 climatic years.*

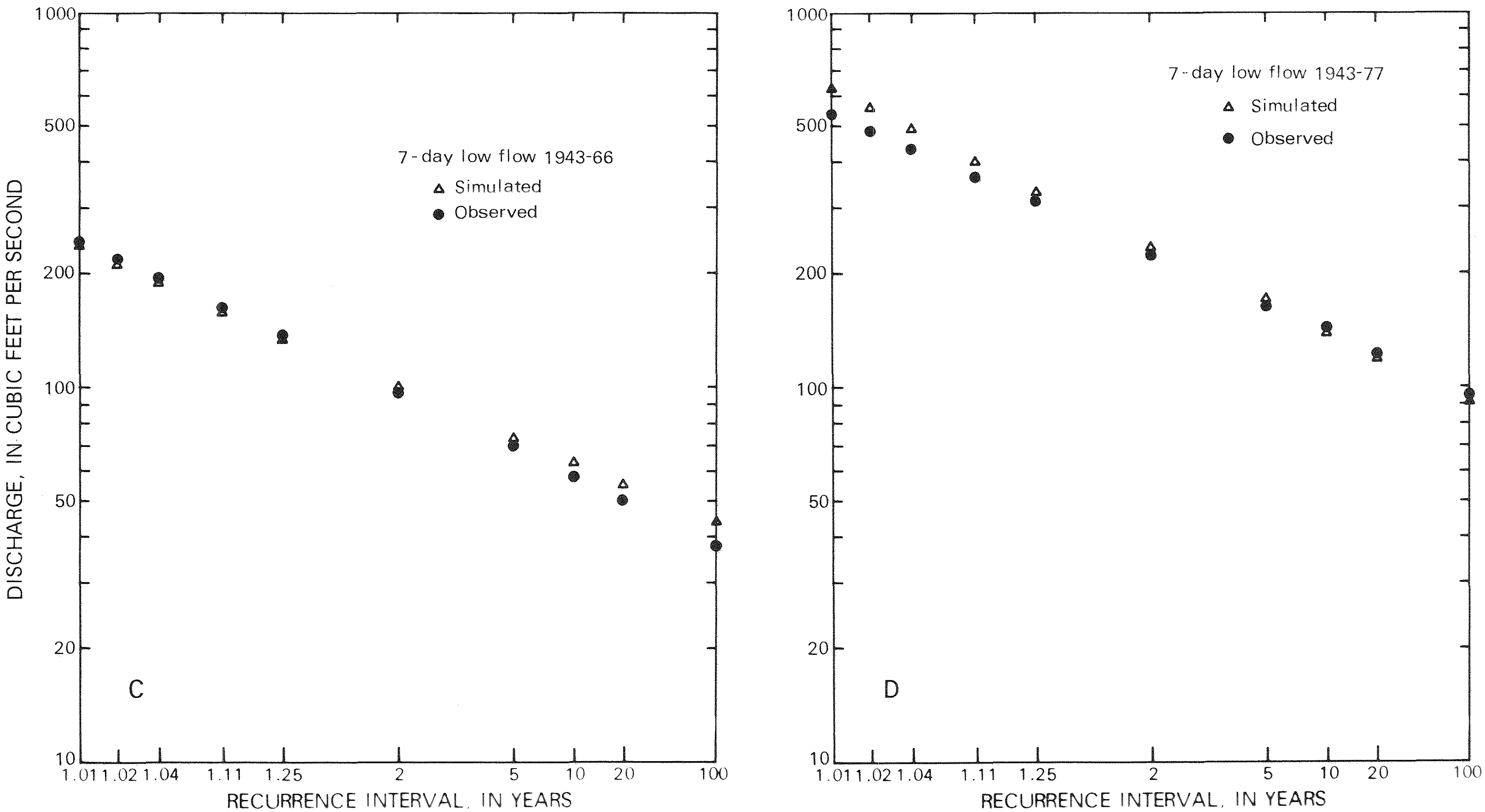



*Figure 5 (continued).--Seven-day low-flow frequency curves computed from observed and simulated daily flows:*
*C, station 01511500, Tioughnioga River at Itaska, 1943-66 climatic years;*
*D, station 01512500, Chenango River near Chenango Forks, 1943-77 climatic years.*

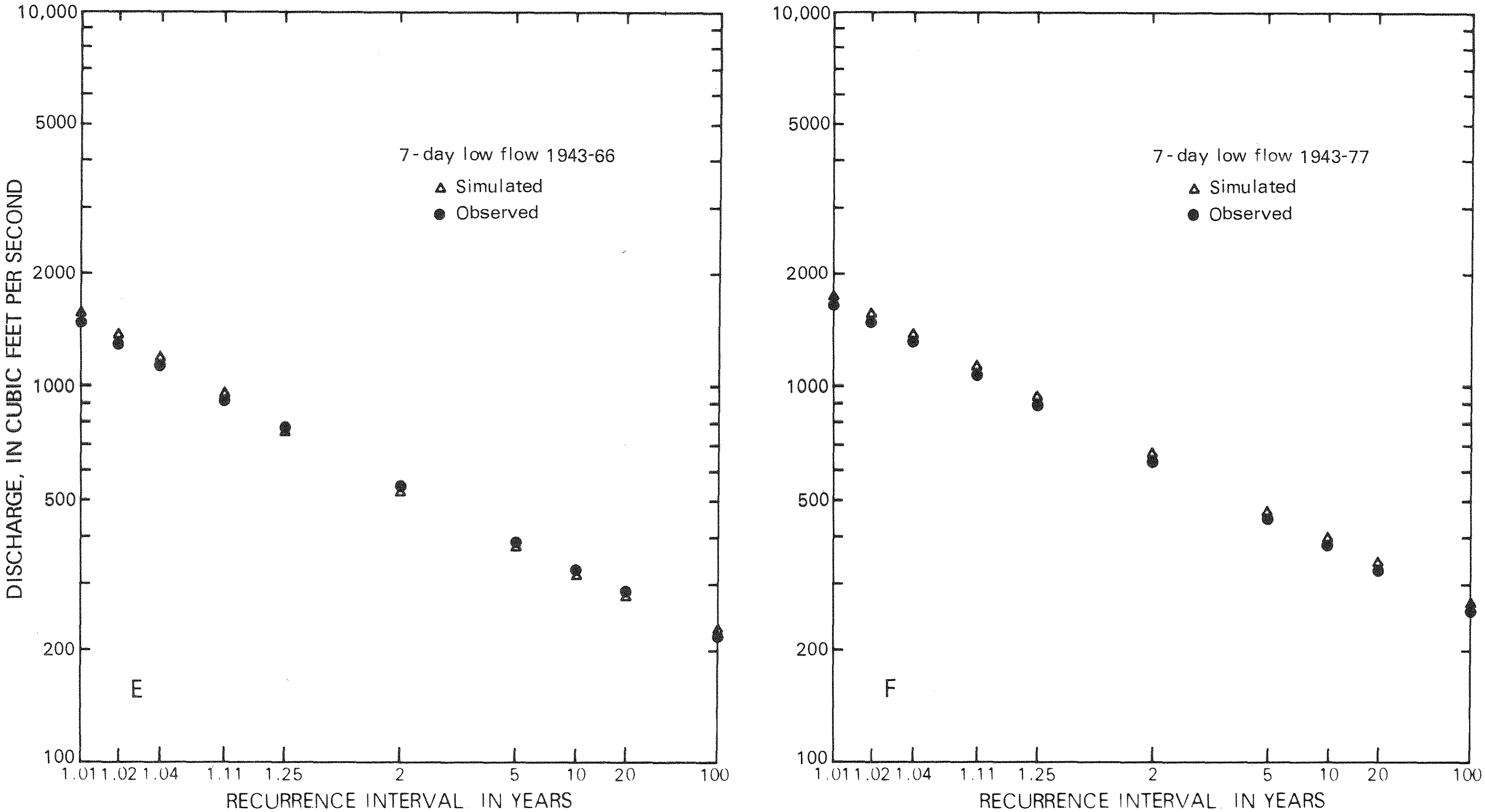



*Figure 5 (continued).--Seven-day low-flow frequency curves computed from observed and simulated daily flows:*
*E, station 01513500, Susquehanna River at Vestal, 1943-66 climatic years;*
*F, station 01515000, Susquehanna River near Waverly, 1943-77 climatic years.*

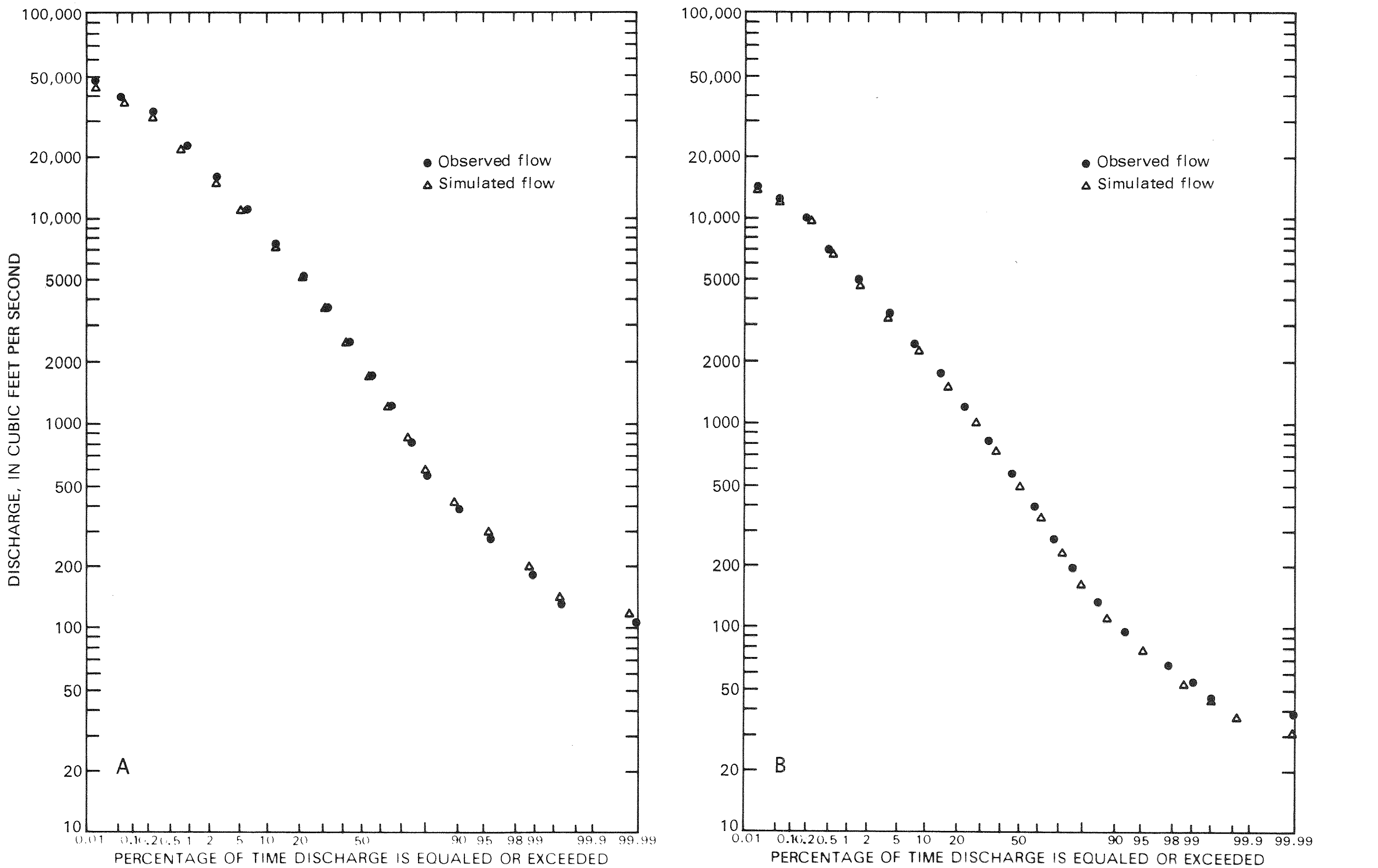



*Figure 6.--Flow-duration curves of observed and simulated daily discharges:*
*A, station 01503000, Susquehanna River at Conklin, 1942-77;*
*B, station 01507000, Chenango River at Greene, 1942-70.*

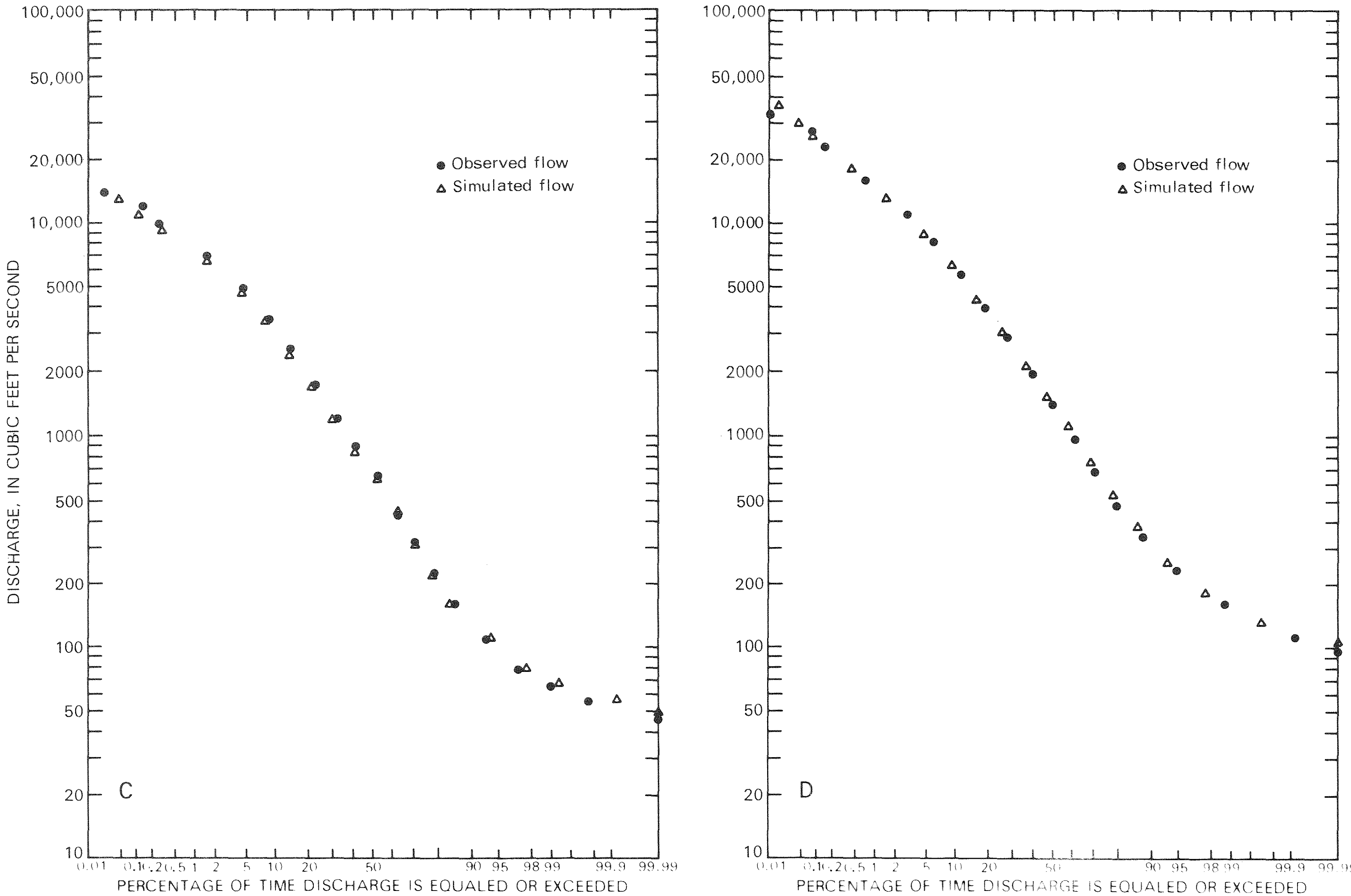



*Figure 6 (continued).--Flow-duration curves of observed and simulated daily discharges: C, station 01511500, Tioughnioga River at Itaska, 1942-66; D, station 01512500, Chenango River near Chenango Forks, 1942-77.*

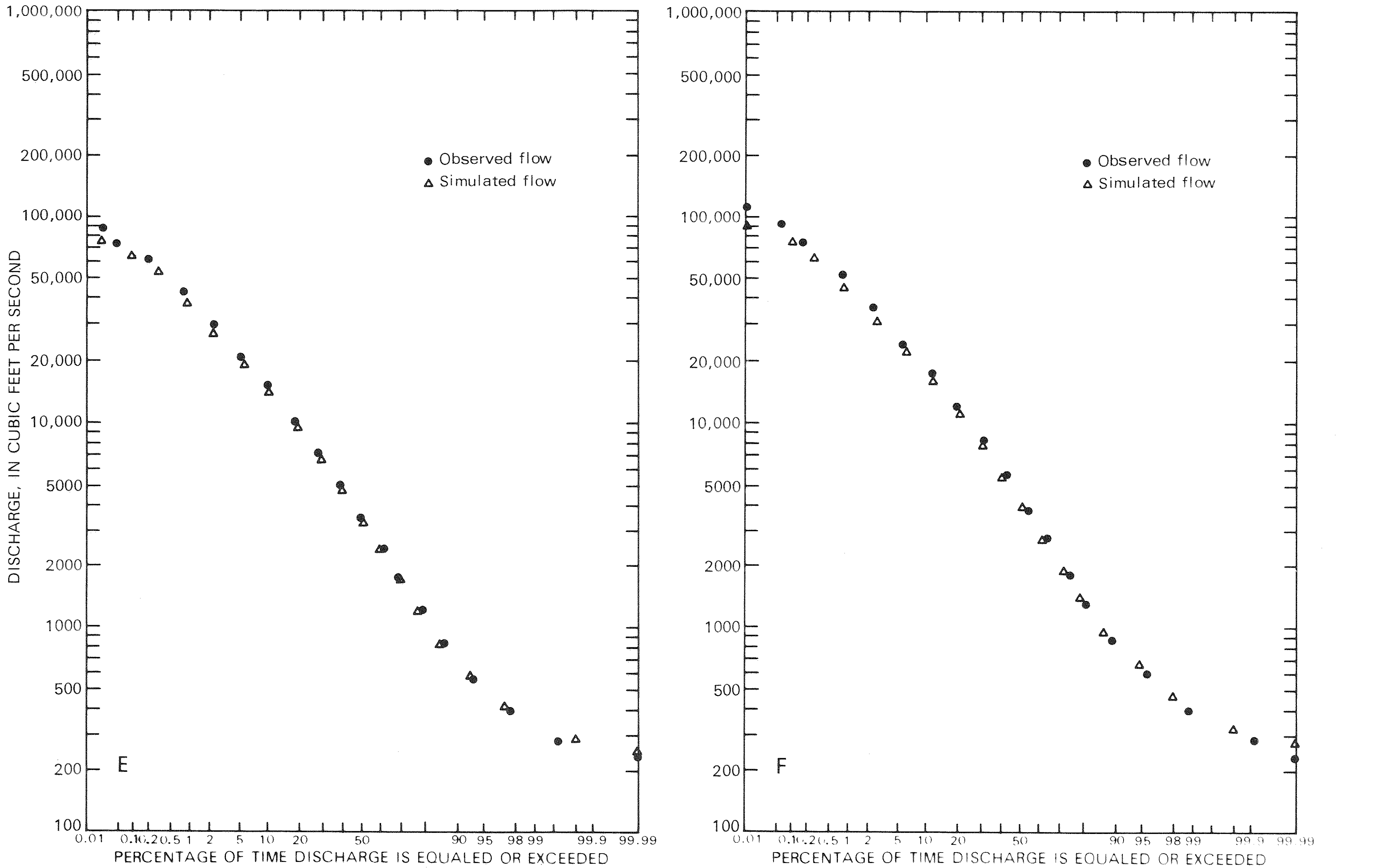



*Figure 6 (continued).--Flow-duration curves of observed and simulated daily discharges:*
*E, station 01513500, Susquehanna River at Vestal, 1942-66;*
*F, station 01515000, Susquehanna River near Waverly, 1942-77.*

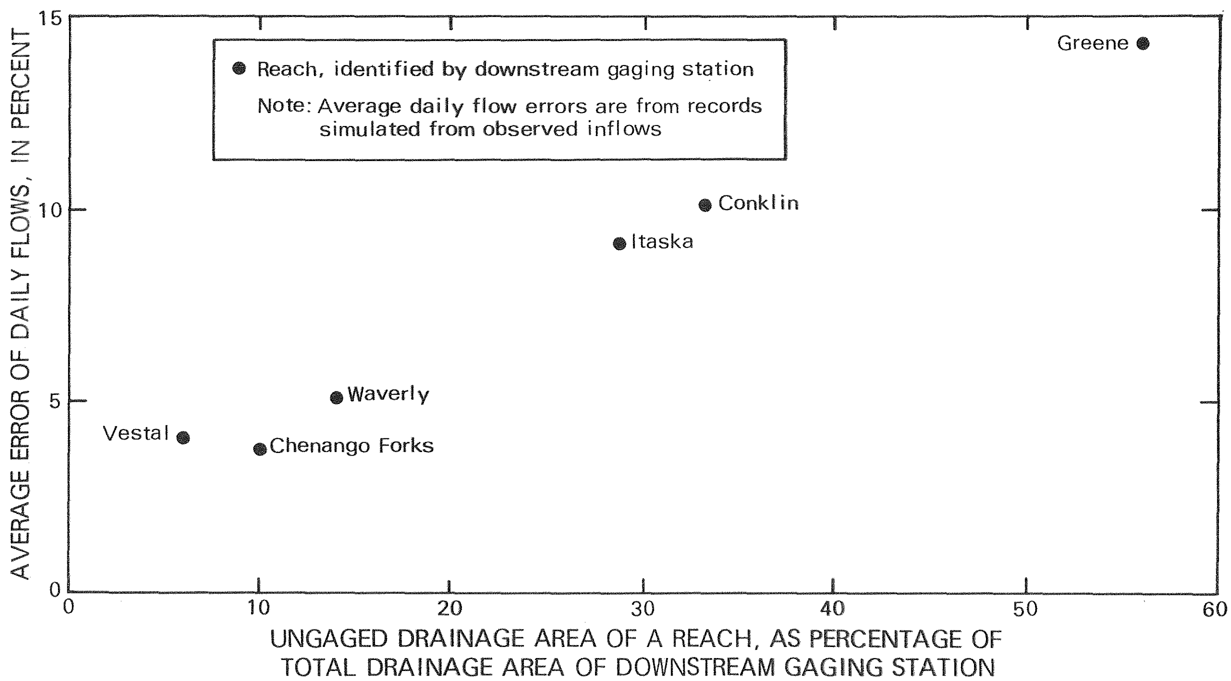



*Figure 7.--Relationship between ungaged drainage area in a reach and average error in simulated daily flows.*

## ALTERNATIVE DATA SOURCES FOR DOWNSTREAM MODELS

In the three downstream models (Greene to Chenango Forks, Conklin to Vestal, and Vestal to Waverly), some error results from the use of simulated rather than observed inflow records. For some applications of the models, certain modifications in use of inflow data result in better simulation of flows at Vestal and Waverly.

If the models are used to trace combined releases from Whitney Point Lake and East Sidney Lake to points downstream, they would be used as presented in figure 4. If the effects of releases only from Whitney Point are needed, however, the observed, rather than simulated, flows of Susquehanna River at Conklin could be used in the model for the Conklin to Vestal reach. Similarly, if the effects of releases from only East Sidney Lake are of concern, the observed rather than simulated flows of Chenango River near Chenango Forks could be used to model the reach from Conklin to Vestal.

The comparisons of average errors in daily flow errors and total volume for all reaches under all three alternatives are summarized in table 6.

*Table 6.--Comparison of errors produced by three data-input options[1] in model for two lowermost reaches.*

| Reach | Period (water years) | Difference (percent) | |
|---|---|---|---|
| | | Daily flows | Flow volume |
| Conklin to Vestal: | 1942-66 | | |
| Option 1 | | 8.8 | -3.9 |
| Option 2 | | 5.8 | -1.5 |
| Option 3 | | 6.9 | -2.7 |
| Vestal to Waverly: | 1942-77 | | |
| Option 1 | | 9.9 | -6.2 |
| Option 2 | | 7.6 | -4.0 |
| Option 3 | | 8.9 | -5.8 |

1 Option 1 uses simulated flows of both Conklin and Chenango Forks (combined Whitney Point Lake and East Sidney Lake releases).
Option 2 uses observed flows of Conklin and simulated flows of Chenango Forks (Whitney Point Lake release).
Option 3 uses simulated flows of Conklin and observed flows of Chenango Forks (East Sidney Lake release).

## APPLICATION OF MODELS

One application of the models is to trace releases from the two reservoirs to points downstream. As an example, hypothetical releases of water from East Sidney Lake and Whitney Point Lake were routed through the river system to Waverly. The releases were applied to flows during the summer and fall of 1964, a period during which sustained flows were the lowest ever recorded in the study area. Both the effect of the releases on flows at Waverly and the affect of the routing process on the releases themselves were examined.

The models treat outflows from each reservoir differently. The outflow from Whitney Point Lake are part of the direct input to the Cortland-to-Itaska model. The outflow of East Sidney Lake is implicitly accounted for in the record of Susquehanna River at Unadilla. Because the distance between East Sidney Dam and the gaging station on Susquehanna River at Unadilla is short (6.4 mi), flows are simply translated to the gaging station and added to the flow at Unadilla.

During the example period (summer and fall 1964), some water was actually being released from both East Sidney Lake and Whitney Point Lake. For the most part, these outflows amounted only to the daily inflows to the reservoirs.

Between September 21 and October 25, 1964, however, a fairly constant release averaging 105 $ft^3/s$ was made from Whitney Point Lake as the water was lowered from the recreation pool level to the conservation pool level. The hypothetical releases analyzed in the case of both reservoirs were made in addition to the observed historical releases mentioned above.

From the simulated flow record (1943-77 climatic years), the computed 7-day, 10-year low flow of Susquehanna River near Waverly is 405 $ft^3/s$. During the example period, the simulated daily flow fell below this level. The difference between the computed 7-day, 10-year low-flow discharge and the simulated historical discharge during the same period was used to derive the magnitude and duration of the hypothetical releases. The proportion of the total release obtained from each reservoir was made arbitrarily; the larger reservoir, Whitney Point Lake, contributed about two-thirds. The hypothetical releases were as follows:

From Whitney Point Lake, a constant release of 80 $ft^3/s$ was made between September 4 and September 20, 1964. No water was released again until October 25, when a constant release of 65 $ft^3/s$ was begun and sustained until November 20. From East Sidney Lake, a constant release of 40 $ft^3/s$ was made from September 10 to September 26, 1964, when the release was reduced to 20 $ft^3/s$ and maintained at that level until November 20.

In addition to routing the combined release from both reservoirs, the release of each reservoir was routed separately to Waverly. The effect of the routing process on the releases themselves is shown in figures 8A-8C. In these figures, the hydrograph of the release for the reservoir is plotted together with the hydrograph of the release for Waverly. The figures show that, at the ambient flow level in the system during the example period, the leading edge of a release from East Sidney Lake takes 4 days to reach Waverly, and the full release takes 6 days. When a release is made from Whitney Point Lake, the leading edge arrives at Waverly in 1 day, and the full release arrives in 3 days. The effect of the combined release on flows at Waverly are shown in figure 9.

Because the example period represented the lowest sustained flows on record in the Upper Susquehanna River basin, the traveltimes of these releases may be regarded as the longest that are likely to occur. As flow in the system increases, traveltimes decrease.

At present, use of either East Sidney Lake or Whitney Point Lake for low-flow augmentation has not been authorized, and no alternative operating schemes for this purpose have been proposed. The streamflow-routing models developed for this study can serve as a useful component in an investigation of downstream effects of releases to augment low flow. By use of reservoir-routing models, reservoir outflow records based on a hypothetical operating procedure can be simulated for the base period (1942-77), and these simulated flows can then be used with the flow-routing models to simulate hypothetical daily flow records at all downstream gaging stations. The effects of the operating procedures may then be measured by comparing simulated historical and hypothetical flow periods, low-flow frequency characteristics, and flow-duration curves.

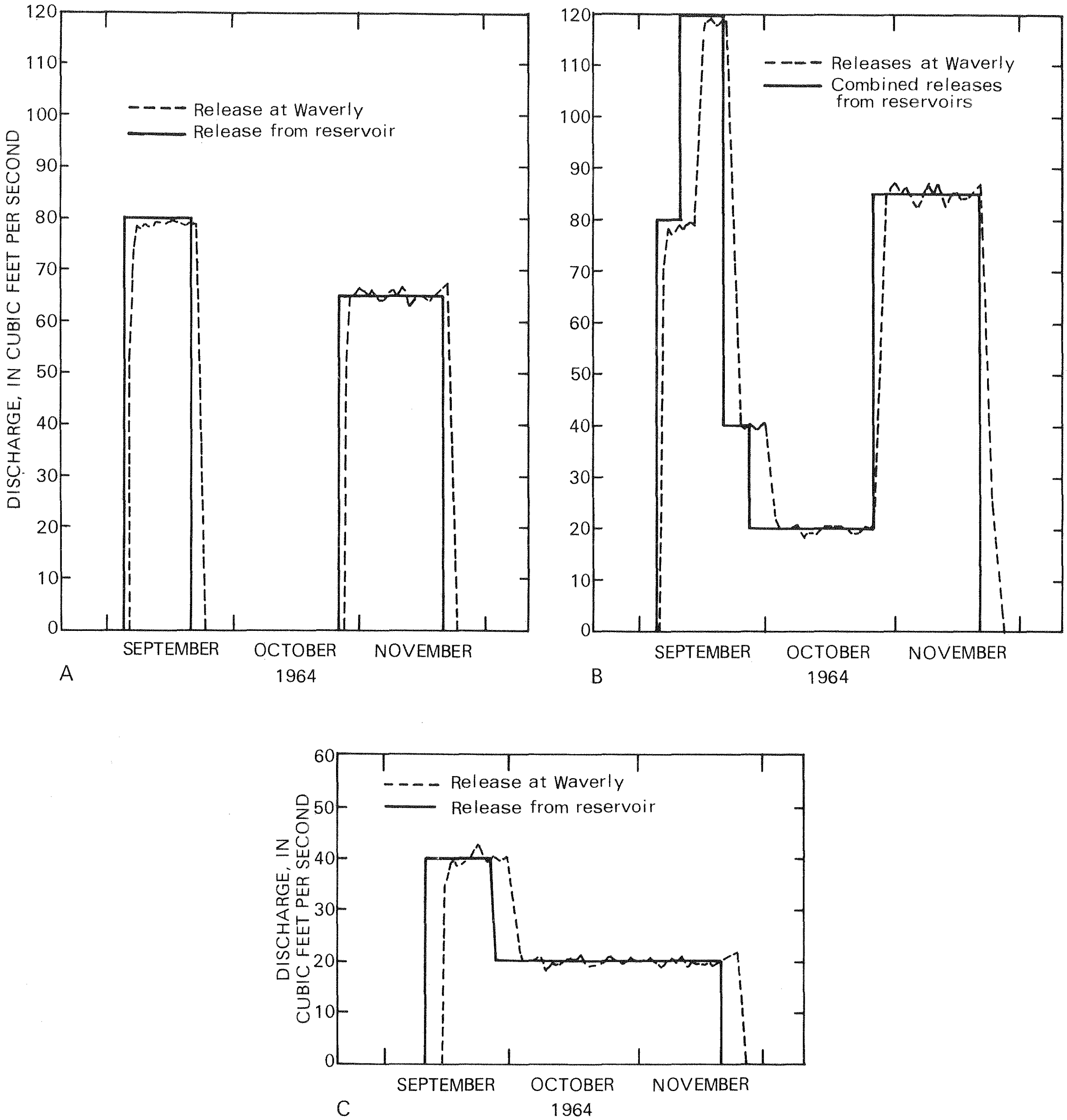



*Figure 8.--Comparison of hypothetical releases as they appear at indicated reservoirs and at Susquehanna River at Waverly, September-November 1964:*
*A, release from Whitney Point Lake;*
*B, release from East Sidney Lake;*
*C, combined releases from Whitney Point and East Sidney Lakes.*

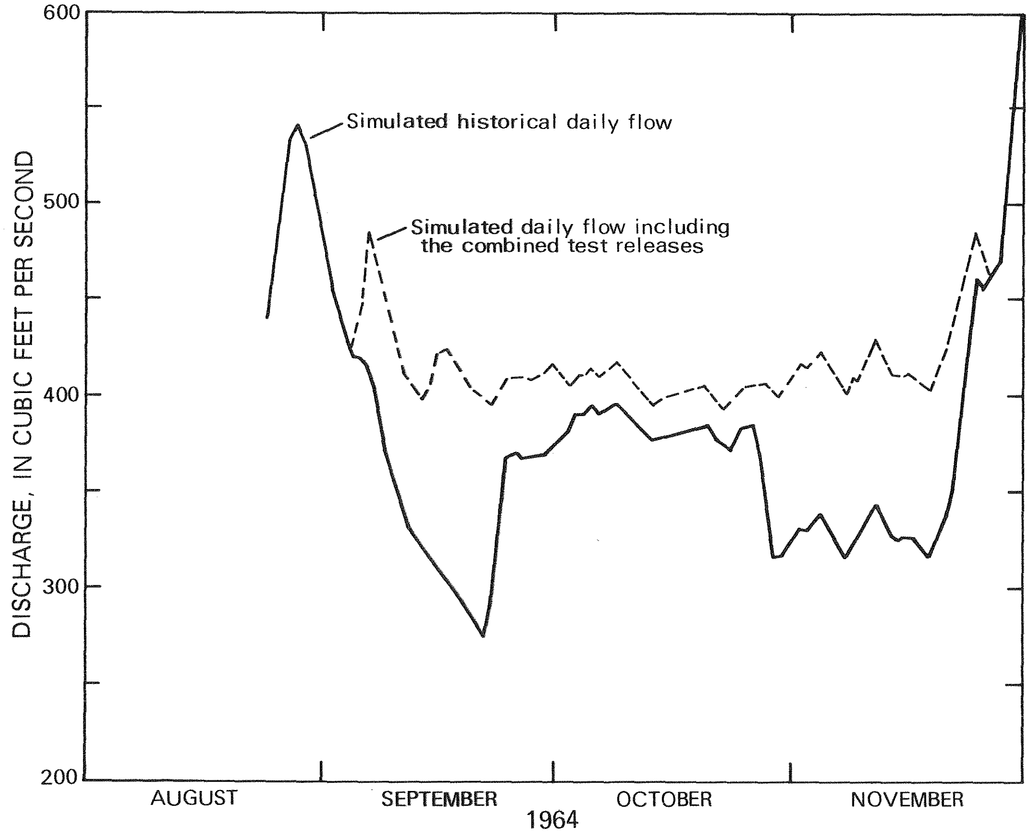



*Figure 9.--Comparison of simulated historical hydrograph and simulated hydrograph containing hypothetical releases, Susquehanna River near Waverly, September-November 1964.*

## SUMMARY

Six flow-routing models of selected reaches of three major streams in the eastern part of the Susquehanna River basin in New York State have been developed. The Susquehanna River models represent the area from the gaging station near Unadilla to the one at Waverly; the Chenango River models extend from the Sherburne gaging station to the mouth, and the Tioughnioga River models represent the reach from the Cortland gaging station to the mouth.

The models are used to simulate daily flows at the downstream end of each reach. They are based on the unit-response method of flow routing, assuming the diffusion analogy and using multilinearization. Convolution techniques were used to generate the downstream hydrograph.

The overall accuracy of the models, as measured by the average difference between observed and simulated daily flows over the base period, 1942-77, was within the average stated accuracy of the published streamflow records used in the simulation. The smaller the percentage of ungaged drainage area in a reach, the more accurately the models performed.

In general, low-flow characteristics and flow-duration curves computed from simulated records compared favorably with those computed from actual records. Differences between observed and computed low flows were relatively large, however, at high recurrence intervals for Chenango River at Greene and Tioughnioga River at Itaska, and at the low recurrence intervals for Chenango River near Chenango Forks, Sherburne to Greene, and Cortland to Itaska.

To illustrate one application of the models, hypothetical releases were made from East Sidney Lake and Whitney Point Lake and traced downstream to the Waverly gaging station. The leading edge of the East Sidney release arrived 4 days after it was begun, and the full release arrived in 6 days. The leading edge of the Whitney Point release arrived at Waverly on the day after it was begun, and the full release arrived in 3 days.

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