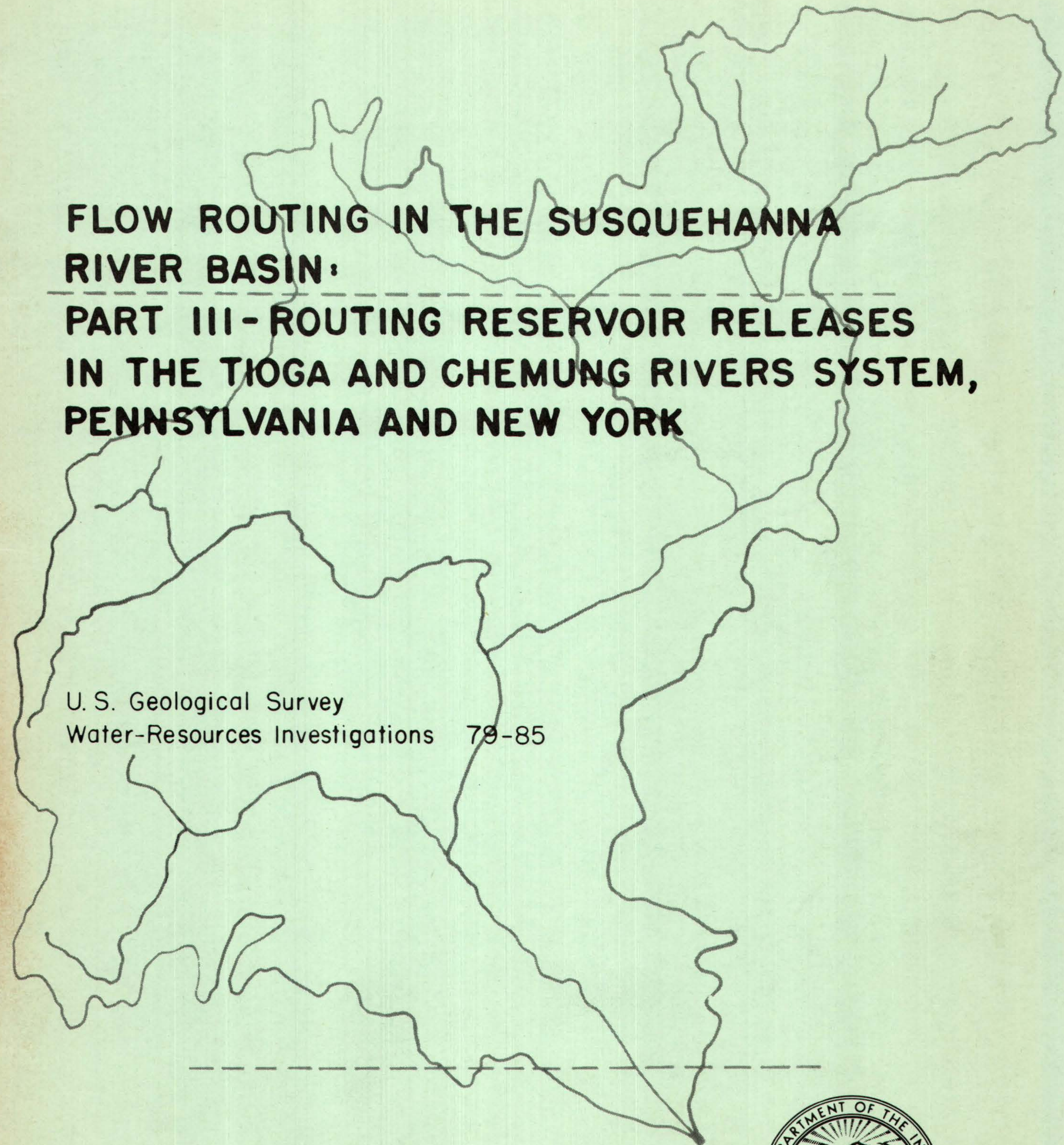

FLOW ROUTING IN THE SUSQUEHANNA RIVER BASIN: PART III - ROUTING RESERVOIR RELEASES IN THE TIOGA AND CHEMUNG RIVERS SYSTEM, PENNSYLVANIA AND NEW YORK

U. S. Geological Survey
Water-Resources Investigations 79-85

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UNITED STATES DEPARTMENT OF THE INTERIOR

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FACTORS FOR CONVERTING INCH-POUND UNITS TO INTERNATIONAL SYSTEM (SI) UNITS

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
	Length	
inch (in)	25.4	millimeters (mm)
foot (ft)	.3048	meters (m)
mile (mi)	1.609	kilometers (km)
	Area	
square mile (mi^2)	2.590	square kilometers (km^2)
	Flow	
cubic foot per second (ft^3/s)	.02832	cubic meters per second (m^3/s)
square foot per day (ft^2/d)	.0929	square meters per day (m^2/d)
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FLOW ROUTING IN THE SUSQUEHANNA RIVER BASIN: PART III - ROUTING RESERVOIR RELEASES IN THE TIOGA AND CHEMUNG RIVERS SYSTEM, PENNSYLVANIA AND NEW YORK

By Jeffery T. Armbruster

ABSTRACT

Channel-routing models were used to route hypothetical releases from reservoirs in the upper Tioga River basin, Pennsylvania. These releases were routed northward down the Tioga River to Lindley, Erwins, and Corning, New York; combined with flows routed down the Cohocton River from Campbell to Corning, New York; and then routed southeastward down the Chemung River from Corning to Chemung, New York. The models used to route the flows of Cohocton and Chemung Rivers accounted for bank-storage discharge and streamflow depletion by well pumpage. In general, 17 water years of concurrent streamflow data were available for model calibration and verification.

Three hypothetical reservoir releases were made from the reservoirs and routed to Wilkes-Barre, Pennsylvania, using the models developed in this study and models developed downstream to Wilkes-Barre in a previous study (Bingham, 1979). A hypothetical make-up water requirement of 65 cubic feet per second was assumed. Two historical low-flow periods were investigated. The first hypothetical release investigated was a constant 100 cubic feet per second, and the second release was a constant 70 cubic feet per second. The third scheme was a hypothetical release of 100 cubic feet per second for 3 days followed by a constant 70 cubic feet per second for the duration of the period considered. Constant 100 cubic feet per second releases arrived downstream more quickly than constant 70 cubic feet per second releases for both test periods, but delivered more water than required to satisfy the assumed make-up requirement. The third release scheme was generally the most efficient of the three schemes tested.

Although inherent modeling errors exist in all the simulated data, the accuracy of the estimated routed reservoir releases at the downstream sites is considered good.

INTRODUCTION

Management of the water resources of a river basin often requires information on the effects of a future change in the water resources system before implementing the change. Hydrologic models can be valuable tools for estimating the probable effects of such changes. The models must be able to reproduce, within reasonable limits, actual or proposed field conditions. Computer routines, based on well-known and proven hydrologic concepts, are used for computations.

In 1975, the U.S. Geological Survey and the Susquehanna River Basin Commission (SRBC) began a series of cooperative projects designed to calibrate flow-routing models for all major streams in the Susquehanna River basin. The flow-routing models will provide the SRBC with the capability to translate or transfer the effects of proposed water resources developments anywhere in the basin to points downstream. The first study (Armbruster, 1977) focused on the Juniata River, downstream from Raystown Lake, and the Susquehanna River from Sunbury, Pa. to Conowingo, Md. Effects of Raystown Lake on downstream low-flow frequency characteristics were estimated. The second project (Bingham, 1979) examined the Susquehanna River from Waverly, N.Y. to Sunbury, Pa.

The current study, third in the series, involves the Tioga River downstream from the Tioga-Hammond and Cowanesque Reservoirs and the Chemung River from the confluence of the Tioga and Cohocton Rivers to its mouth near the N.Y.-Pa. border. Models are developed to route releases of water from the Tioga-Hammond and Cowanesque Reservoirs to downstream points. These flood control reservoirs are currently (1978) under construction by the U.S. Army Corps of Engineers. Consumptive water users in the Susquehanna River basin are required by SRBC regulation to augment streamflow by the amount of their consumptive use whenever streamflow falls below a specific criterion, to be discussed later. Releases from the reservoirs may be able to provide the necessary make-up water.

The streamflow routing model used here (Land, 1977) considers the ground water-surface water interaction near the stream. Water losses due to bank storage and well pumpage are modeled. Bank-storage losses must be considered because the streams flow through alluvial aquifers that significantly affect streamflow. Hereafter, routing with bank-storage and well-pumpage losses considered will be called interactive routing.

Travel time and bank-storage losses are analyzed by releasing volumes of water, using a reservoir release model, from the new reservoirs in the Tioga River basin. Reservoir releases are superimposed onto observed low streamflows and routed downstream. Downstream hydrographs for simulated natural and regulated flows are compared to determine the effects of the release at downstream sites.

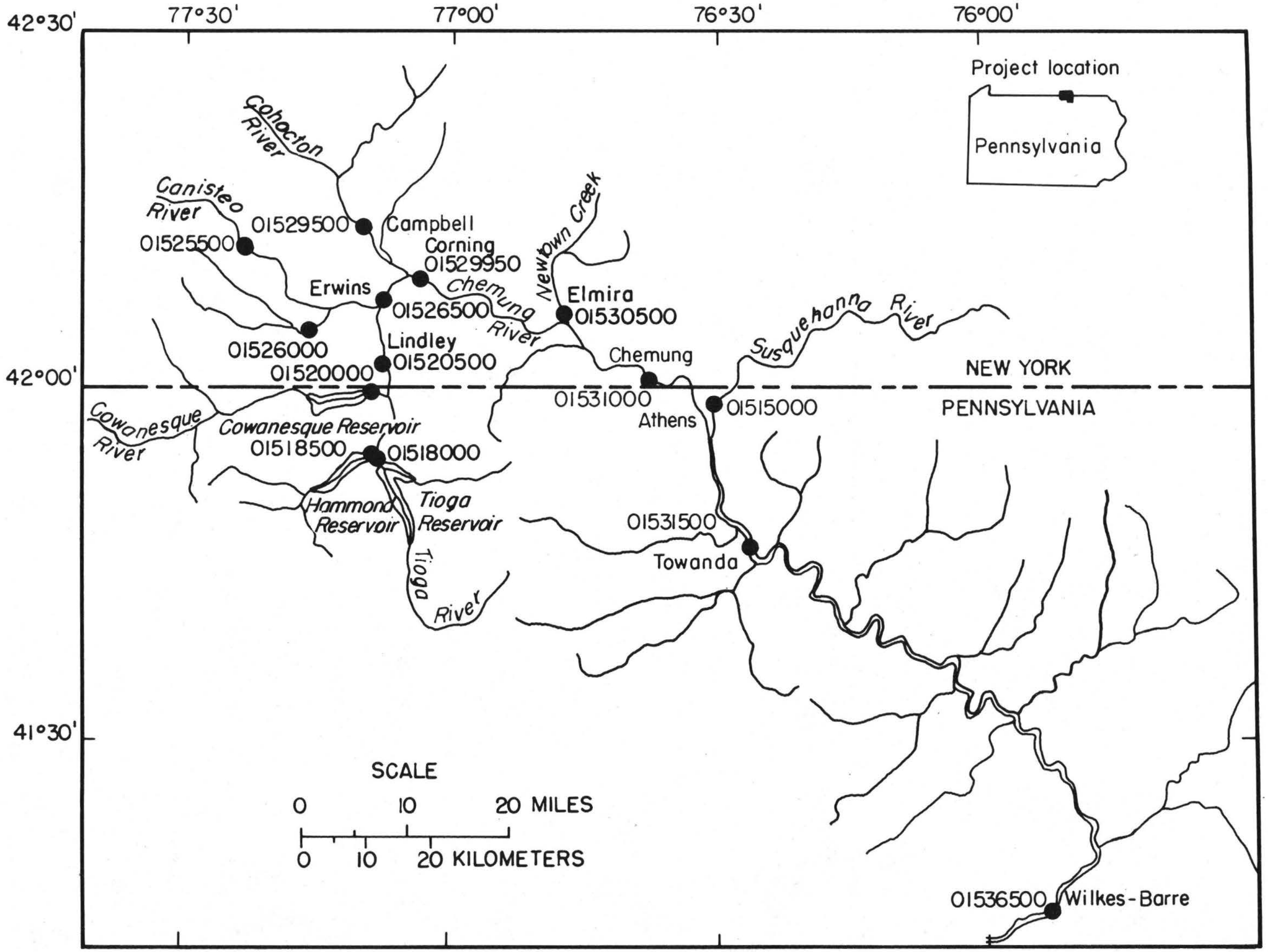


Figure 1.--Map of study area.

The analyses presented here are not intended to simulate the operation of the new reservoirs as done by Armbruster (1977) for Raystown Lake. Instead, calibrated streamflow routing models are used to examine the effects of several hypothetical reservoir release patterns.

DATA USED IN MODELING

Streamflow records for 11 regular gaging stations were used in the modeling of the study reaches. A summary of those data are given in table 1. Locations of the stations are shown in figure 1. The concurrent period of 1954-70 water years was available for direct use in the modeling effort for all of the stations except station 01529950, Chemung River at Corning, N.Y. The 3 years of data (1975-77 water years), which were available for station 01529950, were used indirectly to calibrate and verify a procedure to estimate flows at Corning.

Data on the characteristics of the alluvial aquifer underlying the Cohocton and Chemung River valleys were available from several sources (Seaber, 1968; Hollyday, 1969; MacNish, Randall, and Ku, 1969; and Reisenauer, 1978). Data from these reports include the areal and depth extent of the alluvial aquifers, aquifer properties, volumes of municipal pumpage, and base flow estimates.

Table 1.--Data ~~available for use~~ used in routing study.

Station Number	Station Name	Water years of Record	Drainage area (mi^2)
01518000	Tioga River at Tioga, Pa.	1939-77	282
01518500	Crooked Creek at Tioga, Pa.	1954-74	122
01520000	Cowanesque River near Lawrenceville, Pa.	1952-77	298
01520500	Tioga River at Lindley, N.Y.	1931-77	771
01525500	Canisteo River at West Cameron, N.Y.	1938-70	340
01526000	Tuscarora Creek near South Addison, N.Y.	1938-70	114
01526500	Tioga River near Erwins, N.Y.	1919-77	1377
01529500	Cohocton River near Campbell, N.Y.	1919-77	470
01529950	Chemung River at Corning, N.Y.	1975-77	2006
01530500	Newtown Creek at Elmira, N.Y.	1939-77	77.5
01531000	Chemung River at Chemung, N.Y.	1904-77	2506

DESCRIPTION OF STUDY REACHES

The Chemung River, formed by the confluence of the Cohocton and Tioga Rivers at Corning, N.Y., flows southeastward from Corning to Athens, Pa., where it enters the Susquehanna River. Its total length is about 45 river miles. The Cohocton and Canisteo Rivers drain the northwestern part of the Susquehanna River basin. The Cohocton flows generally southeastward to Corning. The Canisteo also flows generally southeastward and joins the Tioga River about 5 miles upstream from Corning. The Tioga flows generally northward out of Pennsylvania into New York.

The valleys of these rivers are underlain by unconsolidated sediment of glacial and alluvial origin, at least 70 feet thick and locally up to a few hundred feet in thickness. These unconsolidated deposits may be thought of as a single aquifer--or, on a smaller scale, as several separate sand-and-gravel aquifers separated by silt and clay layers. According to Hollyday (1969, Pl. 5) the principal sand-and-gravel aquifers range in thickness from less than 10 to more than 40 feet and generally lie at or not far below river level. In most places, the rivers are in direct contact with these aquifers. The unconsolidated sediments underlying the Chemung River range in width from about 1800 feet in a gorge upstream from Elmira, N. Y., to more than 8000 feet near Big Flats, N.Y. Available data describing the aquifers underlying the Tioga River are only general. No information was found on the transmissivity (T) or storage (S) characteristics of this aquifer. Because of the lack of data on T and S, the ground water-surface water interaction could not be modeled here. More discussion on this topic will be presented later.

Three reservoirs are currently being constructed by the U.S. Army Corps of Engineers in the Tioga River basin. Tioga Reservoir is on the Tioga River near Tioga, Pa. At a normal summer pool elevation of 1081 feet above the national geodetic vertical datum (ngvd), the Tioga Reservoir covers 570 acres and has 9500 acre-feet of storage. Hammond Reservoir is located on Crooked Creek near Tioga, Pa. It has an area of 640 acres and storage of 8850 acre-feet at the normal summer pool elevation of 1086 feet above msl. Tioga and Hammond Reservoirs are connected by a canal and have a common outlet structure. For that reason they are generally considered to be one structure called the Tioga-Hammond Reservoir.

The third reservoir, Cowanesque Reservoir, is under construction on Cowanesque River about 3 miles upstream from its confluence with Tioga River, or 2.3 miles upstream from Lindley. Cowanesque Reservoir has an area of about 410 acres and storage of 7000 acre-feet at the design summer pool elevation of 1045 ft above ngvd.

A summary of distances to key locations in the study area, referenced to the mouth of the Chemung River, is given in table 2.

Table 2.--Distances to key locations in the study areas (from U.S. Army, Corps of Engineers, 1974).

Location	River Mile (mi)
Mouth of Chemung River	0.0
Gaging station 01531000	12.2
Gaging station 01530500	26.4
Gaging station 01529950	43.2
Confluence of Cohocton and Tioga Rivers	45.0
Gaging station 01526500	48.0
Mouth of Canisteo River	49.1
Gaging station 01520500	55.7
Mouth of Cowanesque River	58.1
Gaging Station 01520000	60.6
Mouth of Crooked Creek	65.2
Gaging station 01518500	68.2
Gaging station 01518000	66.2
Mouth of Cohocton River	45.0
Gaging station 01529500	58.0

For the purpose of this study the streams were divided into the four reaches described in table 3.

Table 3.--Description of study reaches.

Put on map

Reach Number	Description
1	Tioga-Hammond and Cowanesque Reservoirs to Erwins, N.Y.
2	Tioga River from Erwins, N.Y. to Corning, N.Y.
3	Cohocton River from Campbell, N.Y. to Corning, N.Y.
4	Chemung River from Corning, N.Y. to Chemung, N.Y.

DESCRIPTION OF MODELS

Two types of models were used to simulate the downstream movement of reservoir releases in the Tioga-Chemung River system: a reservoir-routing model and a channel-routing model. The reservoir-routing model couples the principle of mass conservation with the operation of the outflow structures to determine reservoir outflows. Reservoir outflows are used as inflows to the channel-routing models. While routing upstream flows to points downstream, the channel routing models also accounted for water losses from the stream to bank storage and to ground-water withdrawals in the Cohocton and Chemung River reaches. A daily routing interval was used throughout the study.

Because of the importance of the data being simulated by the models, it is necessary that (1) modeling adequacy be defined as well as possible, and (2) the maximum practical degree of model adequacy be obtained. To achieve these goals, as much observed data as possible must be used to verify and evaluate these models (Shearman and Swisshelm, 1973). A period of 17 years (1954-70 water years) of concurrent streamflow data was available to describe the pre-reservoirs condition at Erwins, Campbell, and Chemung. The observed flows (1975-77 water years) at Corning were used to verify a simulated concurrent record at Corning.

Observed and simulated pre-reservoir streamflows were compared at Erwins, Corning, and Chemung to evaluate the adequacy of the models. About 10 percent of the drainage area of the Tioga River upstream from Lindley is not gaged by the gaging stations on the Tioga River at Tioga, Crooked Creek at Tioga and Cowanesque River at Lawrenceville. All gaging station records near the ungaged area were examined and tried in numerous combinations to account for the ungaged flow between the reservoirs and Lindley. These various combinations all resulted in larger errors in flow simulated at Lindley than were obtained by simple translation of hydrographs from the reservoirs to Lindley. For that reason the simple translation model was used to obtain the flows at Lindley.

Water released from the Tioga-Hammond and Cowanesque Reservoirs was routed downstream to Chemung by the use of models developed for this study, then routed to Wilkes-Barre, Pa. by the use of models presented by Bingham (1979). The following discussion summarizes the concepts and procedures used in routing reservoir releases, including determining travel time and bank-storage losses of reservoir releases in the Tioga, Cohocton, and Chemung Rivers.

Channel-Routing Models

Four channel routing models were developed during this study. The first two, for reaches 1 and 2, were simple hydrograph translation models. The model for reach 1 translates the differences between natural reservoir inflows and regulated reservoir outflows to Lindley then translates the flows at Lindley to the downstream end of the reach at Erwins, estimates ungaged flows, and adds all gaged tributary inflows to the reach. Parts of tributary flows were lagged or time delayed to change the hydrograph shape. Ungaged flow was estimated by multiplying flows for a suitable gaged site by the ratio of ungaged drainage area to area at the gage site. Trial-and-error adjustments to the initial ratios were made to minimize error in both daily discharges and flow volume. The amount of water that was time delayed or lagged was also determined on a trial and error basis. Hydrograph shape was the adjustment criterion. Flows for reach 2 were translated directly from Erwins to Corning. Reach 2 is discussed further later. Ground-water influences were not explicitly included in these simple translation models.

The models used for the second two reaches, reaches 3 and 4, were unit-response flow-routing models that were linked to procedures describing bank-storage discharge and streamflow depletion by wells (Land, 1977). The unit response functions for the streamflow-routing part of the model were computed using the diffusion analogy (Keefer, 1974). The model has two parameters--wave celerity and wave dispersion. Celerity describes how rapidly the water travels downstream. Dispersion describes how the water wave dampens or attenuates. Models of this type were used by Armbruster (1977) and Bingham (1979).

Ground-water discharges were explicitly accounted for by computing discharge into and out of bank storage and by computing streamflow depletions caused by pumping wells. The alluvial aquifers underlying reaches 3 and 4 were assumed to have finite width, that is, have an effective aquifer boundary at a measurable distance from the stream. The bank-storage hydrograph was computed by the "convolution technique" (Hall and Moench, 1972). Convolution is an accumulation process. For each time step in the convolution, the hydraulic gradient at the interface between the river and the aquifer was calculated by a unit-response function for a finite aquifer (Hall and Moench, 1972). Although a stream-aquifer system never reaches steady-state after a pulse of water is input, for practical applications, the response function was allowed to vanish after a specified time, as explained by Land (1977). The hydraulic gradient was then multiplied by the transmissivity of the aquifer and by the change in stream stage during the time step. This product was doubled to include both sides of the stream and multiplied by the length of the alluvium in the stream reach to obtain bank-storage discharge. Bank-storage discharge can be either into or out of the aquifer.

Characteristics of the aquifer used here are transmissivity, storage coefficient, and aquifer width and length. One important limitation placed on these characteristics by the model is that only one value of each can be specified for each reach. This limitation means that the values used must represent the average condition or value for the entire reach. For example, if the aquifer width at the upstream end of the reach is 1000 feet and uniformly widens to 2000 feet at the downstream end, the average width would be 1500 feet.

Water diverted from the stream by well pumping was computed by an analytical expression given by Glover and Balmer (1954). In simple terms, the expression uses time, pumping rate (assumed constant), distance of the well from the stream, and the transmissivity and storage coefficient of the aquifer. After several days, equilibrium is reached--streamflow depletion equals pumpage.

Reservoir-Routing Model

A reservoir-routing model was developed for operating the combined Tioga-Hammond and Cowanesque Reservoirs system. The purpose of this model was to simulate the release of specified volumes of water for specified periods of time from any of the reservoirs. The time periods and volumes were chosen somewhat arbitrarily. The model was operated by routing observed flows into the reservoirs, releasing water from one or both reservoir-outlet structures, and accounting for changes in storage within each reservoir.

The model was designed to release water from one of the reservoirs in specified amounts, to be used in tracing travel time and transmission losses of a slug of water to points downstream. Releases in the hypothetical examples presented later were from the Cowanesque Reservoir. Because data on the aquifer between the Conwanesque Reservoir and the gaging station at Lindley were insufficient the releases were translated directly to Lindley. Insufficient data on the aquifers and surface drainage tributaries between the Tioga-Hammond Reservoirs and Lindley also prevented routing flows. Thus, outflows from the Tioga-Hammond Reservoirs were also translated directly to Lindley. Therefore, if 100 ft^3/s of water was released from either reservoir, the flow of the Tioga River at Lindley (1520500) would increase by 100 ft^3/s. Although some error is introduced here, the error is probably not significant.

The SRBC requires consumptive water users to "make up" consumptive losses. Make-up is required whenever the flow of the source stream drops below the sum of the 7-day 10-year low flow and the consumptive loss. The 7-day 10-year low flow is the flow that is equal to or less than the flow taken from a frequency curve of annual minimum 7-consecutive day average flows at a recurrence interval of 10 years. Releases required from an upstream reservoir to provide a specific volume of flow to locations downstream are made using the reservoir regulation model.

A second release option was planned to simulate a typical daily reservoir-release schedule. The purpose of this option was to simulate the low-flow frequency characteristics of streams downstream from the reservoirs. The actual daily release schedules, however, were not available; therefore, the effect of releases on low-flow characteristics could not be evaluated.

A comparison of evaporation (Rahn, 1973) and precipitation data near the reservoirs indicated little difference between surface evaporation and precipitation onto the lake surfaces. Any improvement in overall accuracy of the model by including these factors would probably have been offset by errors in measuring or estimating their daily values. Therefore, evaporation from and precipitation onto lake surfaces were excluded from the analyses.

MODEL CALIBRATION

Each of the four channel-routing models, required calibration is, determining through successive trials what values of model parameters result in the most accurate simulation of observed streamflow records. Because two general types of channel-routing techniques were used, they will be discussed separately.

The calibration of the models for reaches 1 and 2 was relatively simple.

1. Several periods of concurrent streamflow records at the upstream and downstream ends of the study reaches were selected as calibration periods.

2. A trial set of drainage-area ratios to be used in accounting for flows from ungaged areas was computed. For reach 2, no tributary flows were added to the flows at the upstream end of the reach. Rather, flows from Erwins were translated directly to Corning and added to routed flows from reach 3. Modeling of reach 2, therefore, consisted of translating inflows to the reach to Corning. Flows from station 01530500, Newtown Creek, were used to account for ungaged flows in reach 3.

3. Outflows from reach 1 were simulated by summing observed flows at Lindley and tributary inflows using the drainage area ratios. Regulated flows from the upstream reservoirs do not affect model calibration because calibration was based on observed flows.

4. Simulated outflows from reach 1 were evaluated on the basis of a visual comparison of hydrograph plots of observed and simulated outflows, the average absolute deviations between simulated and observed daily flows, and the volume difference between observed and simulated streamflow sequences for each calibration period.

5. Time delays, or lags, were introduced and (or) drainage area ratios were adjusted. Time delay as used here is simply a method of altering the shape of the downstream hydrograph. For example, if the inflow to the reach were lagged by 1 day, the flow for day 1 arrives downstream on day 2. Steps 3, 4, and 5 were repeated until the errors in step 4 seemed to reach a minimum. On figure 2, the coefficients applied to the Q's are the final drainage-area ratios used and were derived in the calibration process.

Calibration of the models used for reaches 3 and 4 was much more complex because of the many parameters included in those models. In addition to wave celerity and the wave dispersion coefficient used in the streamflow-routing part of the model, aquifer characteristics had to be determined in order to calculate the bank storage changes and pumping effects. Four aquifer properties were included in the model--transmissivity, storage coefficient, and aquifer width and length. The calibration process for these models follows the same guidelines discussed above, plus one additional step. That step is added between steps 2 and 3 and will be called 2a.

see p.9

2a. Initial values of the dispersion coefficient and celerity were estimated by the relations presented by Keefer and McQuivey (1974). Initial estimates of transmissivity and storage coefficients were obtained from Reisenauer (1978) and Hollyday (1969). Pumping data were based on information provided by Randall (personal commun., 1978) and Hollowell (personal commun., 1978). Aquifer width and lengths were estimated from topographic maps, assuming the aquifer to be nearly coincident with the valley bottom.

A schematic diagram of the four study reaches and the final relations used to generate flows at the downstream end of reaches 1, 3, and 4 is presented in figure 2. The relations shown were used for simulating pre-reservoir conditions. Final parameters used with the models for reaches 3 and 4 are given in table 4.

The errors discussed in step 4 and summarized in table 5 were computed using the relations:

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

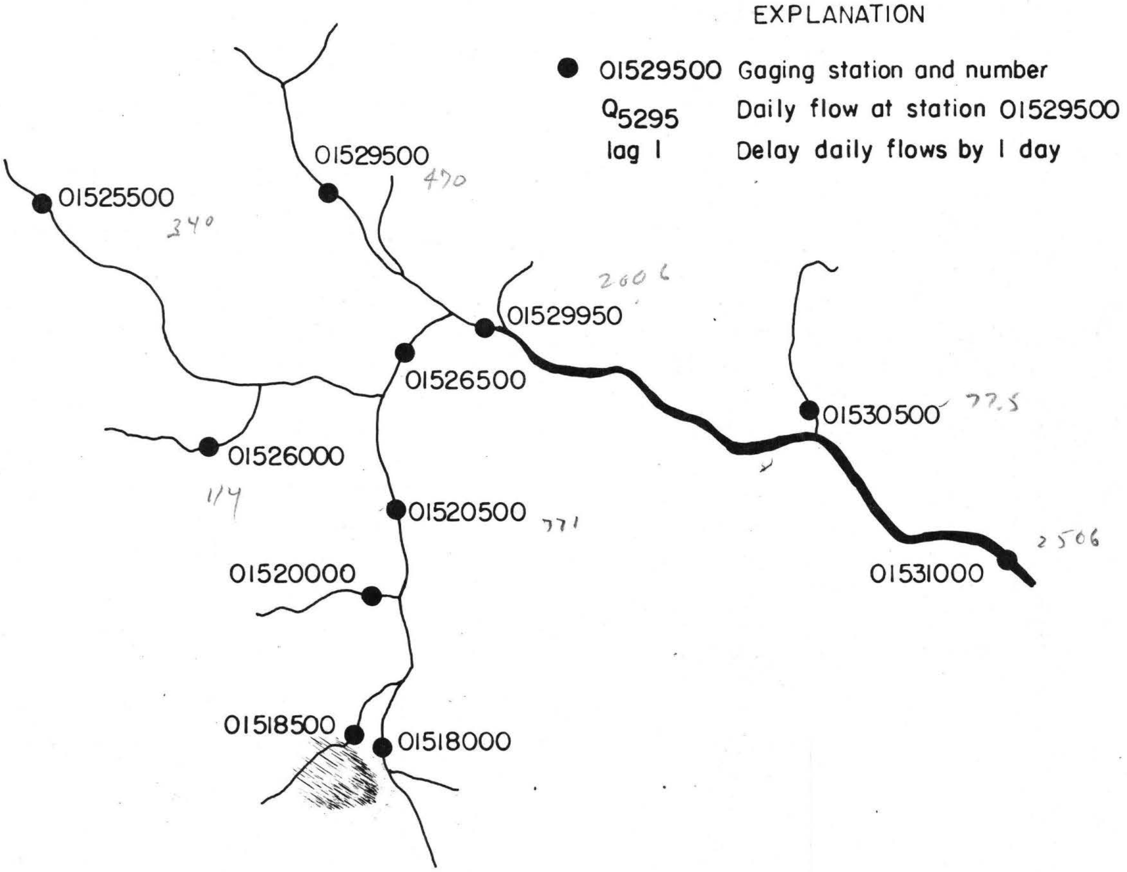
where Q_o and Q_s are observed and simulated flows in ft^3/s, respectively, for the i th day, and n is the number of days in the calibration period; and

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

where V_o and V_s are observed and simulated flow volumes in ft^3/s - days, respectively for a calibration period. Volume errors as used here does not represent water lost or gained in the channel reach. Rather, it is the difference between observed and simulated volumes at the downstream site.

Reaches 2 and 3 have been combined for the purpose of showing calibration errors. The downstream end of both reaches is at Corning, just downstream from the confluence of the two reaches. Thus, there is no basis for comparison, except as a combined reach.

Errors in daily flows encountered during calibration ranged from 6.7 percent in reach 1 to 11.5 percent in reach 4. Errors in flow volume ranged from -6.3 percent in reach 4 to +4.9 percent in reaches 2 and 3.



$$Q_{5265} = Q_{5205} + 0.90 \times Q_{5255}(\text{lag } 1) + 2.00 \times Q_{5260} + 0.20 \times Q_{5295}$$

$$Q_{5299.5} = Q_{5265} + \underbrace{Q_{5295}}_{\text{Routed interactively}} + 2.00 \times Q_{5305}$$

$$Q_{5310} = \underbrace{Q_{5299.5}}_{\text{Routed interactively}} + 3.50 \times Q_{5305}(\text{lag } 1) + 0.50 \times Q_{5295}$$

NOTE: Flows for reach 2 are translated from Erwins to Corning.

Figure 2.--Schematic diagram of the study reaches showing relations used in model calibration.

Table 4.--Summary of parameters used in final interactive channel-routing models

	For gaging station	
	01529950	01531000
Length of channel, mi	14.8	31.0
Length of unconsolidated aquifer, mi	13.0	27.0
Width of unconsolidated aquifer, ft	2400	3200
Transmissivity, ft^2/day	10000	10000
Storage coefficient, dimensionless	0.15	0.15
Wave celerity, ft/s	2.70	6.00
Wave dispersion coefficient, ft^2/s	1000	3000
Well pumpage (ft^3/s)	---	18.0*
Loss from stream using base flow reduction (ft^3/s)	0	20.0*
Average distance of pumped wells from stream (ft)(Randall, personal commun, 1978)	---	300

* Total loss based on data provided by Hollowell (personal commun 1978).

Table 5.--Model calibration errors.

Reach Number	Calibration period	Errors (percent) Daily Flows	Errors (percent) Flow Volume	% ungaged
1	Oct. 10, 1957 to Sept. 30, 1958	6.9	1.6	
	Oct. 10, 1962 to Sept. 30, 1964	6.8	4.7	
	Oct. 10, 1967 to Sept. 30, 1968	6.7	1.3	
2 and 3	Dec. 10, 1974 to Sept. 30, 1975	8.2	-3.0	
	Oct. 1, 1975 to Sept. 30, 1976	9.0	-4.9	18.4
	Oct. 1, 1976 to Sept. 30, 1977	8.0	4.8	
4	Dec. 10, 1974 to Sept. 30, 1975	11.5	-6.0	
	Oct. 1, 1975 to Sept. 30, 1976	10.6	-2.6	16.9
	Oct. 1, 1976 to Sept. 30, 1976	9.9	-6.3	

Figures 3 and 4 are examples of typically good and poor fits, respectively, of the data generated by the models to the observed data. The relations shown on figure 2 were used to compute the simulated flows.

The final criterion used to judge the adequacy of each model was a comparison of observed and simulated flows for the entire period of concurrent records for each reach. Because the observed-flow records at Corning were so short and represented a relatively small range in flow conditions, the model for reach 4 was also calibrated using simulated flows at Corning. The errors (see table 6) ranged from 8.1 percent to 12.0 percent for daily flows and from -5.3 percent to 2.4 percent for flow volume.

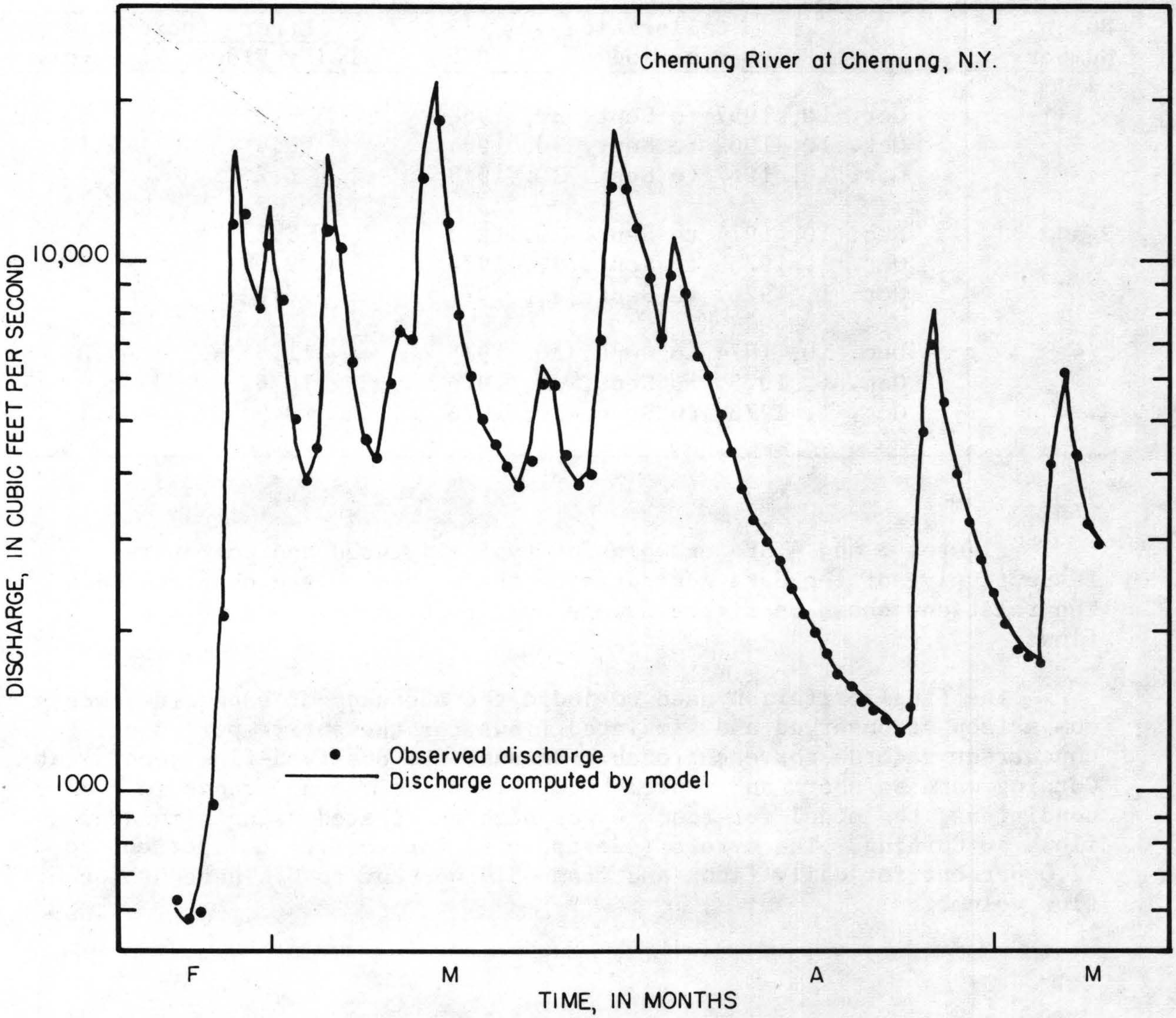


Figure 3.--Typical good fit of the model to observed data for part of a calibration period, February 10 to May 9, 1977.

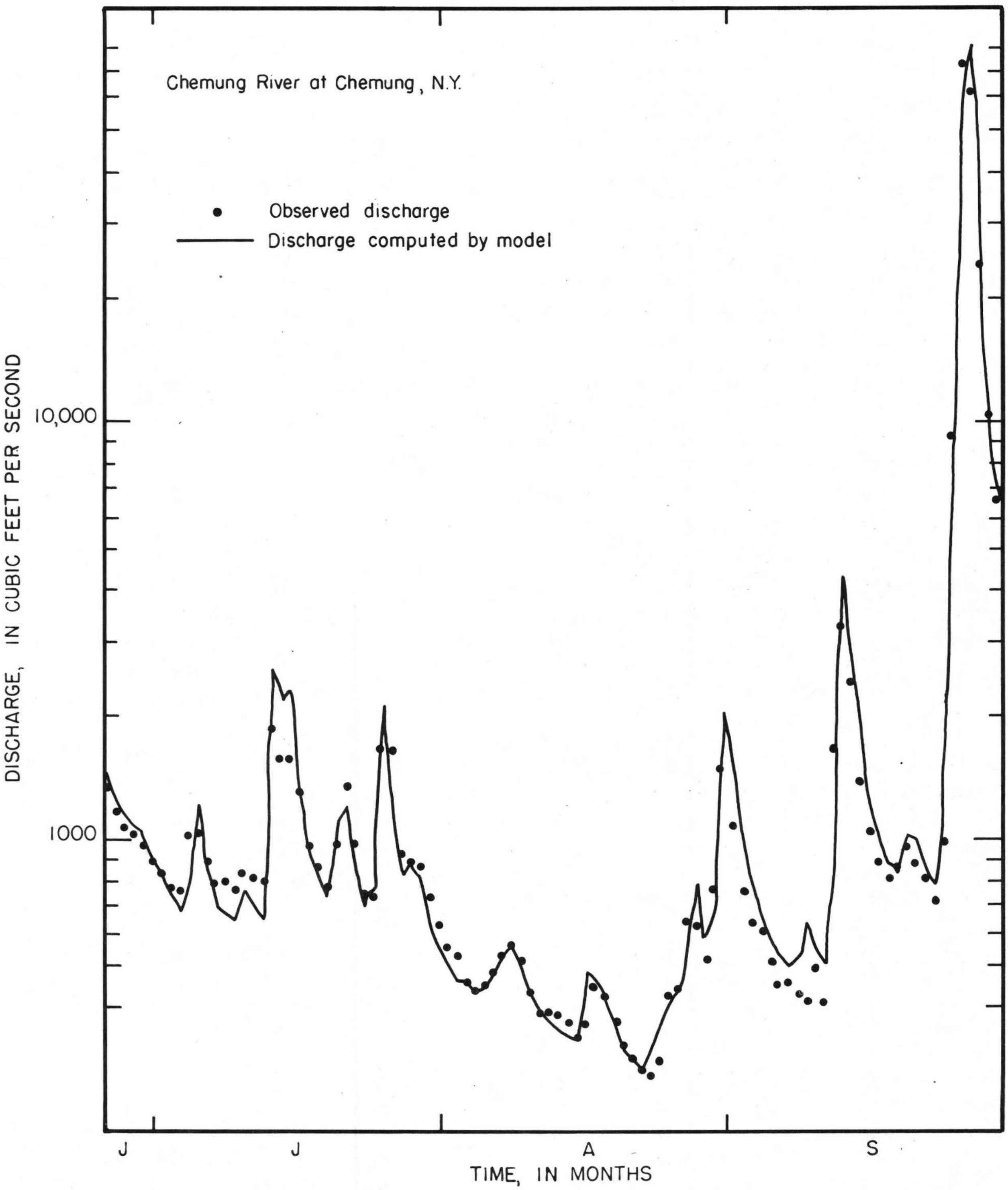


Figure 4.--Typical poor fit of the model to observed data for part of a calibration period, June 25 to September 30, 1975.

Table 6.--Errors, in percent, between simulated and observed flows for pre-reservoir conditions for the specified periods

Reach Number	Period 1/	Daily Flow	Flow Volume
1	Oct. 5, 1953 to Sept. 30, 1970	8.1	2.4
2 and 3	Dec. 10, 1974 to Nov. 30, 1977	8.5	-0.7
4 2/	Dec. 10, 1974 to Nov. 30, 1977	10.6	-5.3
4 3/	Dec. 1, 1953 to Sept. 30, 1970	12.0	-2.2

1/ Periods differ because concurrent records were not available at all sites.
2/ Simulation using observed flows at Corning.
3/ Simulation using simulated flows at Corning.

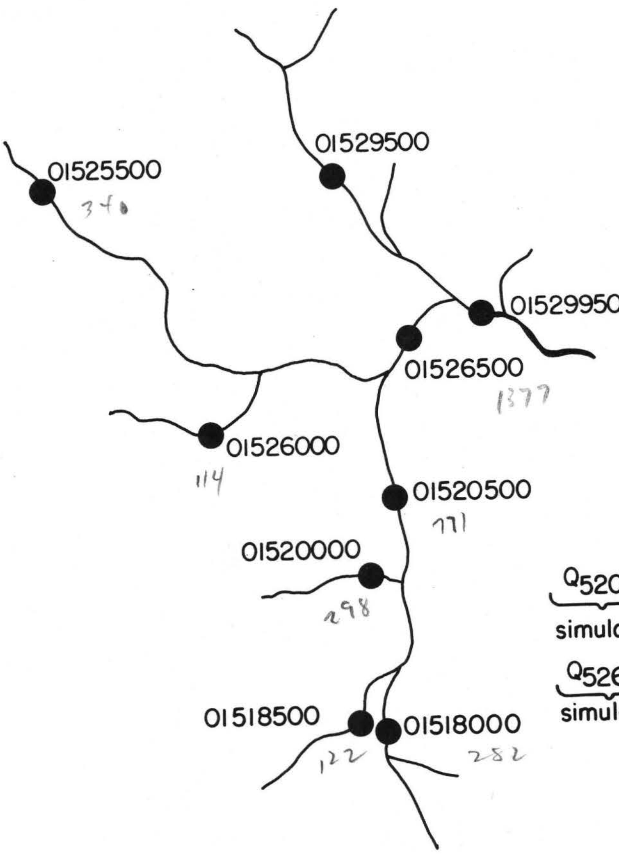
SIMULATION OF HOMOGENEOUS STREAMFLOWS

Daily streamflows were simulated at Erwins, Corning, and Chemung for both pre- and post-reservoir conditions. Simulation of 17 water years of pre-reservoir flows combined the procedures discussed below and reservoir release (QOUT on figure 5) equal to zero. Post-reservoir simulations were made for selected low-flow periods as outlined below.

Reach 1 - Tioga River (from reservoirs to Erwins).--Outflows from Cowanesque Reservoir were simulated using the reservoir release model with specified releases. The reservoir release (QOUT on figure 5) is considered to be the algebraic differences between natural inflow to and regulated outflow from the reservoirs. Reservoir releases were added to the observed flows at Lindley and combined with tributary flows, as shown in figure 5, to simulate flows at Erwins.

Reach 2 - Tioga River (from Erwins to Corning).--The simulated daily flows at Erwins, as computed for reach 1, were translated directly to Corning and added to the routed Cohocton River flows described in the next section.

Reach 3 - Cohocton River (from Campbell to Corning).--Daily streamflows of the Chemung River at Corning were simulated using the outflows from reach 2, as determined above, tributary flows, and daily flows of the Cohocton River routed interactively from Campbell. The interactive flow routing was done with the model for reach 3 and parameters as given in table 4. Using the relation presented in figure 6, the flows were combined to simulate flows of the Chemung River at Corning.



EXPLANATION

● 01526500	Gaging station and number
Q_{5265}	Daily flow at station 01526500
lag 1	Delay daily flows by 1 day
Q_{OUT}	Difference between daily reservoir inflows and outflows

$$\underbrace{Q_{5205}}_{\text{simulated}} = Q_{5205} + Q_{OUT}$$

$$\underbrace{Q_{5265}}_{\text{simulated}} = \underbrace{Q_{5205}}_{\text{simulated}} + 0.90 \times Q_{5255} \text{ (lag 1)} + 2.00 \times Q_{5260} + 2.00 \times Q_{5260} + 0.20 \times Q_{5295}$$

Figure 5.--Simulation of post-reservoir streamflows of the Tioga River at Erwins.

$$\underbrace{Q_{5299.5}}_{\text{simulated}} = \underbrace{Q_{5295}}_{\substack{\text{routed}\\\text{interactively}}} + \underbrace{Q_{5265}}_{\text{simulated}} + 2.00 \times Q_{5305}$$

$$\underbrace{Q_{5310}}_{\text{simulated}} = \underbrace{\underbrace{Q_{5299.5}}_{\text{simulated}}}_{\substack{\text{routed}\\\text{interactively}}} + 3.50 \times Q_{5305}\ (\text{lag } 1) + 0.50 \times Q_{5295}$$

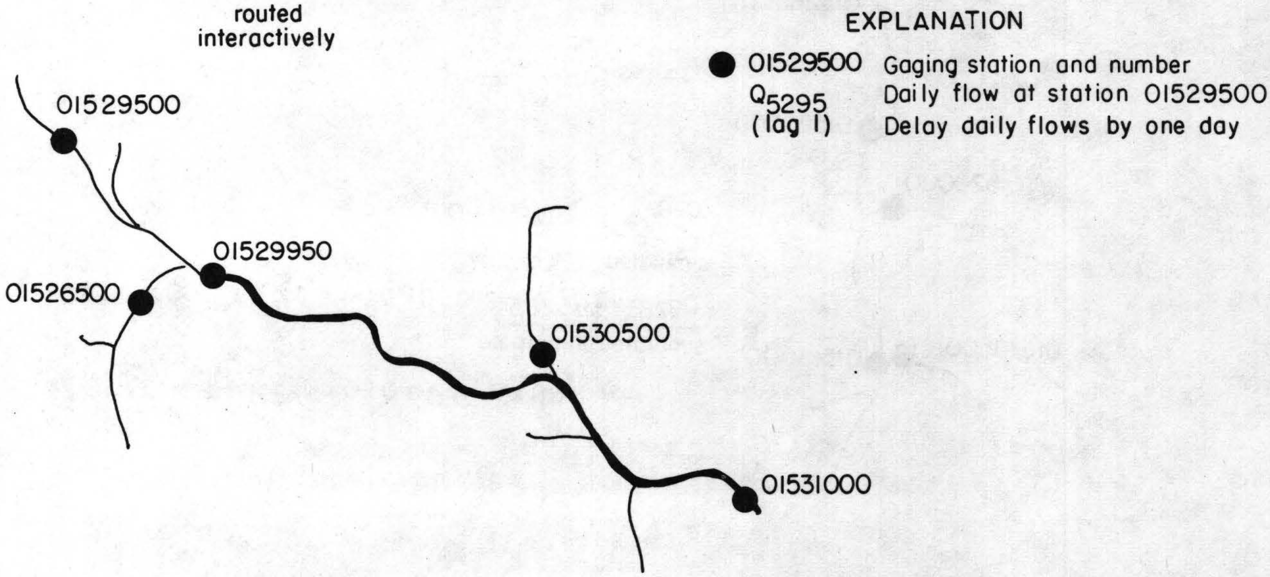


Figure 6.--Simulation of post-reservoir streamflows of the Chemung River at Corning and Chemung.

Reach 4 - Chemung River (Corning to Chemung).--Flows at Corning were interactively routed downstream to Chemung using the reach 4 model with the parameters given in table 4. Tributary flows were accounted for as indicated in figure 6. Outflows from this reach can be used as input to the channel-routing models presented by Bingham (1979) and routed as far downstream as Sunbury, Pennsylvania. Models presented by Armbruster (1977) can be used to route flows from Sunbury to the mouth of the Susquehanna River.

VERIFICATION OF MODELS

The study was concerned especially with routing reservoir releases down the Tioga and Chemung Rivers during periods of low flow. To accomplish this goal, low-flow characteristics of the streams must be simulated adequately by the models. Two commonly used methods of describing low flows are low-flow frequency and flow-duration curves. A 7-day low-flow frequency curve as used here is a frequency plot of annual 7-day minimum average flows. Climatic years (April 1 to March 30) are generally used in this type of analysis -- the year being designated by the year in which the period ends. Only 16 climatic years can be obtained from the 17 water years of data available for analysis. Therefore, all low-flow frequency analyses used 16 years of data. A flow duration curve is a cumulative frequency curve that shows the percentage of time that specified discharges are equalled or exceeded (Searcy, 1959). Flow duration curves describe not only low flows but the remainder of the flow regimen as well. If the models developed here were to be used for other purposes, verification at mid and high flows is important.

Accuracy of the calibrated models was verified by comparing low-flow frequency and flow duration curves at Erwins and Chemung, prepared from observed and simulated pre-reservoir conditions. Insufficient data were available at Corning to make a similar comparison. However, if the model for reach 4 is verified for the 17 water-year period, then the models for reaches 2 and 3 are implicitly verified. Figures 7 and 8 are the low-flow frequency curves of both observed and simulated flows at Erwins and Chemung for the pre-reservoir condition. Examination of the two sets of curves reveals little difference between observed and simulated data. In figure 8 some of the observed data plot below the simulated flows; however, curves drawn through the two sets of data for each station are nearly coincident. Figures 9 and 10 are the flow duration curves at Erwins and Chemung for observed and simulated pre-reservoir conditions. In addition to showing very close agreement at low flows, the curves also verify the capability of the models to simulate flows in the mid and upper ranges that closely resemble observed flows.

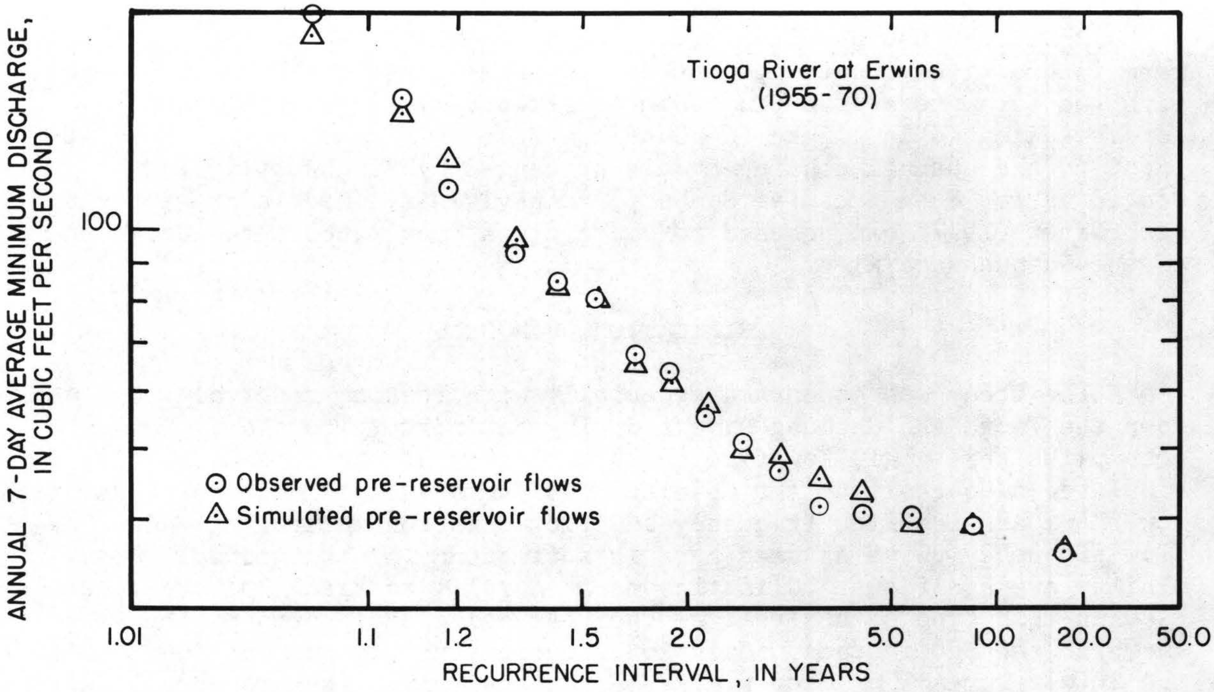


Figure 7.--Comparison of observed and simulated 7-day low-flow frequency curves for station 01526500 for pre-reservoir conditions.

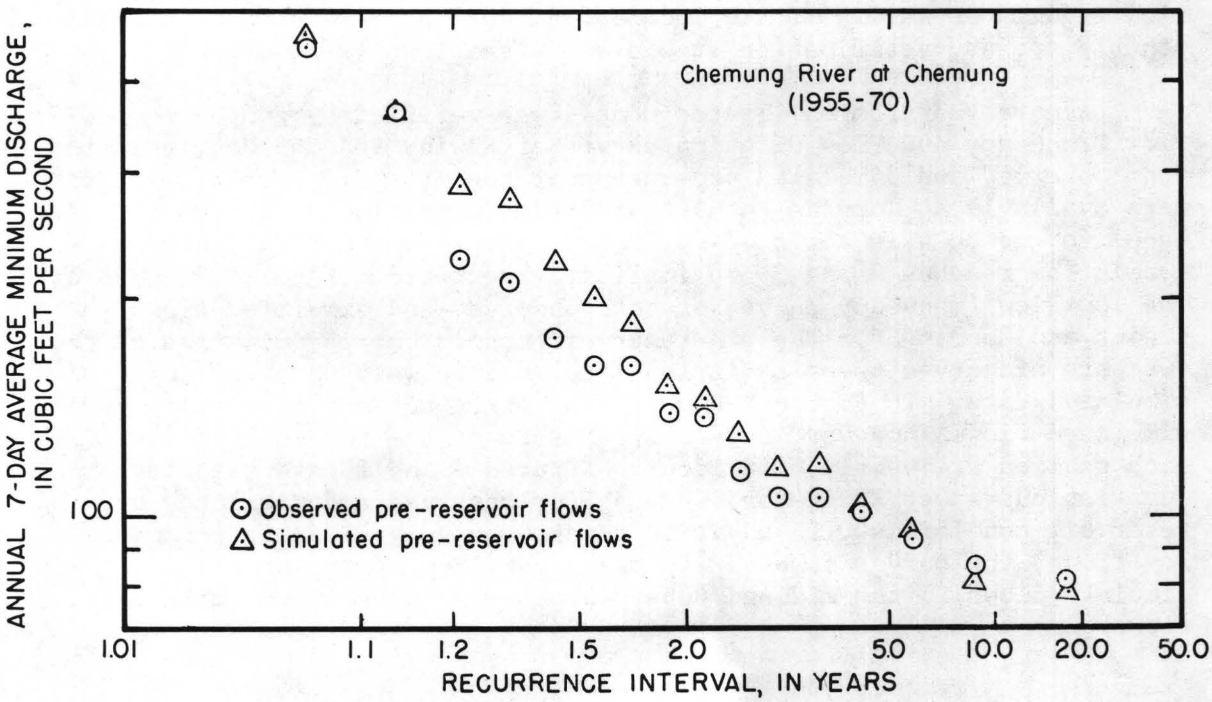


Figure 8.--Comparison of observed and simulated 7-day low-flow frequency curves for station 01531000 for pre-reservoir conditions.

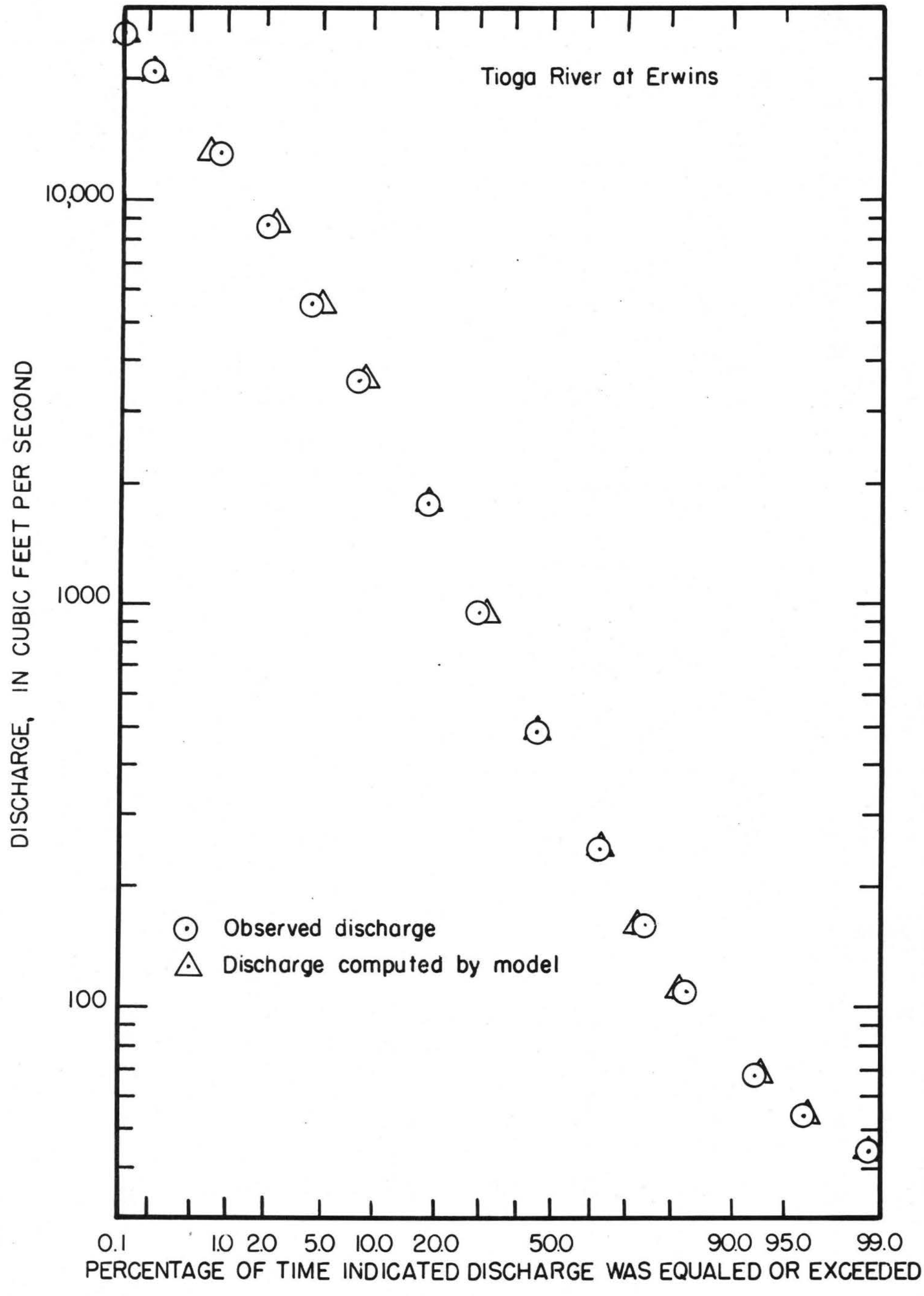


Figure 9.--Comparison of observed and simulated flow duration curves for station 01526500 for pre-reservoir conditions.

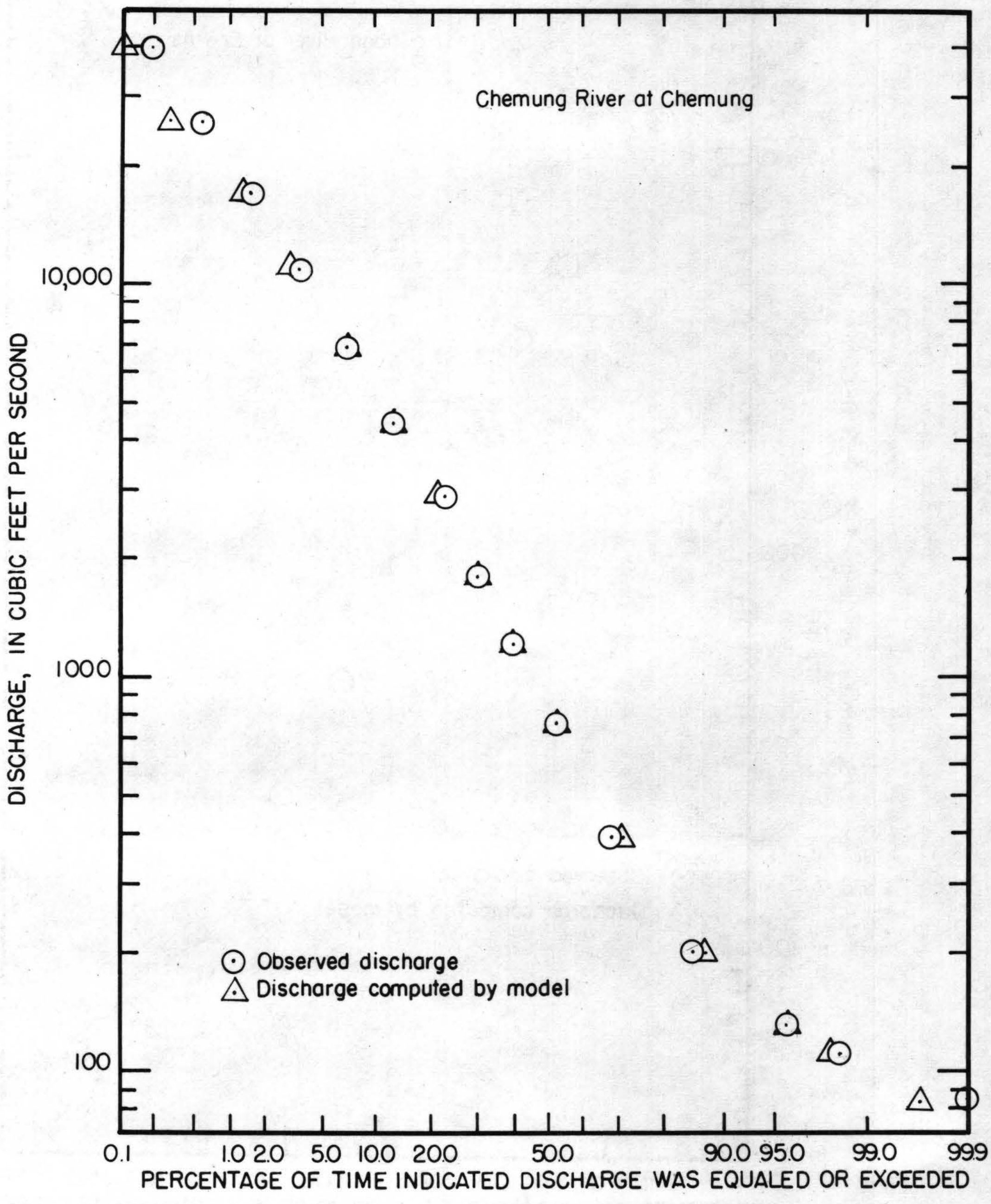


Figure 10.--Comparison of observed and simulated flow duration curves for station 0153100 for pre-reservoir conditions.

APPLICATION OF MODELS

Once all the models were verified, a reservoir release could then be routed to points downstream during periods of low flow. By comparing the results of such simulations to simulated pre-reservoir flows, the effects of the release at downstream sites could be estimated. Two important features of a routed reservoir release are the effective travel time and transmission or bank storage losses of the release at downstream sites. In other words, how long does it take the release to get to the downstream site, and how much of it gets there. To estimate these features, several hypothetical releases were routed. The examples are typical, not actual, applications of routing releases to satisfy the SRBC make-up water requirement, mentioned earlier.

In each of the examples, releases are made from Cowanesque Reservoir and routed down the Tioga and Chemung Rivers with the models developed here, then down the Susquehanna River to Wilkes-Barre, Pennsylvania, using the models presented by Bingham (1979). The releases are made to provide make-up water at Wilkes-Barre. Wilkes-Barre was selected because it is far enough downstream from the reservoir (156 miles) that the leading edge of the release hydrograph requires several days travel time. Wilkes-Barre is also outside the study area, thereby illustrating how the models developed here can be linked to models developed in earlier studies. Release results are also shown at Chemung because Chemung is the downstream limit of the current study and because travel time is much shorter.

The low-flow periods used in the analyses were selected on the basis of low flows of the Susquehanna River at Wilkes-Barre. A typical application of reservoir releases for make-up water at Wilkes-Barre requires releases be made when the flow of the Susquehanna River at that site drops below the sum of the 7-day 10-year minimum low flow and the consumptive use. The 7-day 10-year low flow at Wilkes- Barre for the period 1900-72 is 790 ft^3/s. If the consumptive use is arbitrarily set at 65 ft^3/s, make-up water is required when flow of the Susquehanna River at Wilkes-Barre is less than 855 ft^3/s. Using a flow of 855 ft^3/s as the criterion, two time periods that would require make-up water were selected--October 10 to November 6, 1963, and August 7 to November 26, 1964. The 1964 period contains the lowest average 7-day period on record, and the 1963 period contains the third lowest 7-day period. In the simulations for these periods, reservoir releases were arbitrarily begun 10 days before the date that make-up water was required at Wilkes-Barre and terminated on the day that water was no longer needed at Wilkes-Barre. Water was, therefore, released from September 30 to November 6, 1963, and from July 28 to November 26, 1964. Two different time periods were selected because the natural flow of the rivers for those periods were different. Intuitively, a reservoir release made at one level of ambient river flow should react differently (even if only in a minor way) than a release made at a different ambient flow condition.

Three different reservoir releases were routed to Chemung and Wilkes-Barre for each time period. The first case was a constant 100 ft^3/s for the entire period, and the second was a constant 70 ft^3/s.

At the outset of the test releases, it was recognized that the 7000 acre-feet of usable storage in Cowanesque Reservoir below the design normal pool elevation of 1045 ft was insufficient to meet large release demands for long periods. For the purposes of this test, therefore, normal pool elevation of Cowanesque Reservoir was assumed to be 1085 ft. At this assumed pool elevation, the reservoir has nearly 39,000 acre-feet of water in storage, which is sufficient to meet the example releases.

Because the 1964 test example includes the most severe period of low flow on record, it was analyzed first. Results of routing each example reservoir release is presented in figure 11. Also included, as figure 11d, is a hydrograph of observed daily streamflows of the Susquehanna River at Wilkes-Barre. Figure 11a reveals that a constant reservoir release of 100 ft^3/s provides more water than is needed to satisfy the assumed 65 ft^3/s consumptive loss at Wilkes-Barre. About 5 days lead time is required to deliver the needed 65 ft^3/s to Wilkes-Barre.

The results shown in figure 10b, for the constant 70 ft^3/s release routed to Wilkes-Barre, however, indicate that, on the average, flows very nearly equal to the 65 ft^3/s consumptive loss are delivered. A 10-day lead time seems reasonable for this release scheme. After analyzing the routed results of the first two release patterns, it was found that the rising limbs of the release hydrographs at the downstream sites were steeper for the first case than for the second case. A third release scheme was, therefore, developed. A 100 ft^3/s release was made for the first 3 days then reduced to 70 ft^3/s for the remainder of the test periods. This particular scheme was an attempt to attain a higher level of flow in a shorter period of time at the downstream locations than the level achieved using the constant 70 ft^3/s release.

With the third release pattern, arrival time of the 65 ft^3/s of make-up water is again about 5 days after the start of the release, as presented on figure 11c. The travel time of the leading edge of this reservoir release is nearly identical to the travel time for the constant 100 ft^3/s release. Because this schedule reduces the release from 100 ft^3/s to 70 ft^3/s after 3 days and because 70 ft^3/s is sufficient to maintain the needed 65 ft^3/s, once 65 ft^3/s is attained downstream, this reservoir release is the most efficient scheme of the three analyzed here. Although 100 ft^3/s of water is released for the first 3 days, a smaller total volume of water has to be released because the release can be delayed 4 to 5 days.

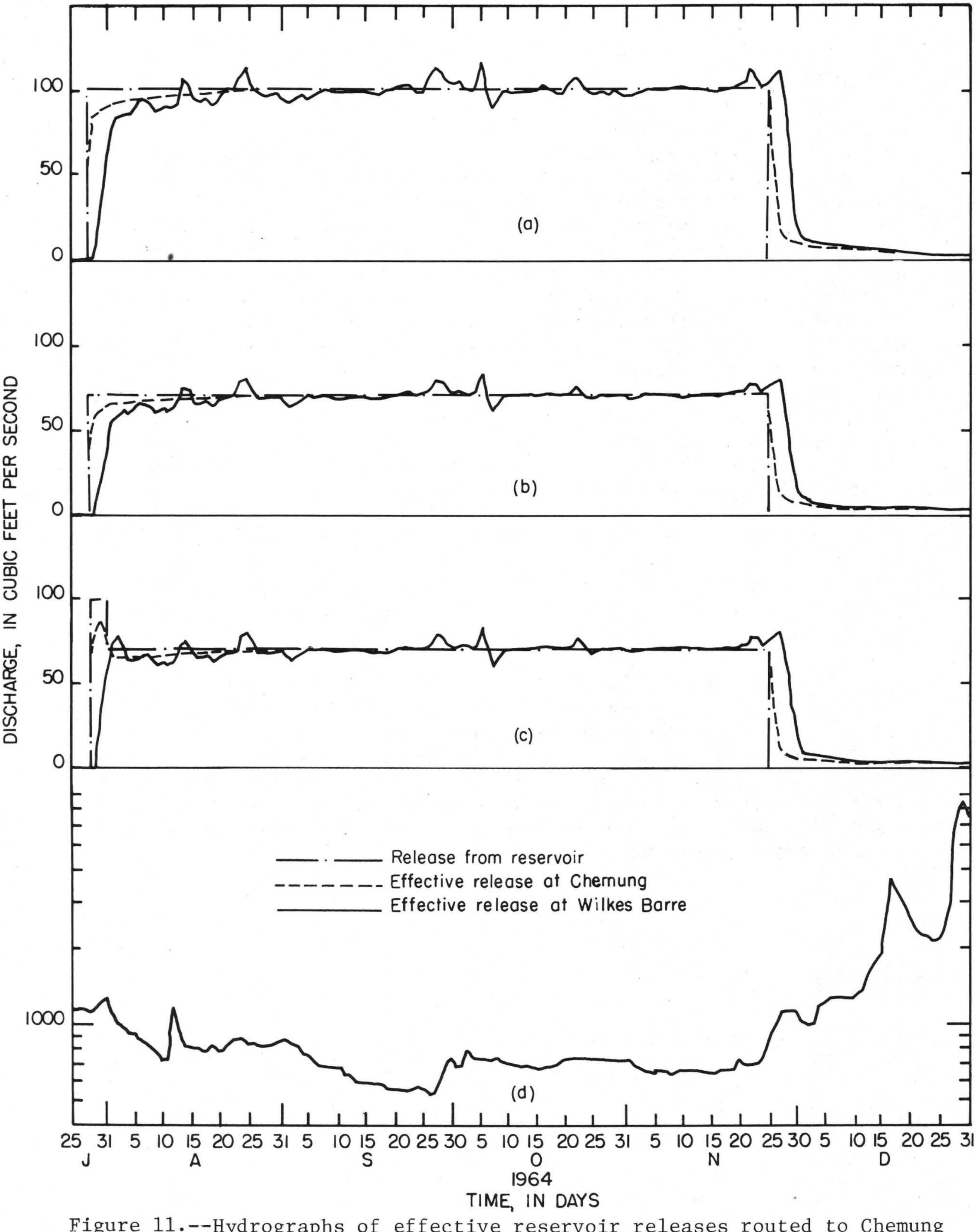


Figure 11.--Hydrographs of effective reservoir releases routed to Chemung and Wilkes-Barre: a) constant 100 ft^3/s release, b) constant 70 ft^3/s release, c) two-level release, and d) observed flows at Wilkes-Barre.

The time required to deliver a specified discharge to a downstream site depends on several major factors. Included are flow in the stream at the time of the reservoir release, distance from the point of release to the downstream site, velocity or speed of the water in the channel, and the amount or rate of water going into or out of bank storage. Many of these features can be seen by examining the reservoir releases routed to Chemung and comparing them to the flows routed to Wilkes-Barre. Hydrographs of the effective reservoir releases at Chemung rise more quickly than those at Wilkes-Barre, maintain a steadier and a more constant discharge, and recede more quickly once the reservoir release is stopped. Each of these results was expected because the travel distance was substantially shorter, only 48 miles. The alluvial aquifer system underlying the stream channel at and upstream from Chemung acts as a damper. It takes in water on the leading edge and releases it from bank storage on the recession. Thus, the rising limb of the release hydrograph rises slower and subsequently recedes slower than it would if the stream were underlain by an impermeable aquifer. The areas under the three hydrographs presented for each release scheme are nearly equal, implying that there is nearly no water lost in transit to the downstream sites. Distribution of flow with time, however, is very important when analyzing the results of routed reservoir releases. One loss not accounted for here is evapotranspiration. Ignoring evaportranspiration introduces error into the results, but the error is probably not significant.

The increase of flow in the stream, shown on figure 11d, at the time the reservoir release is discontinued, causes a slight rise in the effective reservoir releases seen on figures 11a-c. The increased flow of the effective release is caused by the increased velocity of the ambient flow in the stream and the resultant increase in velocity of the reservoir release. Because the rise of the ambient flow of the Susquehanna River is gradual, the increase in the effective release hydrographs at Chemung and Wilkes-Barre is small.

Figure 12 presents the results of routing the same three reservoir releases discussed above during the 1963 test period. The 1963 test period was much shorter than the one in 1964, and ambient flows were higher than during the 1964 test period. Because ambient flows were higher, larger effective releases were attained more quickly at the downstream sites for the 1963 tests. From figure 12a arrival time of the 65 ft^3/s make-up requirement is about 5 days after the beginning of the release. Results for the constant 70 ft^3/s release, shown in figure 12b, indicate that the arrival time of the needed 65 ft^3/s is about 6 days--only slightly longer than for the 100 ft^3/s release. Examining results of routing the third release pattern shows a 5-day travel time to Wilkes-Barre, as expected. There to be at least one advantage to using the third release scheme instead of the constant 70 ft^3/s release. The higher initial release causes bank storage losses to be higher initially. This is advantageous because water levels in the aquifer are raised more quickly, causing subsequently smaller bank storage losses after the reservoir release is reduced to 70 ft^3/s. Bank storage losses are more critical when 70 ft^3/s is released because the margin between the water released and the water needed miles downstream is small.

With a constant release of either 70 ft^3/s or 100 ft^3/s, slightly more than a month is required in both the 1963 and 1964 tests for the effective release to reach the level of the actual release at either downstream site. The time required to reach this steady state depends on the characteristics of the alluvial aquifer and its ability to reach equilibrium after being stressed. The stress applied here is simply the reservoir release and subsequent increase of water levels in the stream.

Probably the most notable feature of the routed-release hydrographs on figure 12 is the rapid increase in the effective release beginning November 7, 1963. This sharp peak is caused by the substantial rise in the ambient-flow hydrograph of the Susquehanna River at Wilkes-Barre. As shown on figure 12d, flow increased from 1090 ft^3/s on November 7 to 2210 ft^3/s on November 8, 1963. The rise caused the release water already in the stream channel to be moved rapidly downstream and out of the system. Thus, instead of the recession being gradual, the peak falls quickly. Several additional test runs were made assuming progressively earlier release termination dates. If the reservoir release were stopped on November 3, 1963, instead of November 6, the tail of the hydrograph does not rise sharply, rather it recedes more slowly than the example shown. Accounting for the 3 day difference in releases, the same volume of water reaches Wilkes-Barre. The reason that no rise appears in the hydrographs of the effective releases at Chemung is that nearly all of the reservoir release water has passed Chemung before the ambient flow increase.

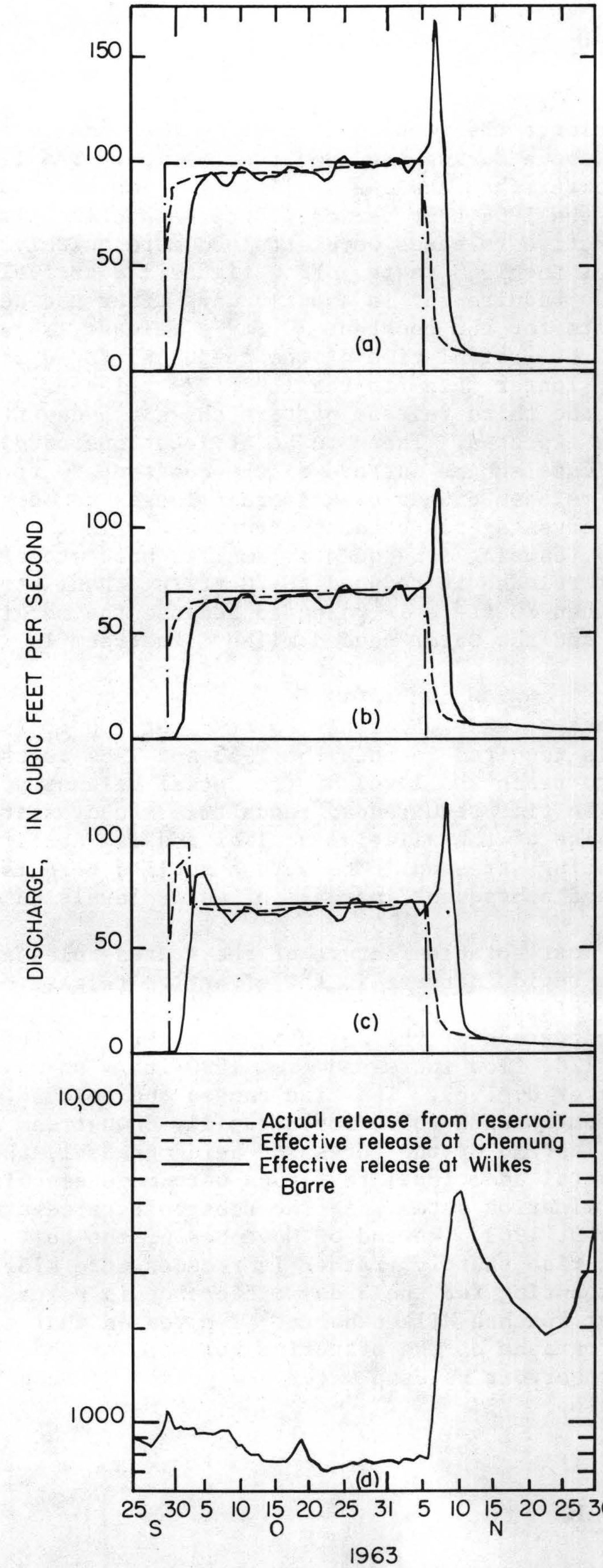


Figure 12.--Hydrographs of effective reservoir releases routed Chemung and Wilkes-Barre: a) constant 100 ft^3/s release, b) constant 70 ft^3/s release, c) two-level release, and d) observed flows at Wilkes-Barre.

CONCLUSION

A combination of reservoir-regulation and channel-routing models has been used to analyze the characteristics of three hypothetical reservoir-release patterns. Reservoir releases were simulated during two different historical low-flow periods and routed down the Tioga River from Cowanesque Reservoir to Corning, where they combined with flows of the Cohocton River routed from Campbell to Corning and then were routed down the Chemung River from Corning to Chemung. All channel-routing models were calibrated and verified with historical data. The channel-routing models used to route both Cohocton and Chemung River flows accounted for water lost or gained to bank storage and to well pumpage.

Several hypothetical releases were studied to illustrate the use of the models developed here. They were linked to models presented earlier to solve typical problems resulting from SRBC regulations.

Reservoir releases of 70 ft^3/s and 100 ft^3/s were routed downstream to Chemung and Wilkes-Barre during two historical low-flow periods. The reservoir releases were made to satisfy a hypothetical make-up water requirement of 65 ft^3/s for a consumptive use from the Susquehanna River at Wilkes-Barre. In all cases, releases were begun 10 days before they were needed at the downstream site. Travel times to Wilkes-Barre of the required 65 ft^3/s for constant releases of 70 ft^3/s and 100 ft^3/s were 6 and 5 days, respectively, for the 1963 tests. Travel times to reach the needed make-up water during the 1964 tests with the same reservoir release were 10 and 5 days, respectively. Based on these results, a third release was made for each test period. The release consisted of a 3-day 100 ft^3/s release followed by a constant 70 ft^3/s release for the remainder of the test periods. A 5-day travel time was needed for each test to achieve an effective release of 65 ft^3/s at Wilkes-Barre.

The recession characteristics of all the effective release hydrographs at Wilkes-barre were similar for all three releases. Each hydrograph rose immediately after the reservoir releases were ended. The rises were caused by the increase in ambient river flows. For the 1964 tests, the rises were gradual for both ambient river flow and effective reservoir releases. The rises computed for the effective releases in the 1963 tests were sharp, corresponding to sharp rises in the ambient river flows. The sharp rises in the effective release hydrographs, however, were followed by rapid recessions.

At Chemung, for all conditions simulated, the effective releases attained higher discharges more quickly and receded more quickly than the routed release hydrographs at Wilkes-Barre. The reason was the short distance between the reservoir and Chemung.

About a month was required for the effective release hydrographs at both Chemung and Wilkes-Barre to attain the level of the constant reservoir releases. In other words, if the release was 70 ft^3/s, the effective release at both downstream sites did not reach 70 ft^3/s for about a month. Thus, at least a month is required for an effective release to equal to the actual release of the same order of magnitude at any site between Chemung and Wilkes-Barre, where make-up water might be required.

Of the three release patterns analyzed, the third one was the most efficient with respect to the total volume of water released to satisfy the need and to time dependability of delivery to downstream sites. Several days less lead time were needed to achieve the required effective release, using the two-level release compared to lead time for the constant discharge levels. By releasing a slightly higher discharge initially and then reducing it to nearly the rate needed downstream, the stream-aquifer-system was brought into equilibrium more quickly. As a result, bank storage losses were minimized during the second phase of the release pattern.

Only three release patterns were tested, and no attempt was made to try all possible releases. Computing effective reservoir release hydrographs at any downstream site where a flow-routing model is available is simple and inexpensive once the needed volume of make-up water at a site is specified.

Although inherent modeling errors are present in all of the routed reservoir releases presented here, the overall quality of the simulated data is considered good. The models developed here can be used for a variety of applications. One example is to estimate the probable downstream effects of normal operating procedures of the new Tioga River basin reservoirs on high, medium, and low flows.

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