LOW-FLOW ROUTING IN THE LEHIGH AND DELAWARE RIVERS, PENNSYLVANIA

By Herbert N. Flippo, Jr.

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 85-4331

Prepared in cooperation with the U.S. ARMY CORPS

OF ENGINEERS PHILADELPHIA DISTRICT

Harrisburg, Pennsylvania

1988

DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
4th Floor, Federal Building
P.O. Box 1107
Harrisburg, Pennsylvania 17108-1107

Copies of this report may be purchased from:

U.S. Geological Survey
Books and Open-File Reports Section
Federal Center
Box 25425
Denver, Colorado 80225

CONTENTS

	Page
Abstract	1
Introduction	2
Purpose and scope	2
Description of the study reaches	3
Data used for digital modeling	3
Flow-routing models	3
Calibration	8
Verification	12
Application of models	12
Time of travel	20
Conclusions	29
Selected references	30

ILLUSTRATIONS

Figure 1.--Map showing location of gaging stations and study reaches	6
2-7.--Hydrographs of routed and simulated daily discharges at the downstream end at sites in selected reaches of the Lehigh and Delaware Rivers for the low-water period of July-September, 1965:	
2.--Reach 1	16
3.--Reach 2	17
4.--Reach 3	18
5.--Reach 5	19
6.--Reach 6	21
7.--Reach 8	22
8.--Graph of travel times for the leading edge of a wave produced by a three-fold augmentative release from Francis E. Walter Reservoir on the Lehigh River	23
9.--Graph of travel times for the leading edge of a mass of a solute or suspended matter in the Lehigh River	28

TABLES

Table 1.--Drainage area and river mileage for key stream sites in the study area	4
2.--Description of study reaches	5
3.--List of gaging stations with daily discharge values available for use in routing models	7
4.--Model calibration and verification errors	10
5.--Equations used to route daily flows from Francis E. Walter Reservoir on the Lehigh River to Trenton, New Jersey on the Delaware River	11
6.--Parameters used in flow-routing models	13
7.--Observed and simulated 7-day, low-flow discharges for the nodal sites	14

Page

Table 8.--Locations of temporary recorders installed to monitor travel times of augmentative releases from reservoirs during September 1982... 24

9.--Exemplary augmentative reservoir releases in the Lehigh River basin used to define low-flow travel times, September 21-23, 1982.................................. 25

10.--Discharge rate and travel times for the wave on the Lehigh River produced by release number 1, September 21, 1982...... 25

11.--Discharge rate and travel times for the wave on the Lehigh River produced by release number 2, September 22, 1982...... 26

12.--Discharge rate and travel times for the wave on the Pohopoco Creek produced by release number 3, September 23, 1982...... 26

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 Internationsl System of Units (SI).

Multiply inch-pound units	By	To obtain SI units
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square foot per second (ft^2/s)	0.09294	square meter per second (m^2/s)
square mile (mi^2)	2.590	square kilometer (km^2)
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

LOW-FLOW ROUTING IN THE LEHIGH AND DELAWARE RIVERS, PENNSYLVANIA

By Herbert N. Flippo, Jr.

ABSTRACT

Flow-routing studies were made to evaluate the response of the Lehigh and Delaware Rivers to low-flow augmentative releases from two reservoirs --Francis E. Walter Reservoir and Beltzville Lake--in the Lehigh River basin. Digital routing models that use diffusion-analogy methods to convolute flows with system-response functions were developed to simulate daily flows at selected sites. Model errors, for five sites and for periods of 1 year or more, were mostly between 3 and 12 percent in terms of absolute errors in daily flows and were mostly within 4 percent for flow volumes.

The developed models were satisfactory for predicting hydrographic response at eight sites in the reach from White Haven, Pennsylvania to Trenton, New Jersey. However, abrupt changes in the flow rate of the Lehigh River at the Bethlehem and the Glendon gaging stations could not be adequately replicated with the model. The model tends to underestimate peaks by as much as 30 percent and to overestimate some low flows of short duration by as much as 20 percent. This occurs primarily because inflows from ungaged areas could not be reliably modeled throughout their ranges by use of flow records for gaged streams. The model will underestimate long-duration low flows at the Glendon site for periods when underflows at the gaging stations on Little Lehigh and Monocacy Creeks are significant.

The models were used to route hypothetical releases from Francis E. Walter Reservoir during a low-flow period. The model for the Lehigh River indicated that an added release of 50 ft^3/s (cubic feet per second) over a 64-day period during the severe drought in the summer of 1965 would have increased minimum flows for this period at Bethlehem and Glendon by approximately the same amount. A hypothetical release of 200 ft^3/s for the period July 20-22, 1965, which is about eight times the actual release in this period, would have been attenuated by about 25 percent when it reached the Bethlehem gage. The synthesized hydrograph for the Bethlehem gage showed such a release would have passed there by July 27. Unresolvable timing errors in the models created an unrealistic hydrographic response for this release at the Trenton gage; but, such a release probably would have passed Trenton by July 29.

In order to time the movement of a release wave more accurately than could be done with the developed model, travel times for the wave of an augmentative low-flow release were obtained by field observations and comparisons of gage-height records. The observed leading edge of an abrupt release of 153 ft^3/s from Francis E. Walter Reservoir, which ended a 2-day release at a rate of 48 ft^3/s, arrived at the gage below the reservoir in 0.5 hour, at White Haven in 3.7 hours, at the mouth of Pohopoco Creek in about 23.1 hours, at Walnutport in 27 hours, at Bethlehem in 39 hours, and at Glendon in 42 hours.

This release could not be detected in the record for the Trenton gage. Travel time for an augmentative release in the Lehigh River is dependent upon the pre-release discharge, the relative magnitude of the release, and antecedent rainfall. Relationships are provided for estimating the time of arrival at Walnutport, Bethlehem, and Glendon of the leading edge of waves generated by augmentative releases of 75 to 600 ft^3/s. Stage observations on Pohopoco Creek indicated a 2.1-hour travel time between Beltzville Lake and the Lehigh River for the leading edge of a wave produced by a typical augmentative release from this reservoir.

INTRODUCTION

The flow characteristics of a regulated stream must often be managed to maintain adequate flow for fish habitat, waste dilution, power generation, or water supplies at downstream points. Proposed modifications to Francis E. Walter Dam on the Lehigh River (U.S. Army Corps of Engineers, 1983) will provide additional storage capacity in the reservoir for flow augmentation during droughts. The additional augmentation thereby provided will partly replenish river water that is lost through consumptive use and will help control the intrusion of saline water in the Delaware River Estuary.

Information on rates of propagation and the attenuation of waves produced by augmentative releases during low-water periods is necessary for the efficient management of these releases. This study to obtain and document such information was conducted in cooperation with the U.S. Army Corps of Engineers, Philadelphia District.

PURPOSE AND SCOPE

This report discusses the results of using unit-response routing models to simulate flows in the Lehigh and Delaware Rivers for the purpose of predicting the hydrographic responses of these rivers to augmentative releases from Francis E. Walter Reservoir and Beltzville Lake in the Lehigh River basin. Rates of wave propagation and the magnitude of wave attenuation caused by channel and bank storage, as demonstrated by model routings of hypothetical releases during an extreme low-flow period, are evaluated.

The routing models were calibrated to reproduce discharge hydrographs that have been observed at gaging stations. Hydrographic responses for eight nodal sites on the Lehigh and Delaware Rivers were then simulated for two hypothetical, augmentative releases from Francis E. Walter Reservoir. These simulated hydrographs were used as an index to the attenuation and spreading of waves generated by releases during low-flow periods. Propagation rates of releases can be timed with such hydrographs to an accuracy of about 1 day, which is the routing interval of the models. The modeling program permits the use of a 1-hour routing interval; however, hourly records were not readily available for that purpose.

Stage records collected from gaging stations, as well as from several temporary stage recorders, provided a simple and precise means for measuring propagation rates. Rates of travel for solutes and particulate suspensions, which were determined under a former study, are provided for comparative purposes.

DESCRIPTION OF THE STUDY REACHES

From its headwaters in Pike County, Pennsylvania, the Lehigh River flows southwestward for 30 mi (miles) to Francis E. Walter Dam, which regulates the runoff from 288 of the 1,368 mi^2 (square miles) in the basin. The river flows southward from the reservoir for 61 river miles and then flows 16 river miles northeastward before emptying into the Delaware River. One regulated tributary, Pohopoco Creek, enters the Lehigh River midway in the reach from Francis E. Walter Reservoir to the Delaware River. Table 1 is a summary of river mileages and drainage areas for key stream sites, which correspond to sites at or near former or present (1983) stream gages. The nodal sites indicated on table 1 mark the downstream termini of nine study reaches. These reaches are briefly described in table 2, and are located as shown in figure 1.

From Francis E. Walter Reservoir to a point about 9 mi south of the Borough of Walnutport, the course of the Lehigh River cuts across folded beds of shale, sandstone, and conglomerate. The lower 24 mi of channel are incised in crystalline and argillaceous dolomites and limestone.

DATA USED FOR DIGITAL MODELING

Daily streamflow records for 21 gaging stations were available for use in modeling the study reaches. These gaging stations and their periods of record are identified in table 3. Locations of the stations are shown in figure 1. No daily flow records are available for miscellaneous gaging sites 01450020 and 01451190. Daily records for the Lehighton station (01449000) were not used because they predated those of the gage below Francis E. Walter Reservoir (01447800).

Concurrent records for the 1968-81 water years were used to calibrate and verify the models. Records for 1964-65 water years were used to simulate hydrographic response for hypothetical releases from the Francis E. Walter Reservoir during extreme low-flow periods. Records collected in 1958-59 on the Lehigh River at Tannery (01448000) were used in developing the routing model for reach 1.

FLOW-ROUTING MODELS

The streamflow routing models were developed by using a daily routing interval with the unit-response method described by Doyle and others (1983). Such models treat the streams as a linear, one-dimensional system in which the flow hydrograph for a downstream site is computed by convoluting the unit response of the system with the hydrograph input for the upstream end of the reach. These convolutions consist of using diffusion-analogy methods to integrate system responses and discharges over a selected time interval. The output hydrograph of a reach is used as the input to the next downstream reach. Tributary, diversion, and storage components for each subreach must be estimated, tested, and adjusted until the model is adequately calibrated for a wide range of streamflow. The calibrated models can be verified by comparing the modeled hydrograph for a period of many years with the observed flows for the same period. Such verification insures that the models were not miscalibrated because of spurious flow records for the calibration period.

Table 1.--Drainage area and river mileage for key stream sites in the study area

Stream site	Drainage area (mi^2)	River mile[1/] (mi)
Delaware River		
*Gaging station 01463500, Trenton, N.J.	6,780	134.4
*Gaging station 01457500, Riegelsville, Pa.	6,328	174.8
Confluence with Lehigh River	6,078	183.7
Lehigh River		
Mouth	1,368	0.0
*Gaging station 01454700, Glendon, Pa.	1,359	2.3
*Gaging station 01453000, Bethlehem, Pa.	1,279	11.8
Confluence with Little Lehigh Creek	1,038	16.7
*Miscellaneous gaging station 01451190, Hamilton Street, Allentown, Pa.	1,037	17.0
*Gaging station 01451000, Walnutport, Pa.	889	33.7
Confluence with Pohopoco Creek	741	41.1
*Gaging station 01449000, U.S. Hwy 209, Lehighton, Pa.	591	43.0
Discontinued gaging station 01448000, Tannery, Pa.	322	70.3
*Pa. Hwy 940, at White Haven, Pa.	315	71.9
Gaging station 01447800, below Francis E. Walter Reservoir, near White Haven, Pa.	290	76.3
Francis E. Walter Reservoir, outlet	288	77.0
Pohopoco Creek		
*Miscellaneous gaging station 01450020, at mouth, at Pa. Hwy 248	111	0.0
Gaging station 01449800, below Beltzville Dam, near Parryville, Pa.	96.4	4.8
Beltzville Dam, outlet	96.3	5.2

*Nodal site in routing models.

[1/]From river mileage listing prepared by the Delaware River Basin Commission, May 1967.

Table 2.--Description of study reaches

Reach number	Description	Length of reach (mi)
1	Lehigh River from Francis E. Walter Reservoir to White Haven, Pa.	5.1
2	Lehigh River from White Haven, Pa. to Lehighton, Pa.	28.9
3A	Pohopoco Creek from Beltzville Lake to mouth	5.2
3B	Lehigh River from Lehighton, Pa. to Walnutport, Pa.	9.3
4	Lehigh River from Walnutport, Pa. to Allentown, Pa.	16.7
5	Lehigh River from Allentown, Pa. to Bethlehem, Pa.	5.2
6	Lehigh River from Bethlehem, Pa. to Glendon, Pa.	9.5
7A	Delaware River at Belvidere, N.J. to mouth of Lehigh River	14.0
7B	Lehigh River from Glendon, Pa. to mouth and Delaware River from mouth of Lehigh River to Riegelsville, N.J.	11.2
8	Delaware River from Riegelsville, N.J. to Trenton, N.J.	40.4

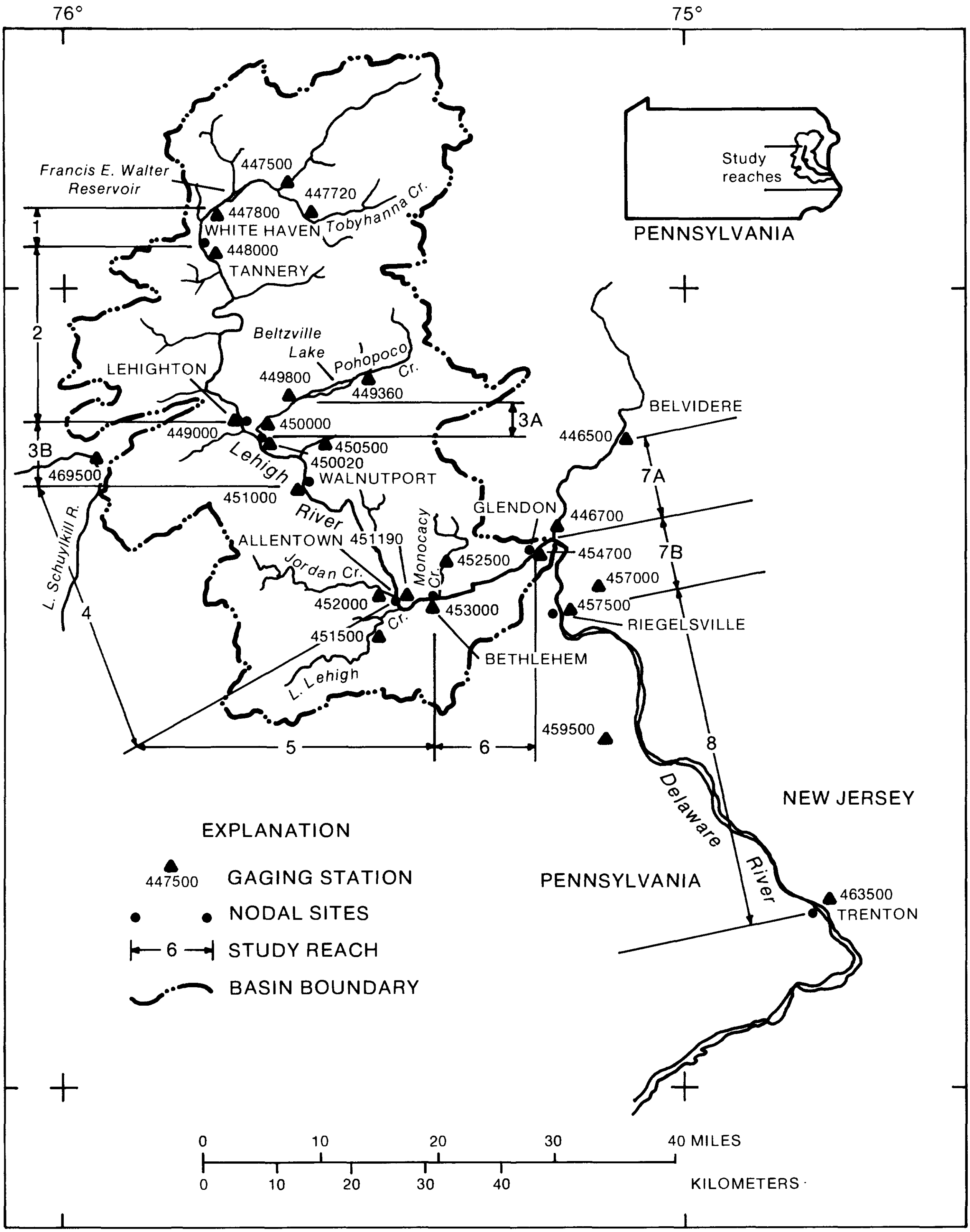

Figure 1.-- Location of gaging stations and study reaches.

Table 3.--List of gaging stations with daily discharge values available for use in routing models

Station number	Station name	Available water years of record	Drainage area (mi^2)
01446500	Delaware River at Belvidere, N.J.	1923-81	4,535
01446700	Delaware River at Easton, Pa.	1968-77	4,636
01447500	Lehigh River at Stoddartsville, Pa.	1944-81	91.7
01447720	Tobyhanna Creek near Blakeslee, Pa.	1962-81	118
01447800	Lehigh River near White Haven, Pa.	1958-81	290
01448000	Lehigh River at Tannery, Pa.	1915-59	322
01449360	Pohopoco Creek at Kresgeville, Pa.	1967-81	49.9
01449800	Pohopoco Creek near Parryville, Pa.	1968-81	96.4
01450000	Pohopoco Creek below Beltzville Reservoir near Parryville, Pa.	1941-70	109
01450500	Aquashicola Creek at Palmerton, Pa.	1940-81	76.7
01451000	Lehigh River at Walnutport, Pa.	1947-81	889
01451500	Little Lehigh Creek near Allentown, Pa.	1946-81	80.8
01452000	Jordan Creek at Allentown, Pa.	1945-81	75.8
01452500	Monocacy Creek at Bethlehem, Pa.	1949-81	44.5
01453000	Lehigh River at Bethlehem, Pa.	1910-81	1,279
01454700	Lehigh River at Glendon, Pa.	1967-81	1,359
01457000	Musconetong River at Bloomsburg, N.J.	1922-81	143
01457500	Delaware River at Riegelsville, N.J.	1907-71	6,328
01459500	Tohickon Creek near Pipersville, Pa.	1936-81	97.4
01463500	Delaware River at Trenton, N.J.	1914-81	6,780
01469500	Little Schuylkill River at Tamaqua, Pa.	1920-81	42.9

The routing coefficients used to define system-response functions are flood-wave celerity, which simulates flood-wave propagation, and a dispersion coefficient, which simulates hydrographic attenuation caused by channel storage. These coefficients can be linearized about a single discharge or between multiple discharges. Multiple linearization is needed for reaches in which the propagation rate or the attenuation of the hydrograph varies markedly with discharge. Initial estimates of these coefficients are computed from hydrologic data and the physical characteristics of the channel.

Calibration

The model for the Lehigh River consists of a series of convolutionary steps that begin with the flow hydrograph for gaging station 01447800, at which the flows are those released from Francis E. Walter Reservoir. Nodal sites (fig. 1) separate the modeled reaches. For calibration purposes, hydrographs of simulated daily flows for water years 1968-70 were generated for the gaged nodal sites at Walnutport (01451000), Bethlehem (01453000), and Glendon (01454700). Gaging stations upstream from Walnutport provide inflow records for only 54 percent of the drainage area. Therefore, calibration to match, as well as possible, the observed hydrograph for the Walnutport site was crucial to the development of an adequate model for the river.

The flow hydrograph for station 01447800 was routed downstream, through reaches 1, 2, and 3B, to simulate the hydrograph for the Walnutport station. Initial estimates of the routing coefficients were calculated for each reach from the width of the channel, the average bed slope, and from discharge rating curves for stream gages in the reach. For most reaches, sub-reach routings were made between principal, ungaged tributaries (not identified on fig. 1). Hydrographs for tributary streams were estimated from gaged flows for stations on these tributaries and other streams in the area, such as Tobyhanna Creek and the Little Schuylkill River. These estimated hydrographs for tributary inflow were added to the generated main-stem hydrograph at representative points in the model. System response was modeled by both single and multiple linearization of the routing coefficients with discharge. These coefficients were modified from their initial values, as necessary, to improve the simulations, particularly for the lower flows. Reaches 4 through 6 were modeled by the same techniques.

Simulated outflows from reaches 3B, 5, and 6 were evaluated by visual comparisons of observed and simulated hydrographs, by the average absolute deviations between observed and simulated daily flows, and by the volume difference between observed and simulated flows for the 3-year calibration period.

Calibration of the two reaches on the Delaware River was begun with the daily-flow record for station 01446500, at Belvidere, New Jersey, as input for the model. The model was calibrated to match the 1968-70 streamflow records for the Easton (01446700), Riegelsville (01457500), and Trenton (01463500) stations, the last two of which serve as the outflow sites for reaches 7 and 8, respectively.

Calibration errors, as the absolute mean error of daily flows and error in flow volume, are summarized in table 4 for the modeled reaches. Comparisons of simulated and observed hydrographs for water years 1968-70 disclosed that the largest negative errors in daily flows resulted from underestimation of discharges on days when flows were rapidly increasing. These errors arose partly from the inability to factor timing adjustments of a fractional day into the model and partly from the use of flow records for stations on large, gaged streams to estimate inflows from small, ungaged tributaries that have more variable, and often non-synchronous, flows. The use of gaged flows to estimate storm runoff to the reaches upstream from Walnutport caused discharges of the Lehigh River to be underestimated by as much as 30 percent on several high-flow days.

Simulated flows for most low-flow periods agreed well with corresponding observed flows; however, the routing model for the Lehigh River overestimated flows for a few such periods. Downstream from Walnutport, the flows of gaged tributaries are strongly moderated by drainage from carbonate rocks. The use of flow records for these streams to estimate inflows from carbonate-rock areas caused some low flows simulated for the Bethlehem station to be as much as 15 percent high. For some protracted periods of low flow the model underestimates the inflow of ground water between Bethlehem and Glendon (reach 6); consequently, for some days in these periods the simulated flows are as much as 20 percent less than the observed flows. Flow records for the Little Lehigh Creek gage (01451500) were used to estimate inflows to reach 6, between Bethlehem and Glendon, as indicated in table 5. At times, flows at this gage are abnormally low, owing to underflow (Wood and others, 1972). Thus, use of flow records for this site to estimate inflow between Bethlehem and Glendon will periodically result in an underestimation of such inflow. However, no other flow record for a tributary stream provides better estimates of this inflow.

One of the original objectives of this study was to develop an interactive model that would account for bank storage as a factor in the attenuation and transit losses of an augmentative wave. However, available data on the transmissivity and storage characteristics of the several carbonate-rock units underlying the Lehigh River were found inadequate for that purpose.

The sporadic incidences of the above-noted differences between simulated and observed flows for the Bethlehem and Glendon sites may be partly caused by undefined low-water shifts in the stage-discharge relationships. Metered measurements of flows at these sites are too infrequent to completely define all such shifts.

Volume errors for the 3-year calibration period, which are less than 3 percent for each of the gaged nodal sites, show that positive and negative errors in daily flow volumes are adequately balanced. Three-year volume errors for these sites on the Lehigh River range from +2.8 percent for the station at Walnutport to -1.5 percent for the station at Glendon. The maximum annual volume error of 6.5 percent was for the Bethlehem station in water year 1970.

Table 4.--Model calibration and verification errors

Reach number	Period[1] Calibration (mo/yr)	Verification (mo/yr)	Errors, percent Daily flows	Flow volume
1-3	10/67 - 9/68		7.7	-1.3
	10/68 - 9/69		8.3	4.2
	10/69 - 9/70		13.7	5.5
	10/67 - 9/70		9.9	2.8
		10/70 - 9/81	9.7	1.8
4-5	10/67 - 9/68		7.0	-2.3
	10/68 - 9/69		8.4	- .8
	10/69 - 9/70		11.6	6.5
	10/67 - 9/70		9.0	1.1
		10/70 - 9/81	11.9	1.3
6	10/67 - 9/68		8.6	-4.0
	10/68 - 9/69		10.6	-2.2
	10/69 - 9/70		9.7	1.9
	10/67 - 9/70		9.6	-1.5
		10/70 - 9/81	8.5	.0
7B	10/67 - 9/68		3.8	-3.8
	10/68 - 9/69		3.0	.0
	10/69 - 9/70		3.8	-1.7
	10/67 - 9/70		3.5	-1.9
		[2]10/67 - 9/70	3.6	-1.5
8	10/67 - 9/68		4.6	-1.9
	10/68 - 9/69		5.6	1.0
	10/69 - 9/70		5.6	-1.7
	10/67 - 9/70		5.2	- .9
		10/70 - 9/81	6.5	- .8

1/Beginning month/year - ending month/year.

2/Observed daily flows, rather than synthesized flows, for Lehigh River at Glendon (01454700) used for inflow from Lehigh River. No daily record was available for Riegelsville (01457500) for 1971-81.

Table 5.--Equations used to route daily flows from Francis E. Walter Reservoir on the Lehigh River to Trenton, New Jersey on the Delaware River

[Station number and discharge symbol (Q) on left side of the equation indicates a synthesized output hydrograph of daily flows, in cubic feet per second, for the designated reach. Station numbers and Qs on right side of the equation indicate input hydrograph of daily flows. Station numbers for synthesized daily flows are underscored. MR and SR indicate multiple and single linearization, respectively, of the routing coefficients with discharge for the flows indicated in brackets. Routing distance, in miles, follows MR and SR notations for successive routing steps, which are identified by closure brackets]

Lehigh River Model

Reach 1:[a] Q01448000 (White Haven) = [Q01447800] (MR, 4.4) + Q01447720 x 0.21

Reach 2: Q01449000 = [[[[$\underline{\text{Q01448000}}$ + Q01447500 x 0.50 + Q01447720 x 0.40
+ Q01469500 x 2.0] (MR, 6.8) + Q01447720 x 0.65
+ Q01469500 x 1.0] (MR, 9.1) + Q01469500 x 2.25] (MR, 10.3)
+ Q01449360 x 0.70] (SR, 2.7)

Reach 3A: Q01450020 = [Q01449800] (SR, 4.7) + Q01450500 x 0.18

Reach 3B: Q01451000 = [$\underline{\text{Q01449000}}$ + $\underline{\text{Q01450020}}$ + Q01450500] (MR, 9.3)
+ Q01450500 x 1.0

Reach 4: Q01451190 = [[$\underline{\text{Q01451000}}$ + Q01452500 x 0.20] (SR, 7.2) + Q01451500 x 1.80
+ Q01452000 x 0.22 + Q01452500 x 1.40] (MR, 9.5)

Reach 5: Q01453000 = [$\underline{\text{Q01451190}}$ + Q01451500 x 0.65] (MR, 5.2)
+ Q01451500 + Q01452000 + Q01452500

Reach 6: Q01454700 = [$\underline{\text{Q01453000}}$ + Q01451500 x 1.60] (SR, 9.5)

Delaware River Model

Reach 7: Q01457500 = [[Q01446500 x 1.045] (SR, 14.0) + $\underline{\text{Q01454700}}$] (SR, 11.2)
+ Q01457000 x 1.60

Reach 8: Q01463500 = [[$\underline{\text{Q01457500}}$ + Q01457000 x 0.40] (SR, 18.4)
+ Q01459500 x 1.60] (SR, 22.0)

---

[a]Model developed for nodal site at Pa. Highway 940 at White Haven, for which the drainage area is 7 mi^2 (2.2 percent) less than that for station 01448000.

Table 6 summarizes the routing parameters used in the models. The indicated distances are those applicable to the various daily-flow summations that are routed, which are indicated in the equations of table 5. Single routing parameters were used for all reaches, and segments thereof, for which multiple parameters were found, by trial-and-error applications, to provide no improvement in the models.

Verification

Verification of the models was performed by comparing the simulated with the observed hydrographs for the nodal sites for water years 1971-81. No observed records are available, for this period, for the nodal sites at Lehighton (01449000), at the mouth of Pohopoco Creek (01450020), at Allentown (01451190), and at Riegelsville (01457500). Flow records for 1982 were not used because of uncertainties in low-water stage-discharge relationships for the Walnutport and Bethlehem stations. The close correspondence in the resultant errors in daily flows and flow volumes with like values for the calibration periods (table 4) verifies the general applicability of the models.

Observed flows for 1971-81 were not available for the Riegelsville station, at the downstream end of reach 7; hence, a verification of the model for this reach was not possible. Calculations for this reach used the observed, rather than the simulated, hydrograph for the 1968-70 record of daily flows for the Glendon station to represent the inflow of the Lehigh River to the reach. The simulated hydrograph for Riegelsville was nearly identical to that generated through use of modeled inflow from the Lehigh River.

An assessment of the adequacy of the models for the simulation of low flows was made by comparing low-flow-frequency distributions for simulated and observed flow records for the gaging stations. Table 7 shows these frequency distributions for 7-day minimum flows at the nodal sites for 1968-80. The maximum difference between corresponding simulated and observed 7-day discharge values is 18 percent, but most values agree within 10 percent. Simulated and observed frequency distributions for durations longer than 7 days exhibit smaller differences than those of table 7. This close agreement between simulated and observed low-flow characteristics confirms the adequacy of the models for simulating low-flow sequences for statistical analysis.

APPLICATION OF MODELS

Hypothetical releases from Francis E. Walter Reservoir were routed to evaluate the response of the river system to conservation releases during extreme low-flow periods. Two release sequences were superimposed upon the flows observed during the drought in the summer of 1965. The first sequence consisted of routing the flows observed at station 01447800 with an added, hypothetical release of 50 ft^3/s for a 64-day period. This period began on July 19, 1965, which was at the onset of the longest period of sustained low flows to occur since operations of Francis E. Walter Reservoir began in 1961. The second sequence was the same, except that 200 ft^3/s were added to the observed flows for the second, third, and fourth days of the 64-day period.

Table 6.--Parameters used in flow-routing models

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

	Q	C	K
LEHIGH RIVER			
	40	1.5	22
	100	2.2	60
Reach 1, distance = 4.4 mi, [a]	200	3.1	120
	500	4.3	290
and	1,000	5.2	510
	6,000	6.4	2,500
Reach 2, distance = 6.8 mi:	15,000	6.5	5,500
Reach 2, distance = 9.1 mi,	50	.9	35
	150	1.9	130
and	300	2.6	240
	500	3.2	365
Reach 2, distance = 10.3 mi:	700	3.7	485
	1,000	4.5	655
	4,000	8.3	2,160
	20,000	11.0	9,900
Reach 2, distance = 2.7 mi:	all	5.0	700
POHOPOCO CREEK			
Reach 3A, distance = 4.7 mi:[b]	all	2.4	175
LEHIGH RIVER			
Reach 3B, distance = 9.3 mi:	130	1.0	110
	200	1.4	160
	500	2.7	400
	1,000	3.9	800
	2,000	5.2	1,600
	4,000	6.6	3,050
	15,000	10.0	10,000
	30,000	11.0	18,000
Reach 4, distance = 7.2 mi:	all	4.9	1,100
Reach 4, distance = 9.5 mi:	200	2.2	200
	500	3.7	450
	1,000	4.8	880
	4,000	6.8	2,800
	16,000	8.7	9,200
	40,000	10.0	19,500
Reach 5, distance = 5.2 mi:	250	3.6	280
	500	5.1	545
	1,000	5.5	1,050
	4,000	6.3	3,480
	15,000	7.4	10,600
	60,000	8.6	36,000
Reach 6, distance = 9.5 mi:	all	6.1	2,800
DELAWARE RIVER			
Reach 7A, distance = 14.0 mi:[c]	all	7.5	16,200
Reach 7B, distance = 11.2 mi:	all	6.9	15,000
Reach 8, distance = 18.4 mi:	all	7.0	14,000
Reach 8, distance = 22.0 mi:	all	7.4	13,000

[a]Distance is for the segment downstream of gaging station 01447800.

[b]Distance is for the segment between gaging stations 01449800 and 01450020.

[c]Distance is that between the gaging station on the Delaware River at Belvidere, N.J. (01446500) and the Lehigh River.

Table 7.--Observed and simulated 7-day, low-flow discharges for the nodal sites

Nodal site number	Gaging station number	Type of record[1]	Discharge, in cubic feet per second, for indicated recurrence interval, in years			
			2	5	10	20
	01447800	O	97	75	66	59
1	at Pa. Hwy 940	S	110	87	77	69
	[2]01448000	S	113	89	79	71
2	[2]01449000	S	286	230	205	186
3A	[2]01450020	S	45	36	32	29
3B	01451000	S	419	341	305	278
		O	380	301	267	242
4	[2]01451190	S	602	498	448	409
5	01453000	S	753	625	563	514
		O	654	531	492	467
6	01454700	S	851	704	632	575
		O	879	732	664	613
7B	[2]01457500	S	3,500	3,140	2,970	2,840
8	01463500	S	3,570	3,190	3,020	2,880
		O	3,560	3,130	2,920	2,740

[1]O - Observed daily flows for 1968-80 water years.

S - Simulated daily flows for 1968-80 water years.

[2]Inactive gaging site during 1968-80.

The purpose of routing an additional 150 ft^3/s release for 3 days near the beginning of the hypothetical-release period was to evaluate the utility of releasing a 'slug' of water to accommodate channel-storage effects and to accelerate the arrival of augmentative releases at downstream points.

Hydrographs of daily flows observed at station 01447800 and those of the modified daily flows that were routed through reach 1 are shown in figure 2 for the months of July, August, and September, 1965. The routed flows at the downstream end of reach 1 closely parallel those input to this reach. At the downstream end of reach 2, at the Lehighton station, the hydrograph of routed flows, shown in figure 3, is considerably different from that of the input hydrograph that was simulated for the White Haven site at PA Highway 940 because inflow to the reach has altered the pattern of daily flows. Dampening of the additional 150 ft^3/s release of July 20-22 is evident in the hydrograph of simulated flows for reach 2. By July 26, all of the additional 450 ft^3/s-days of release for July 20-22 has passed through reach 2. No record of actual flows in reach 2 are available for station 01449000 to compare with the routed flows for this reach.

Routed and simulated hydrographs for the Walnutport station, as well as the contribution of Pohopoco Creek to reach 3, are shown in figure 4. Model errors are such that routed flows are about 20 ft^3/s greater than observed flows for July 19, at the start of the simulation period of added releases. Some of this added flow first appears in the routed hydrograph for the Walnutport station on the same day. The routed hydrograph for the added hypothetical release of 200 ft^3/s, which was begun on July 20, shows the leading edge of augmentative flow to arrive on July 20 as well. Peak flow is predicted to occur on July 22. Field observations of the translation times of flow releases, which were made in September 1982, indicate the travel time for the leading edge of the wave produced by a similar release is about 28 hours. Thus, the arrival of the wave at Walnutport on July 20 (fig. 4), as predicted by the model, is 1 day early. However, the increment to routed flow on this date is only 33 ft^3/s greater than the corresponding increment computed by the model when 50 ft^3/s was added to the daily flows of station 01447800. The use of single celerity and dispersion coefficients, instead of multiple-routing coefficients, throughout the model did not correct this 1-day error in the routing of hypothetical flows. Such timing errors severely limit the usefulness of this type of model for estimating the travel times of a wave from an augmentative release. The use of a routing interval of 1 hour, rather than 1 day, would produce smaller errors in the predicted travel times, but would require considerably more effort to prepare the necessary hydrographic input.

The second simulated discharge is 355 ft^3/s for the Walnutport station on July 22, which is 203 ft^3/s greater than the observed mean flow, and 171 ft^3/s greater than the routed mean flow, for that date. Thus, the modeled attenuation of the peak discharge is 29 ft^3/s, or 15 percent of the hypothetical release.

Routed and simulated hypothetical flows for the Bethlehem station are graphed in figure 5 for July through September, 1965. As for Walnutport, the model predicts the arrival on July 20 of the leading edge of the 200-ft^3/s 'slug' of hypothetical release of the same date. The model indicates such a

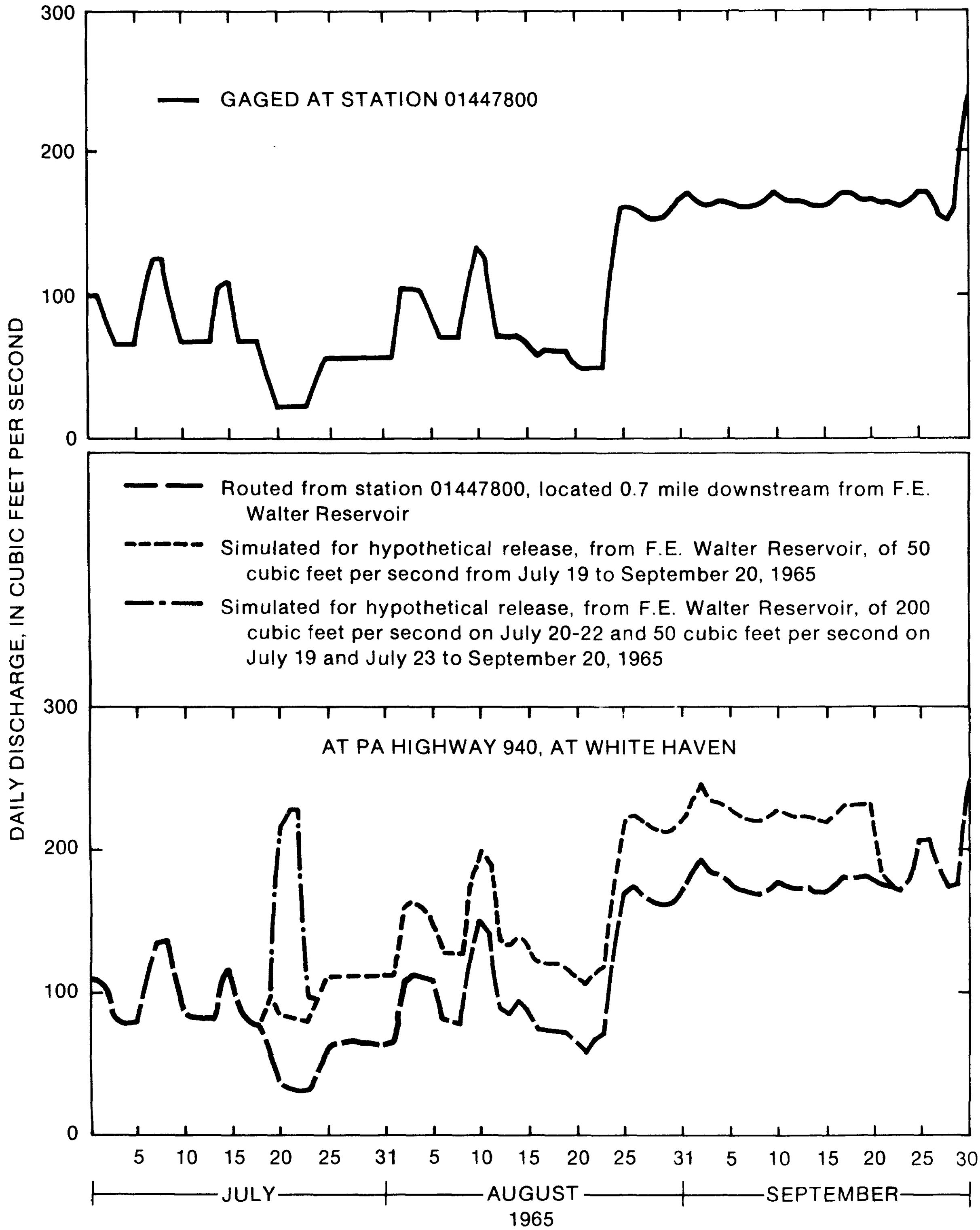

Figure 2.-- Hydrographs of gaged, routed, and simulated daily discharges at sites in reach 1 of the Lehigh River for the low-water period of July - September 1965.

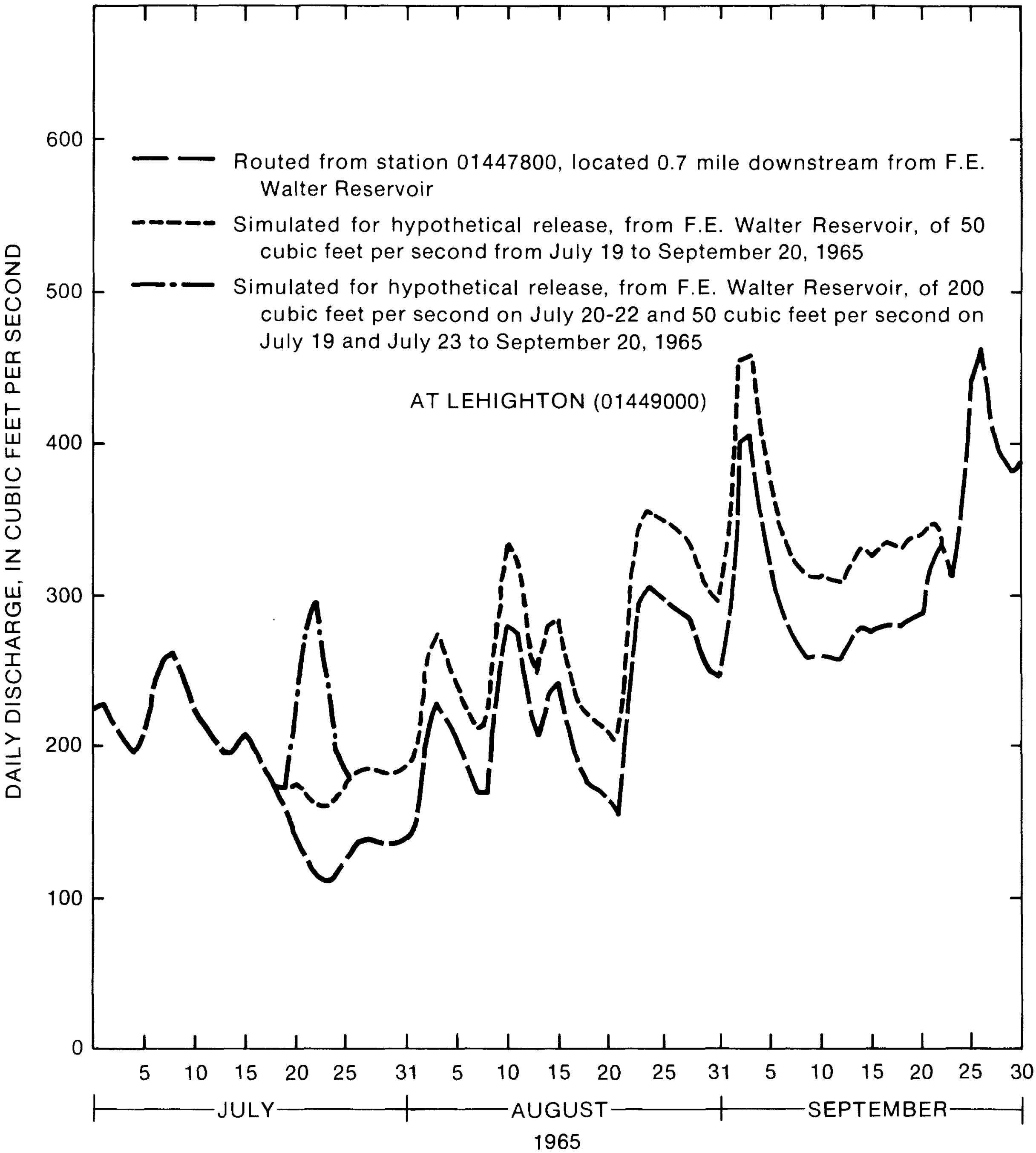

Figure 3.-- Hydrographs of routed and simulated daily discharges at the downstream end of reach 2 of the Lehigh River for the low-water period of July - September 1965.

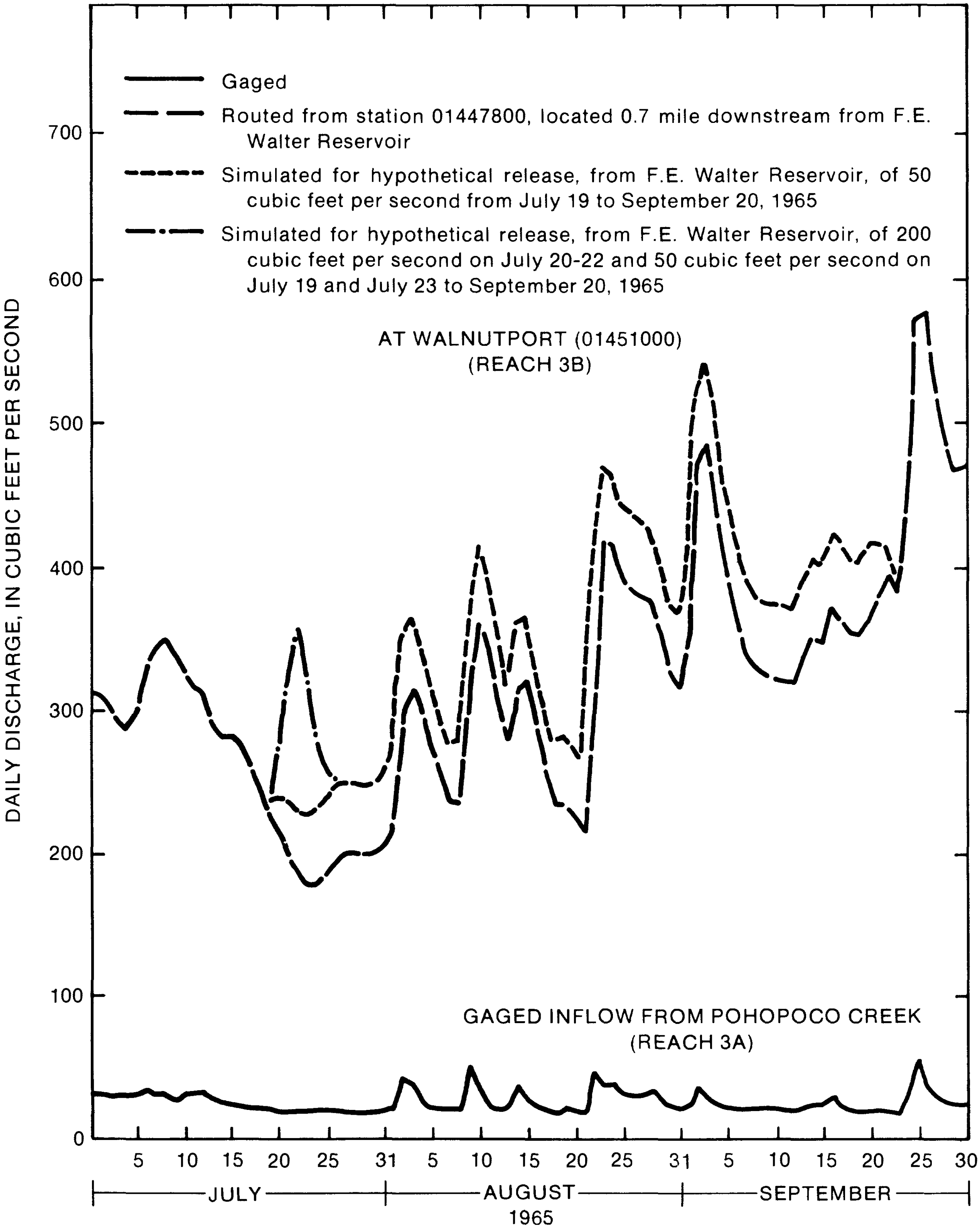

Figure 4.-- Hydrographs of gaged, routed, and simulated daily discharges at the downstream ends of reaches 3A of Pohopoco Creek and 3B of the Lehigh River for the low-flow period of July - September 1965.

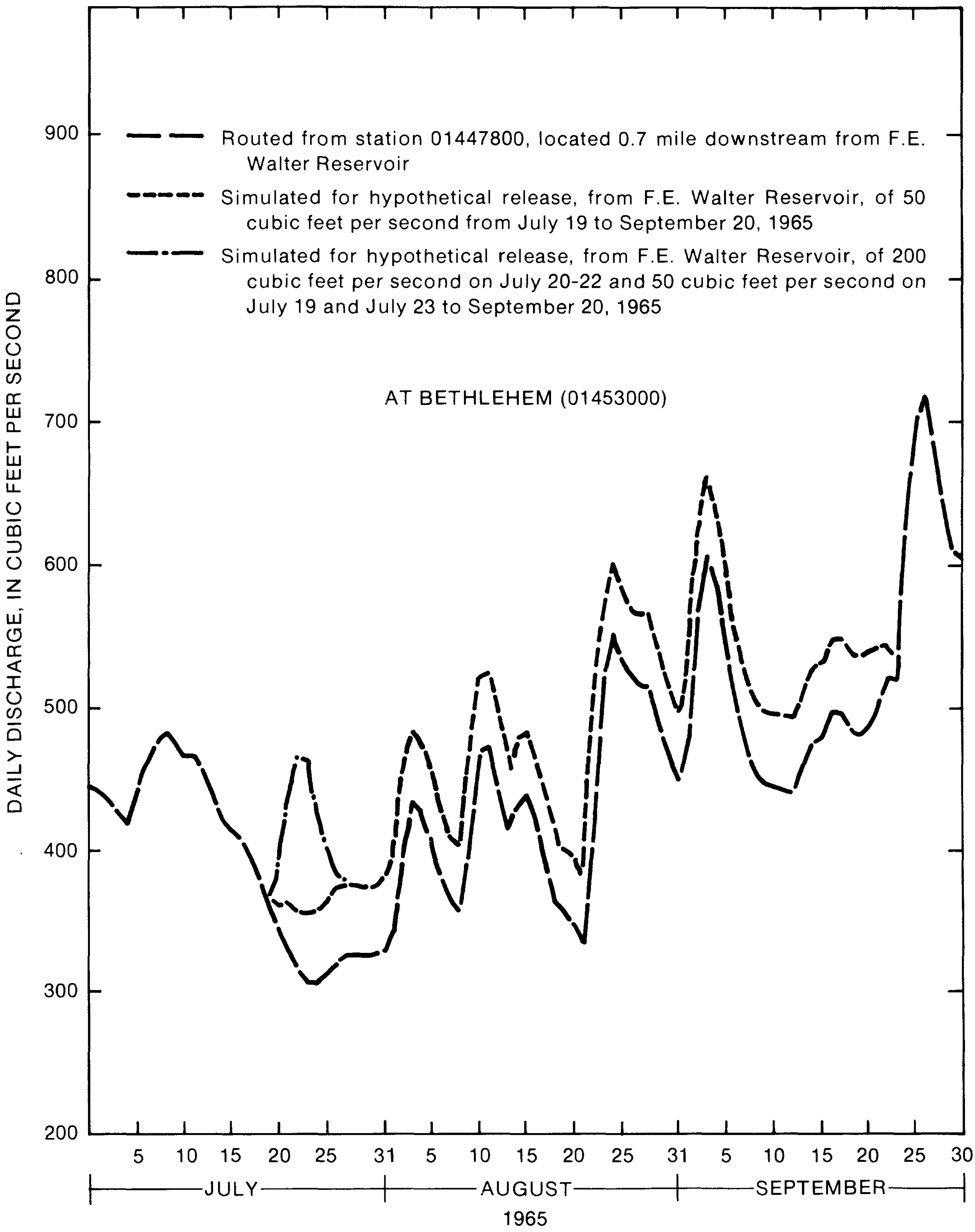

Figure 5.-- Hydrographs of routed and simulated daily discharges at the downstream end of reach 5 of the Lehigh River for the low-water period of July - September 1965.

'slug' of water would have passed Bethlehem by July 28. Routed daily flows for the extreme low-water period of July 23-31 are 40-50 ft^3/s greater than the observed flows, owing to model error. However, the second simulation for July 21-24 indicates that approximately 75 percent of a 3-day, 200-ft^3/s release 'slug' will reach Bethlehem in as many days during extreme low-flow conditions. Routed flows for low-water periods in August and September match observed flows within 10 percent. The highest of the routed daily peaks lag the observed by 1 day and all are less than those observed, owing to underestimation of the inflow from small, ungaged tributaries during storm events.

The relationship of routed to simulated flows for the Glendon station, shown in figure 6, is nearly identical to that for the Bethlehem station (fig. 5). A comparison of the hydrographs of figure 6 with those of figure 5 discloses no attenuation of release waves between Bethlehem and Glendon (reach 6).

Routed daily flows for the summer of 1965 at the Trenton station (fig. 7) follow the general trend of corresponding observed flows, but routed flows are in error by more than 10 percent on several days during periods of low water. The 50-ft^3/s hypothetical release routed for the period July 19 to September 20, 1965 appears as the difference between the routed and simulated hydrographs in figure 7. The routed wave for the 200 ft^3/s hypothetical 'slug' release of July 20-22 is predicted by the model to arrive at Trenton on July 22, peak there on July 23, and to completely pass the site by July 28. These predicted dates for the arrival and peak are about 2 days earlier than expected on the basis of hydrographic records for similar releases from Francis E. Walter Reservoir. This 200 ft^3/s of hypothetical release is not apparent in the simulated hydrograph for the Trenton station when it is compared to the observed hydrograph for that site. Corresponding routing, simulated, and observed hydrographs for the Riegelsville station (not shown) follow the same pattern on those for the Trenton station. Thus, the routing models developed for the Delaware River could not be calibrated with sufficient reliability to allow a realistic simulation of travel times to Trenton for typical augmentative releases from reservoirs in the Lehigh River basin.

TIME OF TRAVEL

Hydrographic data were used to precisely time the propagation of release waves on the Lehigh River.

Inspection of stage hydrographs for the several gages on this river disclosed that travel times of waves produced by augmentative releases from Francis E. Walter Reservoir are related to the pre-augmentation release rate and the magnitude of the release. Figure 8 shows, for selected reaches, the relationships between steady-state pre-release discharge and travel time for the leading edge of a wave produced by a three-fold augmentative release. These relationships were developed from hydrographic records collected during periods of low base flow in the basin. During such periods, discharges at the Walnutport station are approximately three times those that would occur at the White Haven station (01447800) if there were no regulation. Thus, when a sustained release from Francis E. Walter Reservoir is equal to the natural base flow at the reservoir site for the prevailing climatic conditions,

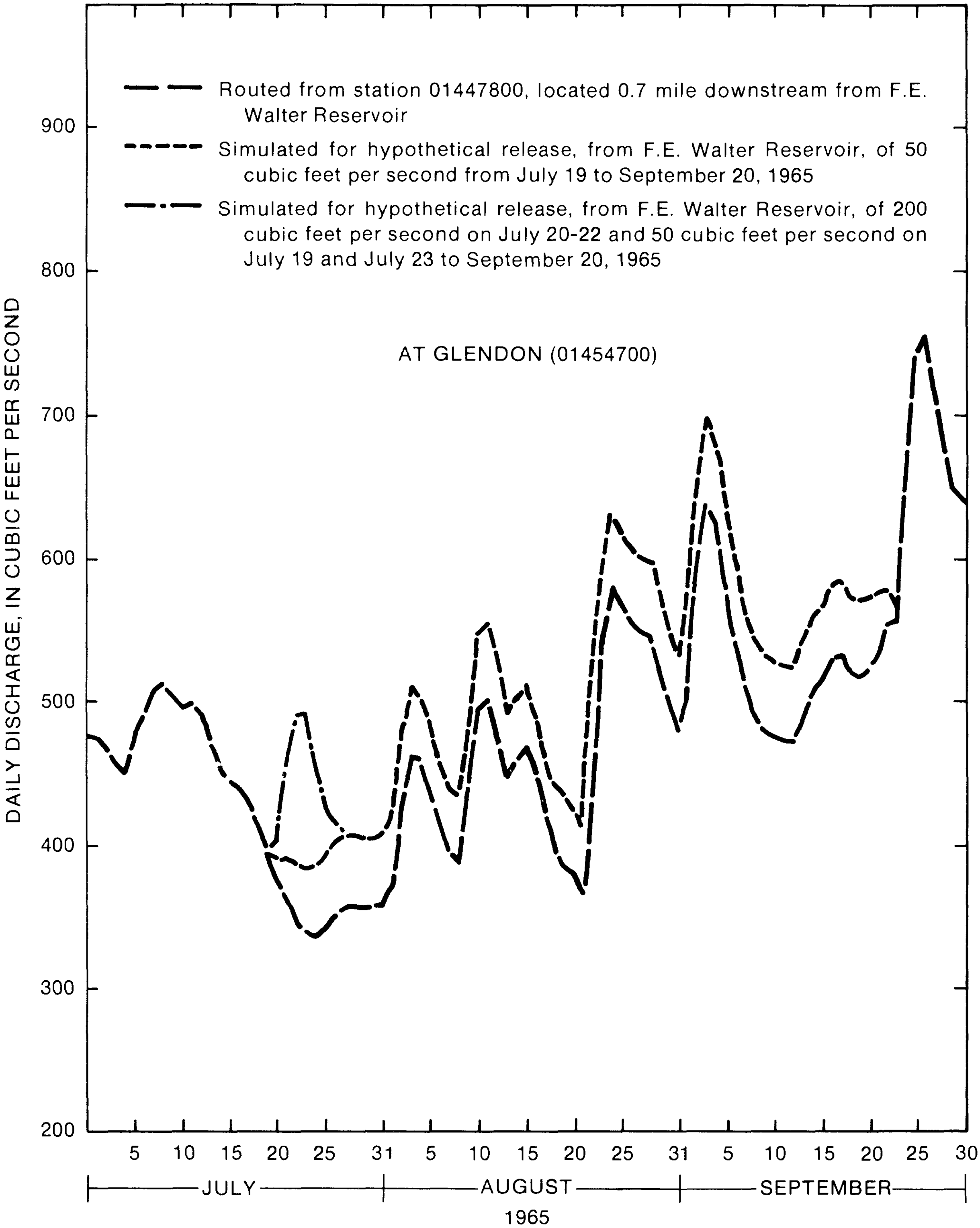

Figure 6.-- Hydrographs of routed and simulated daily discharges at the downstream end of reach 6 of the Lehigh River for the low-water period of July - September 1965.

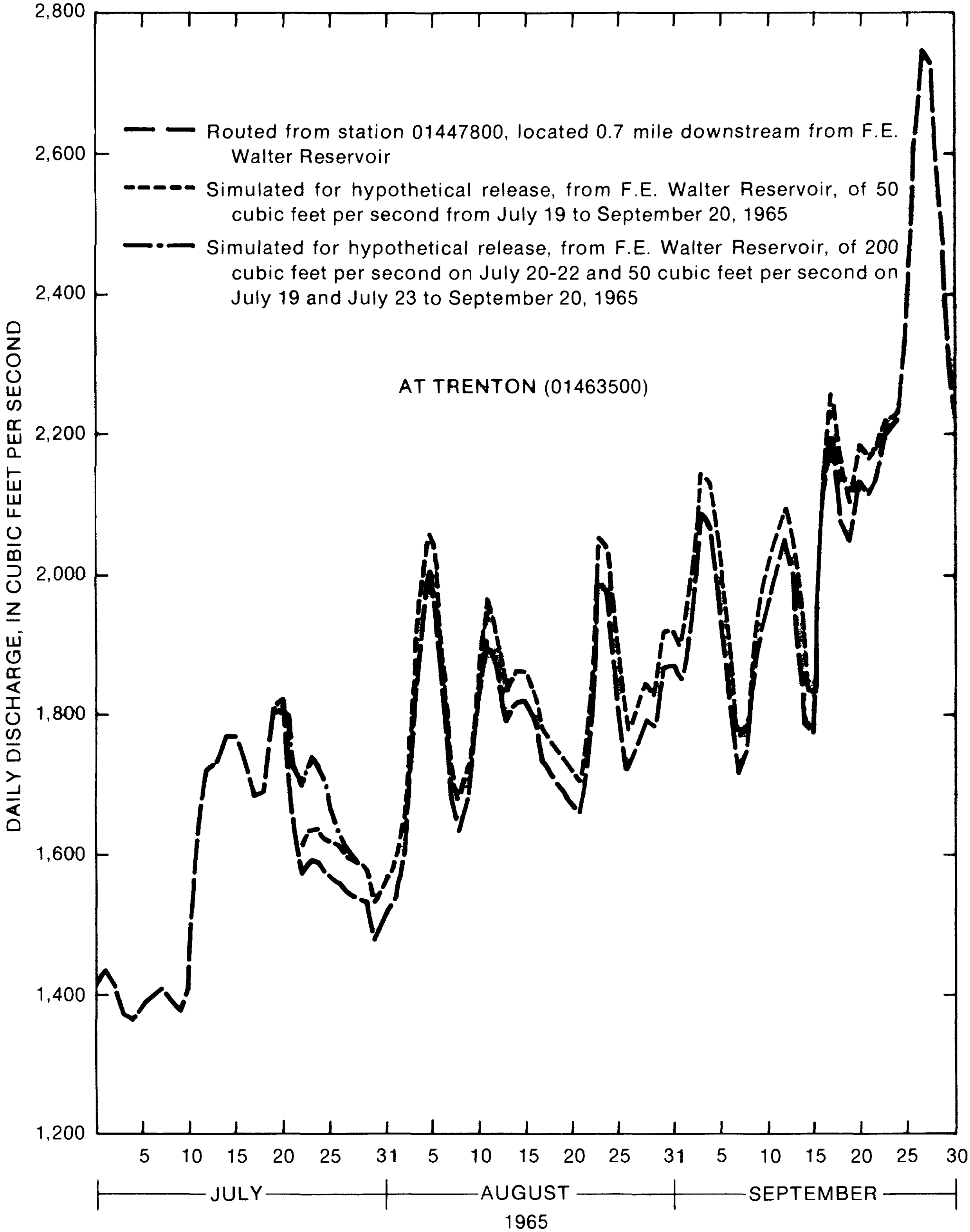

Figure 7.-- Hydrographs of routed and simulated daily discharges at the downstream end of reach 8 of the Delaware River for the low-flow period of July - September 1965.

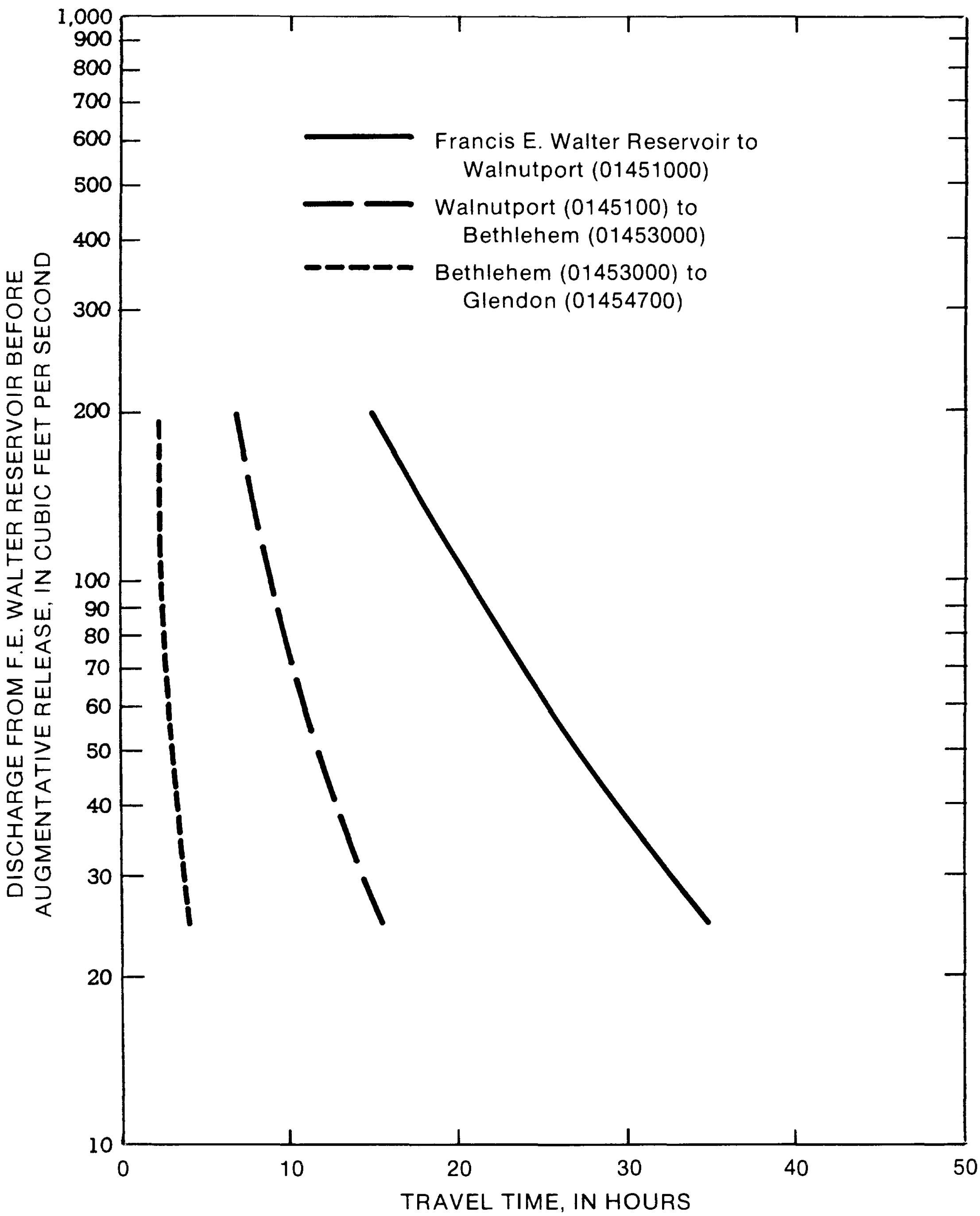

Figure 8.-- Travel times for the leading edge of a wave produced by a three-fold augmentative release from Francis E. Walter Reservoir on the Lehigh River.

then base flow at the Walnutport station (01451000) will stabilize at approximately three times the rate of release. Figure 8 can be used, for such conditions, to estimate the travel time for the leading edge of a wave that is produced when an augmentative release is made by opening the control gates in the dam sufficiently to triple the release rate. For example, the wave generated by rapidly changing the release rate from 50 ft^3/s to 150 ft^3/s will begin to arrive at the Walnutport station in about 27 hours. Its arrival at Bethlehem will be 12 hours later, and it will first appear at Glendon in another 3 hours. The total travel time for the leading edge of this wave, as it moves from the reservoir to Glendon, will be 42 hours.

Augmentative releases from Francis E. Walter Reservoir often do not produce an identifiable hydrographic response at the Trenton station, owing to stage fluctuations on the Delaware River caused by regulation, withdrawals of water, and the return of waste water to the river. Therefore, it was not possible to determine reliable discharge-travel time relationships for low flows in the reach from Glendon to Trenton.

Travel times of augmentative releases from Francis E. Walter Reservoir and Beltzville Lake were investigated in September 1982 by installing temporary stage records at three sites, which are identified in table 8.

Table 8.--Locations of temporary recorders installed to monitor travel times of augmentative releases from reservoirs during September 1982

Site	Reach number (from table 2)
Lehigh River at PA Highway 940, at White Haven, Pa.	1
Lehigh River at U.S. Highway 209, at Lehighton, Pa. (station 01449000 re-established here in October 1982)	2
Pohopoco Creek at Centre Street, 850 ft upstream from mouth, near miscellaneous gaging station 01450020	3A

Release times and changes in release rates for the three exemplary releases that were made are summarized in table 9. Antecedent release rates (see footnotes to table 9) were maintained at levels typical of those used during severe droughts.

These investigations confirmed the travel times for release waves shown by figure 8. Additionally, information was obtained on travel times for low-water conditions in reaches 1, 2, 3A, and 3B. Tables 10-12 show observed arrival times and travel times of the three releases for selected sites on the Lehigh River and Pohopoco Creek. Travel times observed on the Lehigh River for release number 1 confirm the relationships of figure 8. Stage

Table 9.--Exemplary augmentative reservoir releases in the Lehigh River basin used to define low-flow travel times, September 21-23, 1982

Release number	Source	Date	Time of release	Change in release rate, ft^3/s		
1	Francis E. Walter Reservoir	9-21	0800 hours	1/48	to	153
			1500 hours	153	to	46
2	Francis E. Walter Reservoir	9-22	1700 hours	47	to	117
3	Beltzville Lake	9-23	0800 hours	2/29	to	73
			0900 hours	73	to	62
			1400 hours	62	to	32

1/Release stabilized at 48 ft^3/s for 20 hours prior to abrupt 3-fold augmentative release.

2/Release stabilized at 29 ft^3/s for 2 days prior to augmentative release.

Table 10.--Discharge rate and travel times for the wave on the Lehigh River produced by release number 1, September 21, 1982

Reach	Site	Discharge, ft^3/s		Leading edge of wave		
		At leading edge of wave	At crest of wave	Arrival time day	Arrival time hour	Travel time hours
1	Near White Haven (station 01447800)	48	153	9-21	0830	0.5
1	White Haven, Pa. Hwy 940	57	160	9-21	1140	3.7
2	Lehighton (station 01449000)	210	283	9-22	0600	22.0
3B	Mouth of Pohopoco Creek	-	-	9-22	1/0705	23.1
3B	Walnutport (station 01451000)	358	500	9-22	1100	27.0
4	Allentown, Hamilton Street (misc. station 01451190)	-	-	9-22	2/2010	36.2
5	Bethlehem (station 01453000)	800	895	9-22	2300	39.0
6	Glendon (station 01454700)	826	894	9-23	0215	42.2

1/Estimated from arrival times at Lehighton and Walnutport. Crest arrived at approximately 1050 hours.

2/Estimated from arrival times at Walnutport and Bethlehem.

Table 11.--Discharge rate and travel times for the wave on the Lehigh River produced by release number 2, September 22, 1982

		Discharge, ft^3/s		Leading edge of wave		
		At leading	At crest	Arrival time		Travel time
Reach	Site	edge of wave	of wave	day	hour	hours
1	Near White Haven (station 01447800)	47	117	9-22	1730	0.5
1	White Haven, Pa. Hwy 940	60	135	9-22	2110	4.2
2	Lehighton (station 01449000)	252	295	9-23	1/1520	22.3
3B	Mouth of Pohopoco Creek	-	-	9-23	2/1630	23.5
3B	Walnutport (station 01451000)	473	495	9-23	2115	28.2
4	Allentown, Hamilton Street (misc. station 01451190)	-	-	9-24	3/0600	37.0
5	Bethlehem (station 0145300)	785	845	9-24	0845	39.8
6	Glendon (station 01454700)	4/	4/	4/	4/	4/

1/Advanced by wind, runoff from light rainfall, and high base flow.

2/Estimated from arrival times at Lehighton and Walnutport. Crest arrived at approximately 2030 hours.

3/Estimated from arrival times at Walnutport and Bethlehem.

4/Affected by wind, arrival times for leading edge and crest are indeterminate.

Table 12.--Discharge rate and travel times for the wave on the Pohopoco Creek produced by release number 3, September 23, 1982

		Discharge, ft^3/s		Leading edge of wave		
		At leading	At crest	Arrival time		Travel time
Reach	Site	edge of wave	of wave	day	hour	hours
3A	Near Beltzville (station 01449800)	29	73	9-23	0805	0.1
3A	At mouth (misc. station 01450020)	33	70	9-23	1/1005	2.1

1/Projected from arrival time at temporary gage site 850 ft upstream from mouth. Crest arrived at approximately 1340 hours. Leading edge and crest arrived at Walnutport (station 01451000) at 1415 and 1815 hours, respectively.

records collected on the Lehigh River since 1961 indicate travel times for 2-fold augmentative releases are usually about 20 percent greater than those for 3-fold releases, the average times of which are depicted by figure 8. However, the wave from release number 2 moved about 15 percent more quickly than most similar 2.5-fold augmentative releases that have been made during actual droughts. This increase in the propagation rate is believed to have occurred mostly because antecedent flow in the channel downstream from White Haven was unusually large in comparison to the antecedent release rate of 47 ft^3/s. For example, during an actual drought the flow at Lehighton for this antecedent release rate would be about 100 ft^3/s instead of the 252 ft^3/s that was gaged prior to release number 2. Travel times for 6-fold augmentative releases are about 15 percent less than those of figure 8. Available stage records are inadequate, owing to the effects of runoff, for the estimation of travel times of augmentative releases that exceed the antecedent rate of release by more than six fold.

Data from the three timed releases and figure 8 can be used to estimate the temporal relationship for augmentative releases from the two reservoirs. For example, observed travel times for the three exemplary augmentative releases show that if the rate of release from Francis E. Walter Reservoir is changed from 50 to 150 ft^3/s, then this change must precede a release from Beltzville Lake by 21 hours in order to make the two wave crests coincide at the mouth of Pohopoco Creek.

The timing for other magnitudes of augmentative releases from Francis E. Walter Reservoir can be adjusted, by approximation, on the basis of figure 8 and observed variations in travel times for waves from 2- and 6-fold releases, as noted above. For example, the wave crest of a 6-fold augmentative release (50 to 300 ft^3/s) from Francis E. Walter Reservoir will coincide with a release wave on Pohopoco Creek if the Francis E. Walter release is made about 18 hours in advance of the Beltzville release. A shorter advance time will be required for making the release waves coincide if the pre-augmentative release at Francis E. Walter Reservoir is greater than 50 ft^3/s or if there is appreciable runoff in the upper part of the basin. However, this study did not evaluate travel times for other than base-flow conditions.

Travel times to Walnutport for releases from Beltzville Lake during low-flow periods can be estimated from figure 8, provided the discharge from Francis E. Walter Reservoir has been relatively constant for no less than 1 day prior to the Beltzville release. For such conditions, the travel time to Walnutport for the leading edge of a wave generated by a moderate augmentative release from Beltzville Lake will be approximately 2 hours plus 18 percent of the travel time indicated by the right-most (solid) curve in figure 8 for the pre-augmentative release rate for Francis E. Walter Reservoir.

Transit losses to bank storage were negligible for the three exemplary releases made in September 1982. The releases (table 9) produced rises in stage of less than 0.2 ft (feet) at points downstream of Lehighton; thus, the change in head was too small, and the translation rate too large, to cause a measurable loss to bank storage.

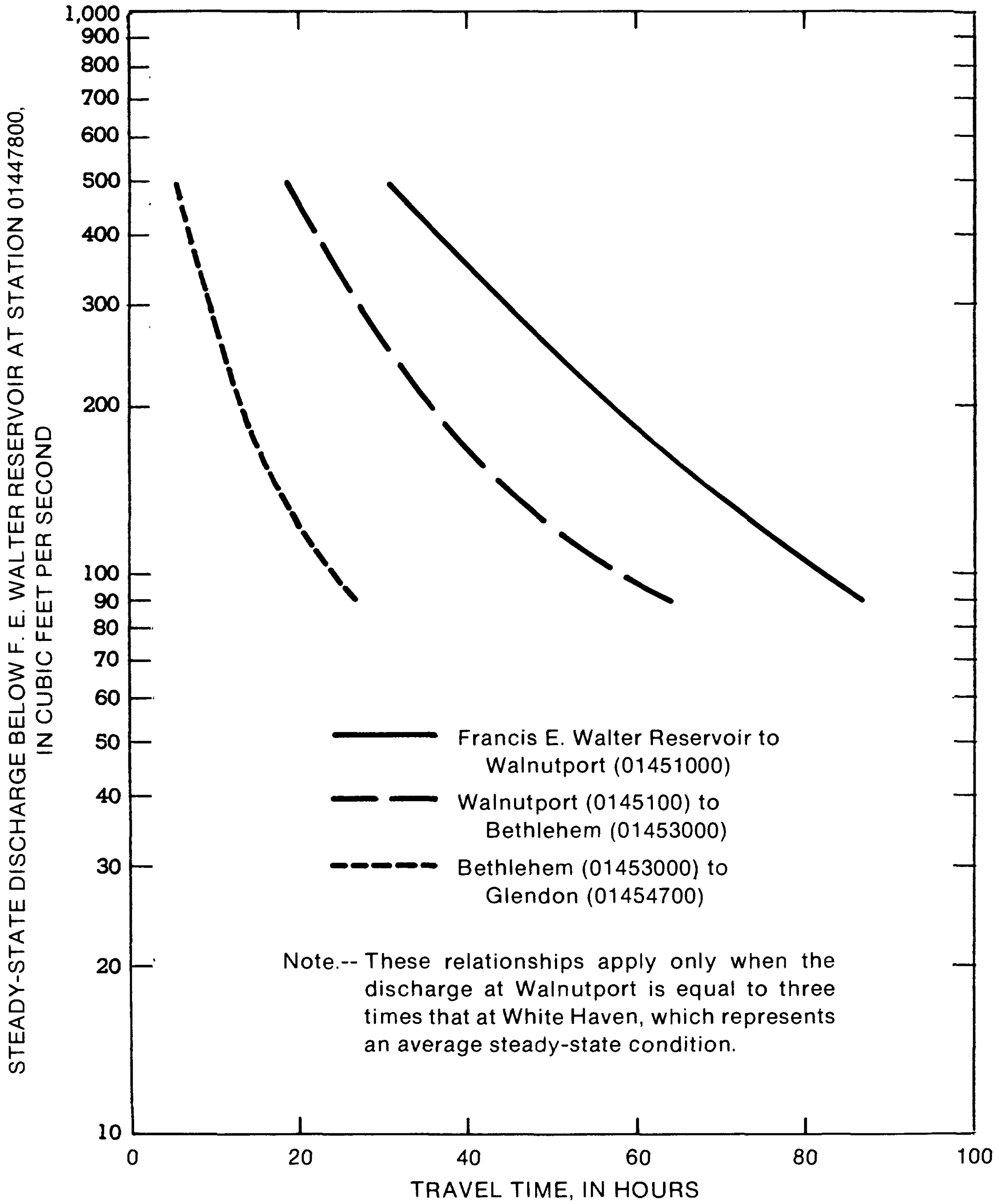

Figure 9.--Travel times for the leading edge of a mass of a solute or suspended matter in the Lehigh River (after Kauffman, 1983, fig. 17).

A comparison of the hydrographs collected at the Walnutport and Bethlehem stations during the 1965 drought suggests that attenuation of waves by bank storage in reaches 4 and 5 is negligible during extreme droughts as well. Extreme low-flow records are not available for the Glendon station; therefore, a similar hydrographic comparison for reach 6 was not possible.

Movement in the Lehigh River of colloidal dispersions, particulate suspensions, or a water-soluble substance is much slower than that of a release wave under the same flow conditions. Figure 9 (after Kauffman, 1983) shows relationships, for the same reaches as in figure 8, between the release rate from Francis E. Walter Reservoir, as measured at station 01447800, and travel time, in hours, for such substances. These relationships are applicable only for high-base-flow conditions and steady-state releases from the reservoirs. Travel times of solutes and suspended matter in the river could be reduced by rainfall or releases from the reservoirs.

CONCLUSIONS

The unit-response routing models that were developed to simulate flows on the Lehigh and Delaware Rivers were adequate for predicting the hydrographic response of the rivers to augmentative releases from Francis E. Walter Reservoir during extreme low-water periods. Flows were simulated for eight sites in the reach from White Haven, Pennsylvania to Trenton, New Jersey.

A satisfactory calibration of the models could be achieved only by stepwise routing between major tributaries on the Lehigh River. This calibration required the use of multiple-routing coefficients for each of the five selected reaches between the gaging station below Francis E. Walter Reservoir (01447800) and the Bethlehem station (01453000). Single routing coefficients were suitable for five segments of the three reaches between Bethlehem and Trenton, as shown in table 6 for reaches 6-8.

Model errors stem primarily from the use of gaged tributary inflow to estimate inflows from ungaged areas of different hydrologic character. Consequently, the models will underestimate some major peaks, in the reach from Walnutport to Glendon, by as much as 30 percent. Under certain conditions, simulated low flows for the reach from Bethlehem to Glendon will be as much as 20 percent in error.

The development of unit-response routing models to predict travel times of release waves is not as practical as the use of stage hydrographs. Satisfactory timing of augmentative waves on the Lehigh River was achieved through hydrographic comparison of stage records for four gaging stations and through the use of auxiliary gages to time exemplary augmentative releases. Stage fluctuations on the Delaware River seriously limited the utility of the routing models for predicting the time of arrival at Trenton of waves produced by modest augmentative releases in the Lehigh River basin.

Most of the attenuation of waves produced by augmentative releases appears to result from channel filling and spreading of the wave. Stage-discharge relationships for the Walnutport, Bethlehem, and Glendon gaging stations show that the wave produced during extreme low water by releases as great as 200 ft^3/s will raise the level of the river in the reach where it crosses carbonate bedrock by less than 0.2 ft. Thus, a large channel conveyance and a rapid translation rate result in negligible attenuation of typical augmentative waves by bank storage during low base-flow periods. The primary benefit of releasing a pre-release 'slug' of water at the start of a period of increased augmentative release is to shorten the travel time of the wave.

SELECTED REFERENCES

Doyle, W. H., Jr., Shearman, J. O., Stiltner, G. J., and Krug, W. R., 1983, A digital model for streamflow routing by convolution methods: U.S. Geological Survey Water-Resources Investigations Report 83-4160, 130 p.

Kauffman, C. D., Jr., 1983, Time-of-travel and dispersion studies, Lehigh River, Francis E. Walter Lake to Easton, Pennsylvania: U.S. Geological Survey Open-File Report 82-861, 32 p.

U.S. Army Corps of Engineers, 1983, Modification of the Francis E. Walter Dam and Reservoir: U.S. Army Corps of Engineers, Philadelphia District, Information Bulletin No. 2, 23 p.

Wood, C. R., Flippo, H. N., Jr., Lescinsky, J. B., and Barker, J. L., 1972, Water resources of Lehigh County, Pennsylvania: Pennsylvania Geological Survey, 4th ser., Water Resource Report 31, 263 p.