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Determination of Traveltime in the Delaware River, Hancock, New York, to the Delaware Water Gap by Use of a Conservative Dye Tracer

Kirk E. White
USGS

Todd W. Kratzer
USGS

DETERMINATION OF TRAVELTIME IN THE DELAWARE RIVER, HANCOCK, NEW YORK, TO THE DELAWARE WATER GAP BY USE OF A CONSERVATIVE DYE TRACER

by Kirk E. White and Todd W. Kratzer

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BRUCE BABBIT, Secretary

U.S. GEOLOGICAL SURVEY

Robert M. Hirsh, Acting Director

For additional information write to:

District Chief
U.S. Geological Survey
840 Market Street
Lemoyne, Pennsylvania 17043-1586

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To Obtain
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
foot per mile (ft/mi)	0.1894	meter per kilometer
pound (lb)	453.6	gram
foot per second (ft/s)	0.3048	meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
mile per hour (mi/h)	1.609	kilometer per hour

Temperature

°C=5/9 (°F-32)

Abbreviated water-quality units used in report:

micrograms per liter (µg/L)

DETERMINATION OF TRAVELTIME IN THE DELAWARE RIVER, HANCOCK, NEW YORK, TO THE DELAWARE WATER GAP BY USE OF A CONSERVATIVE DYE TRACER

by Kirk E. White[1] and Todd W. Kratzer[2]

ABSTRACT

Traveltime of a soluble substance was determined for a 120-mile reach of the Delaware River from the confluence of the East Branch Delaware River and the West Branch Delaware River at Hancock, N.Y., to the Delaware Water Gap. Dye studies were conducted at the 85-95 percent and 25-30 percent flow durations. Discharges ranged from 500-1,740 cubic feet per second during the 85-95 percent flow duration and 3,070-7,500 cubic feet per second for the 25-30 percent flow duration. The data were used to develop a set of time-concentration curves that would enable estimation of the traveltime of a spill at any point in the river within the study reach for 10 flow durations. The leading edge of a contaminant spill at Buckingham Access would take about 70 hours to reach the Delaware Water Gap when flows are at the 30-percent flow duration. The trailing edge (location of the dye cloud when concentrations would decrease to 10 percent of the peak concentration) would take about 50 hours after the arrival of the leading edge.

INTRODUCTION

Resource managers and health agencies need traveltime information on rivers at various flows to respond effectively in the event of a toxic spill into the river. Traveltime information also is valuable in the calibration of the hydrodynamics for toxic spill and water-quality models.

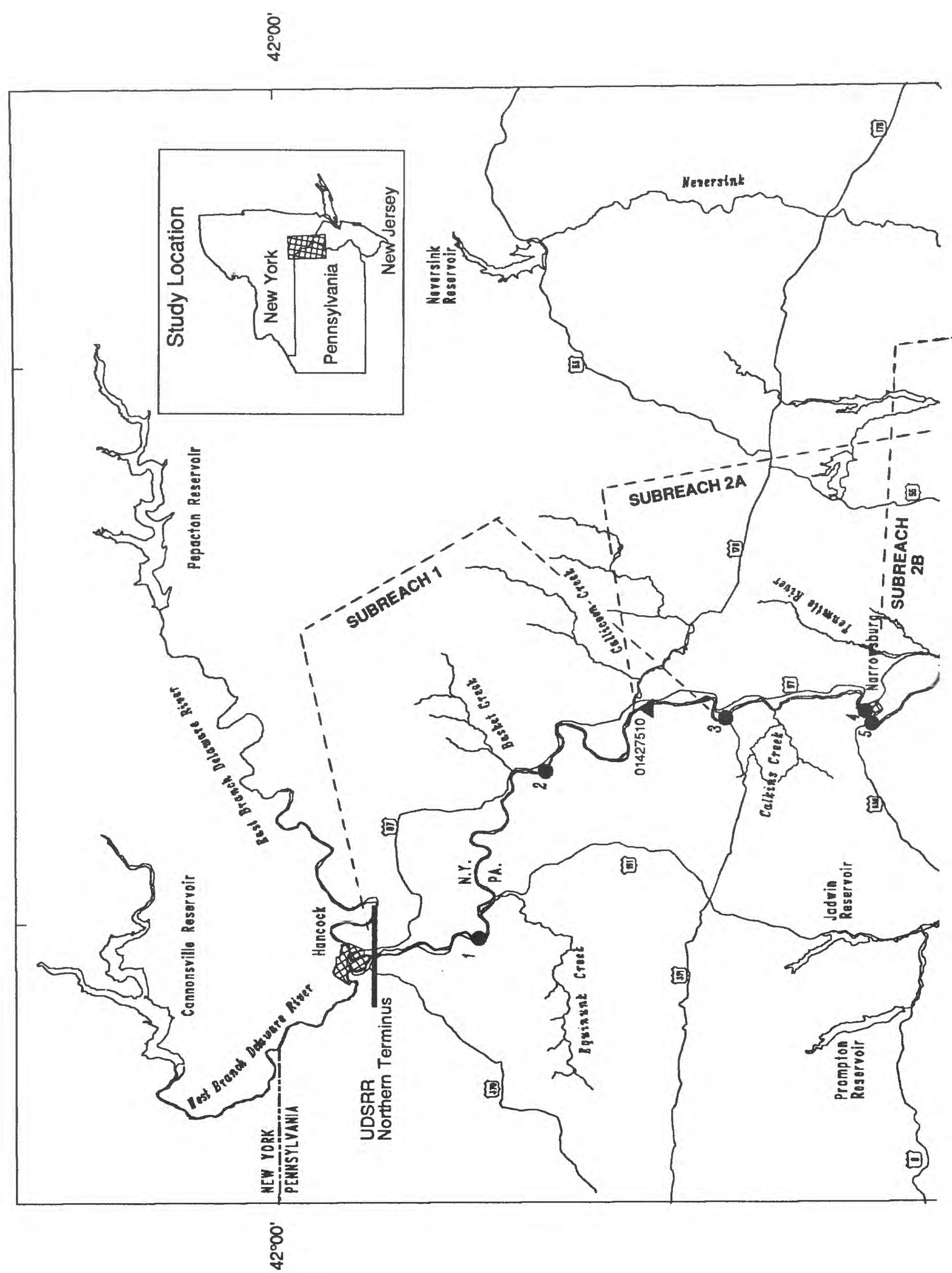
In 1990, the Delaware River Basin Commission (DRBC) proposed a study to determine the traveltime characteristics of a 120-mi reach of the upper Delaware River (fig. 1) from Hancock, N.Y., to the Delaware Water Gap. The study was done as a cooperative effort by the U.S. Geological Survey (USGS) and the DRBC; substantial support was provided by the National Park Service and the Upper Delaware Council.

Purpose and Scope

This report describes the movement of a conservative soluble substance in the upper Delaware River and presents methods of estimating traveltimes in the event of a spill or discharge of a soluble contaminant at various locations in the study reach.

On May 1, 1991, rhodamine WT, 20-percent dye was injected into the Delaware River near river mile 295. The resulting dye cloud was sampled 5 mi downstream at Narrowsburg, N.Y. A dye study was conducted May 6-9 at a medium-flow regime (3,070 to 7,500 ft^3/s) on a 120-mi reach of the Delaware River between Hancock, N.Y., and the Delaware Water Gap. Dye studies were conducted at low-flow regimes (500 to 1,740 ft^3/s) August 5-7 and August 12-15 on the reaches from the mouth of the Lackawaxen River to the Delaware Water Gap and from Hancock, N.Y., to Barryville, N.Y., respectively. On August 7-8 and 14-15, dye was injected into the Delaware River at three locations. The resulting dye clouds were sampled while surge waves, created by reservoir releases, passed through them.

[1] K.E. White, Hydrologist, U.S. Geological Survey.
[2] T.W. Kratzer, Water Resources Engineer, Delaware River Basin Commission.



42°00'
74°45'
75°15'
42°00'
Study Location
New York
Pennsylvania
New Jersey
Neversink
Neversink Reservoir
Pepacton Reservoir
Cannonsville Reservoir
East Branch Delaware River
West Branch Delaware River
Hancock
UDSRR Northern Terminus
NEW YORK
PENNSYLVANIA
SUBREACH 1
SUBREACH 2A
SUBREACH 2B
N.Y.
PA.
Basket Creek
Equinunk Creek
Callicoon Creek
Calkins Creek
Tenmile River
Narrowsburg
01427510
1
2
3
4
5
Jadwin Reservoir
Prompton Reservoir

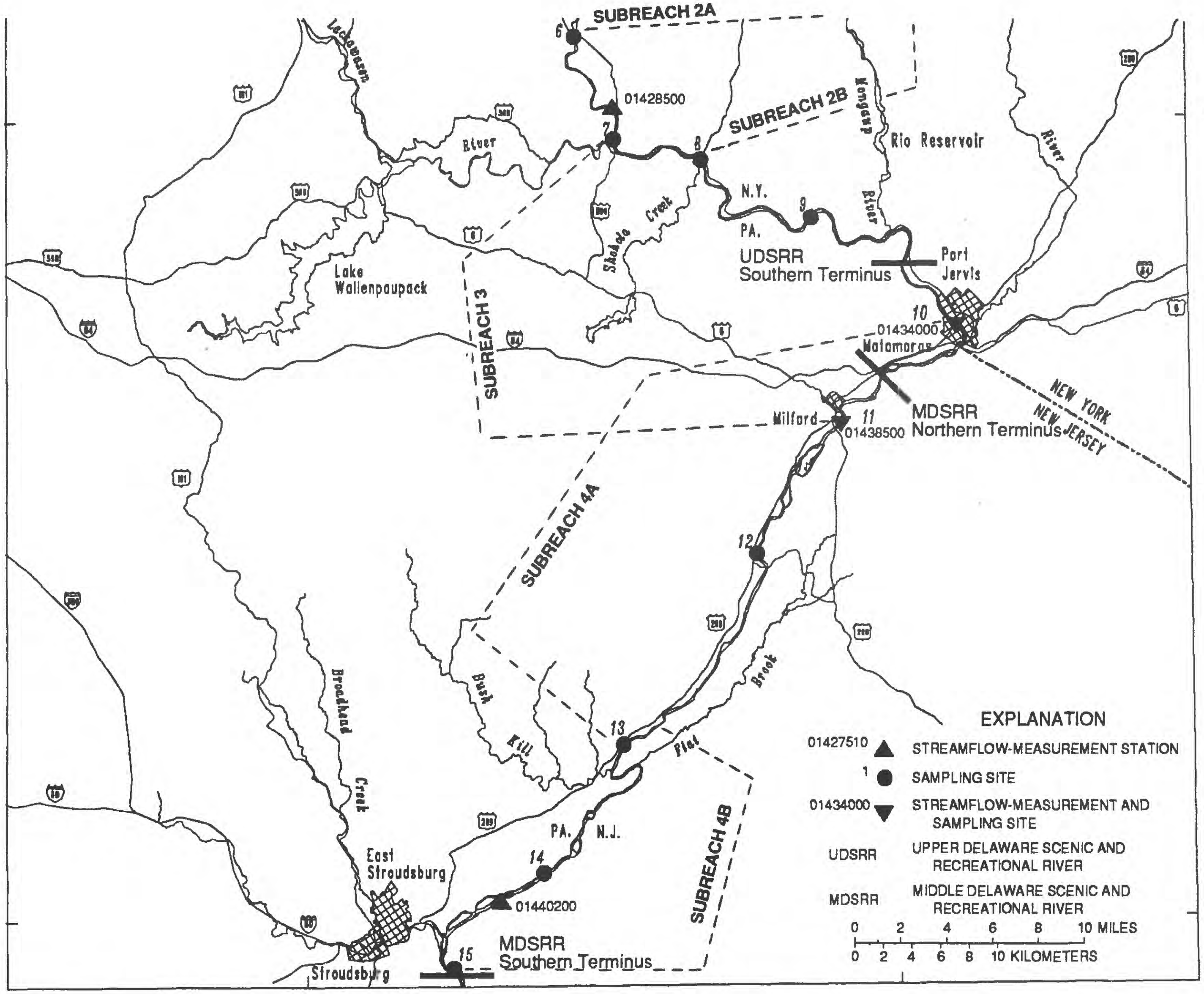


Figure 1. Location of injection sites, sampling sites, and streamflow-measurement stations on the Delaware River, Hancock, N.Y., to the Delaware Water Gap.

Acknowledgments

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The following is a list of individuals who provided assistance with this study:

National Park Service, Delaware Water Gap National Recreational Area

Ramona Abraham	Deborah Drelich	Karl Klein	Victor Perez
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National Park Service, Upper Delaware Scenic And Recreational River

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William Douglass	Janice Fischer	Kathy Johnson	David Soote

Delaware River Basin Commission

Richard Albert	Warren Huff	Christian Mainelli	Darryl Rulon
Robert Everest	Robert Limbeck	Donald Miller	Ronald Rulon
Cynthia Faunce	Bruce Laughlin	Christopher Roberts	Paul Scally
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Charles Kanetsky	Margaret Passmore

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David Spots	Leroy Young

City of New York

Raphael Hurowitz	Stephen Shindler

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Monroe County Planning Commission

Sebastian Degregorio	Lisa Surma

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Description of Study Reach

The study reach (fig. 1) is approximately 120 mi long and extends from just downstream of the confluence of the East Branch Delaware River and the West Branch Delaware River at Hancock, N.Y., to the Delaware Water Gap. The study reach includes the Upper and Middle Delaware Rivers. In this reach, the river flows southeast until reaching Port Jervis where it changes direction and flows southwest to the Delaware Water Gap. The largest tributaries to the Delaware River in this section are the Lackawaxen River, which has a drainage area of 597 mi^2; the Neversink River, which has a drainage area of 349 mi^2; and Brodhead Creek, which has a drainage area of 287 mi^2.

The Delaware River in the study reach is a series of alternating pools and riffles with several major rapids. The average slope over the entire reach is approximately 5.5 ft/mi. Large eddies throughout the study reach affect traveltime. Depths in the study reach range from several feet at low flow to about 110 ft at Narrowsburg (river mile 290).

River mileage used in this report was determined by the DRBC (1988) and is the number of miles upstream from the Atlantic Ocean-Delaware Bay interface. Table 1 lists landmarks in the study reach and their river miles. All of these landmarks are on USGS 7 1/2-minute topographic maps, but not all are shown on figure 1.

A number of reservoirs regulate the flow of the river in the study reach. Cannonsville Reservoir is on the West Branch of the Delaware River; Pepacton Reservoir is on the East Branch of the Delaware River; and Neversink Reservoir is on the Neversink River, the latter entering the main stem of the Delaware River just below Port Jervis at river mile 254. These reservoirs are operated by New York City. Lake Wallenpaupack, operated by Pennsylvania Power and Light Company, is on Wilson Creek, a tributary to the Lackawaxen River. The Mongaup Reservoir system, consisting of three reservoirs operated by Orange and Rockland Power Company, is on the Mongaup River. During low-flow periods, reservoir releases often make up a majority of the river flow. All reservoir releases are coordinated with the Delaware River Master to insure that flow does not fall below criteria established by the U.S. Supreme Court or the DRBC.

Methods of Data Collection and Analysis

Measurements of traveltime of a dye tracer are used to define the movement of a solute in a river. Standard sampling procedures (Hubbard and others, 1982; Kilpatrick and Wilson, 1989) and fluorometric procedures (Wilson and others, 1984) are well documented. In general, the described standard procedures were followed during this study. One exception was the use of a specific gravity value of 1.10 for the dye, as determined by hydrometer, to calculate concentrations of the calibration standards.

Field and Laboratory Procedures

A preliminary dye study was conducted for a short, isolated reach of the river at Narrowsburg, N.Y., to determine the effect that a deep pool and associated eddy would have on traveltime. Concern that dye would not exit the Narrowsburg pool in measurable concentrations led to the division of subreach 2, which contains the pool, into subreach 2A and 2B.

During the May study, the threat of severe thunderstorms and tornadoes after injection prompted a split in subreach 4, the most downstream subreach, into subreach 4A and 4B and an additional dye injection. The additional dye injection was performed to expedite sampling at the downstream sites.

The 120-mi reach was divided into a total of 6 subreaches (1, 2A, 2B, 3, 4A, 4B) containing 15 stream segments for both the May and August 1991 study. A subreach is characterized by a dye injection site with three to four downstream sampling points. The 15 sampling sites that define the segments are shown on figure 1 and are numbered in ascending order in the downstream direction. Table 2 gives the sampling site name, river mileage, river segment length between sampling sites, and drainage areas. The Dingmans sampling locations for the medium- and low-flow studies were about 0.5 mi apart. Dingmans is shown as a single point on figure 1, but both locations are listed in table 2.

Table 1. River mileage for bridge crossings, U.S. Geological Survey streamflow-measurement stations, dye study locations, and selected tributaries on the Delaware River, Hancock, N.Y., to the Delaware Water Gap

Location	Dye sampling site no.	Delaware River mile[1]
East and West Branch Delaware River confluence		330.70
Subreach 1 and Cannonsville Reservoir surge-wave dye injections		330.50
Buckingham Access	1	325.14
Lordville Bridge		321.60
Kellam's Bridge	2	312.59
Callicoon Bridge		303.70
Callicoon Creek confluence		303.62
Subreach 2A dye injection		303.61
USGS streamflow-measurement station at Callicoon, N.Y.		303.20
Cochecton Bridge	3	298.40
Skinners Falls Bridge		295.40
Just downstream from Skinners Falls Bridge (Narrowsburg Pool dye injection)		295.33
Narrowsburg (N.Y. Access)	4	290.34
Narrowsburg Bridge (US Rt. 106)		289.90
Narrowsburg (Pa. Access) Subreach 2B dye injection	5	289.43
Erie Railroad Bridge		285.20
Tenmile River confluence		284.27
Just downstream from Tenmile River confluence	6	284.15
USGS streamflow measurement station upstream from Lackawaxen River confluence		279.70
Just upstream from Lackawaxen River confluence	7	277.81
Lackawaxen River confluence		277.65
Subreach 3 dye injection		277.49
Lackawaxen Bridge		277.40
Lake Wallenpaupack surge-wave dye injection		275.50
Barryville Bridge	8	273.50
Pond Eddy Bridge	9	265.50
Mongaup River confluence		261.10
Erie Railroad Bridge		258.40
Rio Reservoir surge-wave dye injection		257.05
Port Jervis Bridge (US Rt. 209)	10	254.75
Subreach 4A dye injection and USGS streamflow-measurement station at Port Jervis, N.Y.		254.73
US Route 84 Bridge		253.65
Neversink River confluence		253.64
Milford Beach and USGS streamflow-measurement station at Montague, N.J.	11	246.31
Milford Bridge (US Rt. 206)		246.00
Just upstream from Dingmans Creek confluence (medium-flow sampling location)	12A	239.24
Dingmans Creek confluence		239.20
Just upstream from Dingmans Ferry Toll Bridge (low-flow sampling location)	12B	238.73
Dingmans Ferry Toll Bridge		238.70
Eshback Access (Subreach 4B dye injection)		231.97
Bushkill Access	13	228.11
Bushkill Creek confluence		226.90
Smithfield Beach	14	218.34
USGS streamflow-measurement station near Delaware Water Gap, Pa.		216.10
Brodhead Creek confluence		213.00
Delaware Water Gap Toll Bridge (US Rt. 80)		212.10
Kittatinny Access		211.50
Just downstream from Kittatinny Access	15	211.37

[1] River mile zero is located at the mouth of the Delaware Bay.

Table 2. River mileage, river segment length, and drainage areas for sampling sites on the Delaware River, Hancock, N.Y., to the Delaware Water Gap

[mi^2, square mile]

Location	Site no.	River mile	Segment length (miles)	Drainage area (mi^2)
Upstream study boundary	Injection	330.50	0.00	1,506
Buckingham Access	1	325.14	5.36	1,524
Kellam's Bridge	2	312.59	12.55	1,667
Cochecton Bridge	3	298.40	14.19	1,834
Narrowsburg (N.Y. access)	4	290.34	8.06	1,909
Narrowsburg (Pa. access)	5	289.43	.91	1,911
Just downstream from Tenmile River confluence	6	284.15	5.28	1,975
Just upstream from Lackawaxen River confluence	7	277.81	6.34	2,029
Barryville Bridge	8	273.50	4.31	2,659
Pond Eddy Bridge	9	265.50	8.00	2,820
Port Jervis Bridge (US Rt. 209)	10	254.75	10.75	3,070
Milford Beach	11	246.31	8.44	3,480
Dingmans				
Medium-flow sampling location	12A	239.24	7.07	3,520
Low-flow sampling location	12B	238.73	7.58	3,540
Bushkill Access	13	228.11		3,615
Medium-flow			11.13	
Low-flow			10.62	
Smithfield Beach	14	218.34	9.77	3,850
Just downstream from Kittatinny Access	15	211.37	6.97	4,167

At each injection site, rhodamine WT, 20-percent dye was injected at a continuous rate from a boat as it traversed the river. Each injection was well upstream from the computed distance required for 95-percent mixing at the first sampling site in each subreach (Kilpatrick and Wilson, 1989). Dye injection crews and equipment were segregated from sampling crews to avoid sample contamination.

The first two sampling sites downstream from each injection site were sampled at three transect points (left, right, and mid-channel), to determine if complete mixing had occurred. All stream samples were analyzed in the field by use of a fluorometer to determine the arrival of the dye cloud and the position on the time-concentration curve, and to adjust the sampling frequency.

Immediately following the low-flow studies that took place in August, three short reaches were sampled during typical releases from Cannonsville Reservoir, Lake Wallenpaupack, and the Mongaup System reservoirs. Data were collected from two sampling sites per release as the surge wave passed through the dye cloud. The surge-wave data were compared to the data collected from those same sampling sites during the preceding low-flow study to observe the relative effect of a flood wave on traveltime and dispersion.

All samples collected during the study were analyzed in the laboratory on the same fluorometer. Sample temperatures, determined during analysis, varied over a range of several degrees. The fluorometer was calibrated with standard solutions prepared from the same dye lot used in the study. The fluorescence values of all samples were adjusted by use of a temperature-correction curve to compensate for the effect of temperature on fluorescence.

Data Analysis

Following laboratory analysis of all dye samples, concentrations and traveltimes were entered into computer files for data analysis. Time-concentration curves[3] were analyzed for continuity, area under the curve, and centroids. Continuity includes the curve "smoothness" and the completeness of the leading and trailing edges of each time-concentration curve. During the medium-flow study, dye clouds overlapped and were separated by use of regression and extrapolation techniques.

Dye-cloud data periodically showed irregularities in the time-concentration curve profile caused mainly by channel nonuniformity. Other causes may include instrument and human error. These curves were smoothed for area and centroid analysis by visually inspecting the curve for the best-fit upward or downward tendency and adjusting the data accordingly. Figure 2 illustrates this method on a curve created from a hypothetical data set.

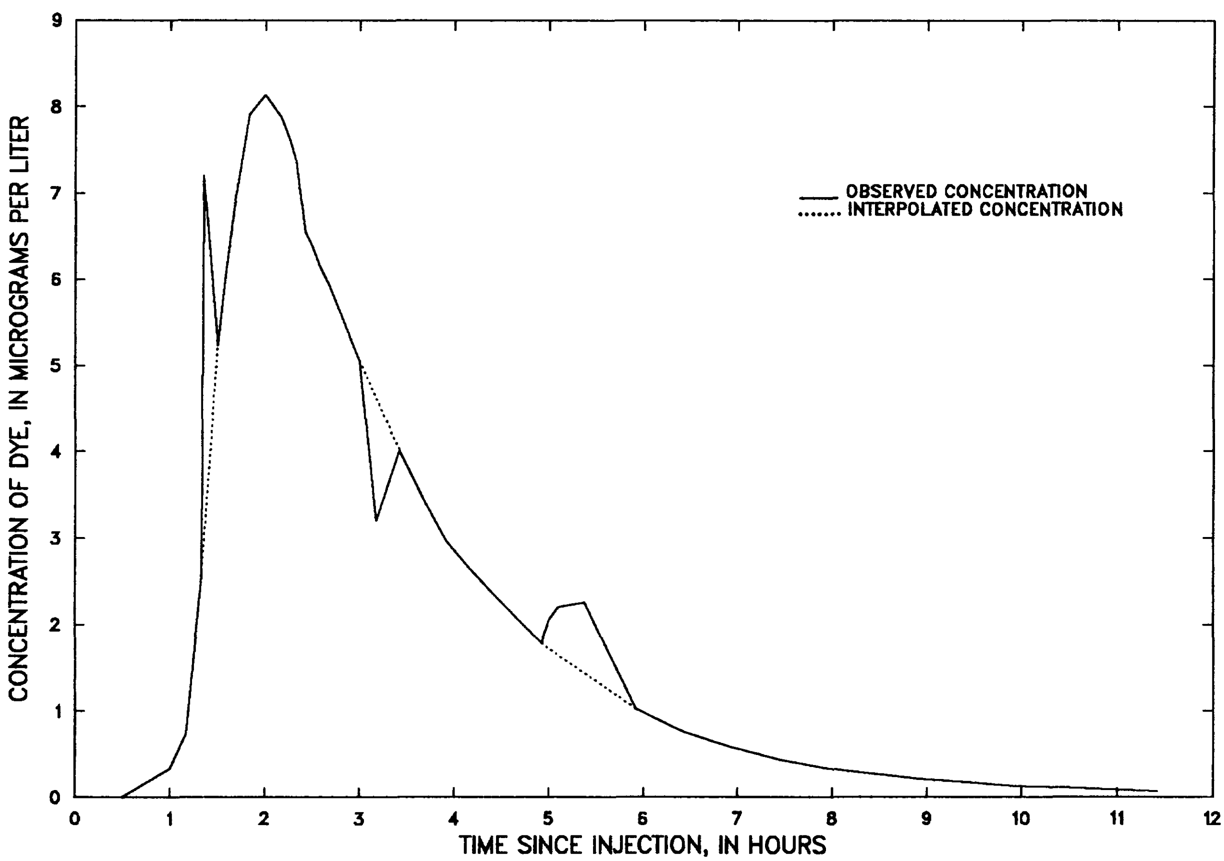


Figure 2. Smoothing of time-concentration curve irregularities for a hypothetical data set.

[3] Time-concentration curve is used in place of "dye-cloud" when referring to a longitudinal profile of the three dimensional dye-cloud mass.

When time-concentration data were incomplete for the trailing or leading edge, extrapolation or interpolation was used to construct these curve components. A least-squares statistical estimate was performed on the last three to five data points to determine coefficients for the regression equation

$$Y = mX + b, \qquad (1)$$

where Y is concentration,
m is slope of the regression line,
X is time since injection, and
b is Y-intercept of the regression line.

In equation 1,

$$m = \frac{\Sigma_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\Sigma_{i=1}^{n}(x_i - \bar{x})^2}, \qquad (2)$$

where x_i is individual X values,
y_i is individual Y values,
$\bar{x}$ is average of X values, and
$\bar{y}$ is average of Y values.

The Y-intercept (b) is determined with the following equation:

$$b = \bar{y} - m\bar{x} \qquad (3)$$

If data were missing at the leading or trailing edges of the time-concentration curve and no curvilinear trend was evident, the existing data were linearly extrapolated to no lower than 0.2 μg/L and exponentially extrapolated to 0.01 μg/L for the leading edge and to 1 percent of the peak concentration for the trailing edge. If a curvilinear trend was evident, exponential extrapolation was used to construct the leading edge or trailing edge of the curve. Figures 3 and 4 illustrate the methods of extrapolation and interpolation, respectively, on curves created from hypothetical data sets. When data voids existed prior to the extreme points of the time-concentration curve, exponential interpolation was used to construct that part of the curve (fig. 4). Exponential extrapolation and interpolation methods use logarithmic values for x_i and y_i in equation 2.

Area under each time-concentration curve was computed to determine the approximate location of "complete mix" and to determine longitudinal dye losses. Complete mix is defined as a homogenous concentration existing both vertically and laterally within a channel cross section and is represented as cross-sectional concentrations not exceeding ±10 percent of the cross-sectional average. Dye losses occur from dye adsorption onto channel substrates including sediment, aquatic plants, and debris and from retainment in eddy zones. Many of these losses are temporary as dye is slowly resupplied to the water column. Nonuniform mixing of dye across a transect presents conditions that seem to indicate a loss or gain of dye mass when these data are compared to the data collected at the next upstream site. However, no change in dye mass has actually occurred. Tables 3, 4, and 5 present the time-concentration curve peak concentrations, areas, and centroids for the medium-flow, low-flow, and surge-wave studies, respectively.

Although dye was injected laterally across the river, nonuniform flow velocities across the transect moved the dye downstream at different rates. This created a line of dye in the river channel that was spreading longitudinally (upstream and downstream) as well as laterally (side to side). Lateral spread continued from 15 to more than 18 mi downstream of the injection site during the medium-flow study and

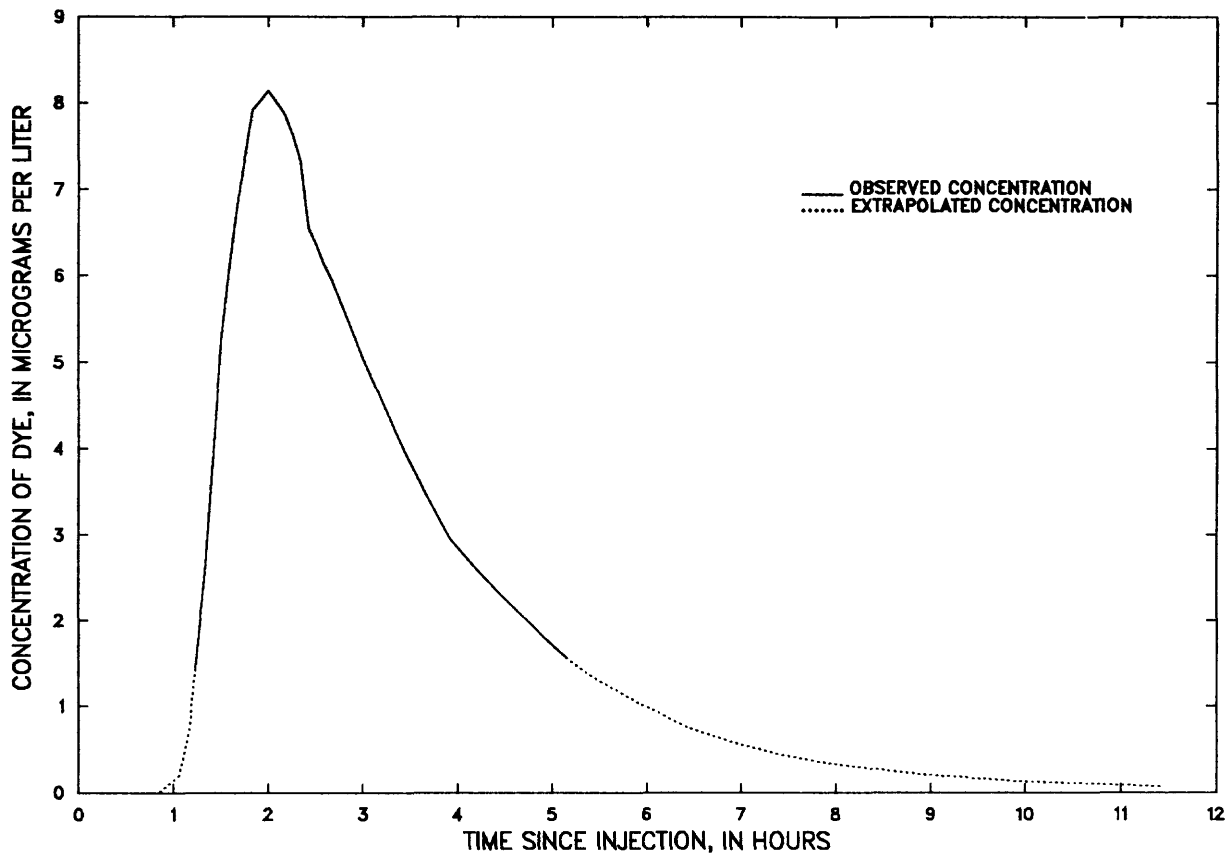


Figure 3. Extrapolation of data at the leading and trailing edges of the time-concentration curve for a hypothetical data set.

from 6 to more than 14 mi downstream for the low-flow study. Prior studies (Fischer and others, 1979) have shown that vertical mixing occurs nearly instantly in relatively shallow waterways such as the Delaware River. The Narrowsburg pool, where depths exceed 100 ft, is one possible exception.

The centroid (or center of gravity) of each dye cloud was computed and used as another indicator of complete mix in transects with more than one sampling site. Centroid data are presented in tables 3, 4, and 5 for the medium-flow, low-flow, and surge-wave studies, respectively. Time-averaged concentrations (vertical centroid coordinates) were compared across those transects with more than one sampling site. Time-averaged concentrations approaching unity throughout a cross-section indicate a more even spread approaching complete mix.

During the medium-flow study in May, the injection at Eshback Access, for subreach 4B, was added to provide a supplemental, faster moving dye cloud from the injection site to Kittatinny Access (site 15). Preliminary dye-cloud velocity estimates showed that sampling crews at the Kittatinny Access would be able to cease sampling approximately 10 hours sooner than originally scheduled for the Port Jervis injection. Unfortunately, data collected at the first site downstream (Bushkill Access, site 13) of the Eshback Access injection showed that the Port Jervis injection-site dye cloud was farther downstream than anticipated, and dye-cloud overlapping had begun. The overlapping continued as the clouds moved downstream. Data collected at the most downstream site (Kittatinny Access) showed that the two clouds had merged into a single cloud.

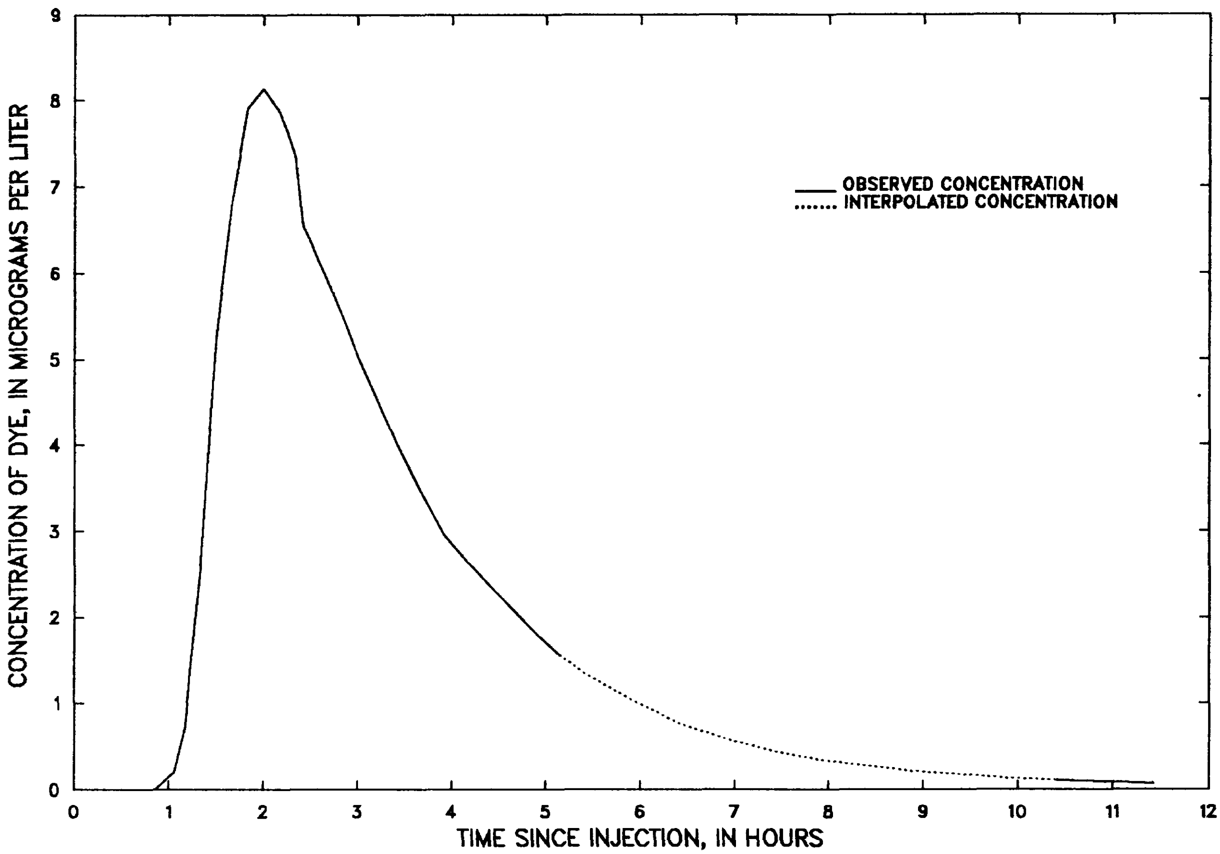


Figure 4. Interpolation of data at the trailing edge of the time-concentration curve for a hypothetical data set.

Data for each time-concentration curve were separated by use of an extrapolation technique that utilized the linearity of dye-cloud spread between the upstream sites and extrapolated the linear spread to the downstream sites. Linearity of dye-cloud spread within this reach of the Delaware River was supported by both the medium-flow and low-flow studies.

Time-concentration curves of the three upstream sites, Milford Beach (site 11), just upstream from Dingmans Creek (site 12A), and Bushkill Access (site 13), were separated into percentages of the peak concentrations in combination with the associated traveltimes. Concentration increments of 10 percent (such as 10, 20, and 30 percent) of the peak concentration were determined for the leading and trailing edge of each time-concentration curve and matched to the respective traveltime. These traveltimes were regressed (equations 1-3) against river miles. Peak concentrations were regressed (equations 1-3) with the reciprocal of the square root of the travel times ($1/\sqrt{T_p}$). This method was illustrated by Thomann and Mueller (1987). The resultant regression equations were then used to extrapolate the traveltimes and associated concentrations to the downstream sites. All of the regression analyses showed correlation coefficients greater than 0.97; most were greater than 0.99. A correlation coefficient of 1 or -1 signifies a perfect relation between the compared variables.

The extrapolated time-concentration curve area was subtracted from the observed area to define the remaining (extracted) area. The remaining area and its characteristics represented the dye cloud from the Eshback Access injection. Figure 5 shows the overlap and separations of the Kittatinny Access time-concentration curves.

Table 3. Time-concentration curve peak concentrations, areas, and centroids for the May medium-flow study on the Delaware River, Hancock, N.Y., to the Delaware Water Gap

[µg/L, microgram per liter; hr, hour]

						Time-concentration-curve centroid		
Site number	Transect location	Peak concentration (µg/L)	Average peak concentration (µg/L)	Area under time-concentration curve (µg/L) × hr	Average time-concentration area (µg/L) × hr	Time since injection (hr)	Time-averaged concentration (µg/L)	Average concentration (µg/L)
Subreach 1 - Injected 10.31 liters of rhodamine WT, 20-percent dye at 1000 on May 8, 1991, at river mile 330.50								
1	Left	10.10		9.31		4.05	2.57	
	Middle[1]	14.18		9.23		3.65	4.25	
	Right	11.05	11.78	9.94	9.49	3.99	3.36	3.39
2	Left	3.19		8.23		13.18	1.03	
	Middle[1]	3.17		8.38		13.36	1.03	
	Right	2.52	2.96	8.26	8.29	13.94	.86	.97
3	Middle	1.73		7.51		22.77	.60	
Subreach 2A - Injected 33.24 liters of rhodamine WT, 20-percent dye at 0800 on May 8, 1991, at river mile 303.61								
3	Left	29.11		24.83		3.77	7.80	
	Middle[1]	38.19		21.89		3.41	10.60	
	Right	27.44	31.58	17.43	21.38	3.52	7.45	8.62
4	Left	10.74		25.08		8.70	3.57	
	Middle[1]	13.04		24.20		8.24	4.04	
	Right	12.83	12.20	21.73	23.67	8.31	3.75	3.79
5	Middle	5.73		22.35		11.18	1.70	
6	Middle	5.11		25.34		14.73	1.54	
Subreach 2B - Injected 8.00 liters of rhodamine WT, 20-percent dye at 0500 on May 8, 1991, at river mile 289.43								
6	Left	2.14		4.24		5.50	.56	
	Middle[1]	7.51		5.05		3.59	1.72	
	Right	4.01	4.55	2.83	4.04	3.47	.98	1.09
7	Middle	3.54		4.51		7.54	.94	
8	Middle	1.93		3.53		10.40	.59	
Subreach 3 - Injected 30.93 liters of rhodamine WT, 20-percent dye at 0910 on May 6, 1991, at river mile 277.49								
8	Left	14.81		13.11		3.20	4.30	
	Middle[1]	30.99		14.78		2.87	8.44	
	Right	21.70	22.50	18.97	15.62	3.23	5.85	6.20
9	Left	5.00		14.64		9.45	1.65	
	Middle	6.64		15.05		8.85	2.08	
	Right[1]	6.74	6.13	14.66	14.78	8.89	2.14	1.96
10	Right	4.19		13.89		14.70	1.43	
11	Middle	2.48		11.06		20.40	.85	
Subreach 4A - Injected 51.55 liters of rhodamine WT, 20-percent dye at 0525 on May 6, 1991, at river mile 254.73								
11	Left[1]	18.05		22.14		5.37	5.43	
	Middle	17.60		21.83		5.36	5.33	
	Right	11.70	15.78	18.97	20.98	5.95	3.42	4.73
12	Left	7.43		21.73		12.78	2.17	
	Middle	7.77		22.41		12.14	2.56	
	Right[1]	8.31	7.84	22.71	22.28	12.17	2.49	2.41
13	Middle	4.20		19.89		20.07	1.37	
14	Middle	2.77		18.41		28.18	.89	
15	Middle	1.85		14.28		33.74	.60	
Subreach 4B - Injected 20.62 liters of rhodamine WT, 20-percent dye at 1800 on May 6, 1991, at river mile 231.97								
13	Middle	8.34		8.51		15.51	2.44	
14	Middle	2.20		6.36		23.06	.72	
15	Middle	1.34		5.81		28.98	.42	

[1] Site selected for traveltime analyses.

Table 4. Time-concentration curve peak concentrations, areas, and centroids for the August low-flow study on the Delaware River, Hancock, N.Y., to the Delaware Water Gap

[µg/L, microgram per liter; hr, hour]

Site number	Transect location	Peak concentration (µg/L)	Average peak concentration (µg/L)	Area under time-concentration curve (µg/L)*hr	Average time-concentration area (µg/L)*hr	Time-concentration-curve centroid: Time since injection (hr)	Time-concentration-curve centroid: Time-average concentration (µg/L)	Time-concentration-curve centroid: Average concentration (µg/L)
Subreach 1 - Injected 6.00 liters of rhodamine WT, 20-percent dye at 0900 on August 12, 1991, at river mile 330.50								
1	Left	7.77		20.45		9.24	2.36	
	Middle[1]	8.14		20.40		9.32	2.36	
	Right	7.73	7.88	26.61	22.49	10.31	2.28	2.33
2	Left	1.93		20.28		36.40	.65	
	Middle[1]	2.00		21.15		36.23	.66	
	Right	1.72	1.88	20.40	20.61	38.83	.56	.62
3	Middle	1.09		15.68		62.22	.41	
Subreach 2A - Injected 16.50 liters of rhodamine WT, 20-percent dye at 0655 on August 12, 1991, at river mile 303.61								
3	Left	13.00		50.23		11.04	3.88	
	Middle	15.10		51.15		10.08	4.69	
	Right[1]	15.10	14.40	58.24	53.21	10.43	4.61	4.39
4	Left	6.70		53.55		24.77	2.18	
	Middle[1]	7.38		53.64		22.93	2.42	
	Right	6.68	6.92	54.69	53.96	24.89	1.90	2.17
5	Middle	3.66		51.37		33.17	1.03	
6	Middle	2.90		51.66		43.20	.89	
Subreach 2B - Injected 5.50 liters of rhodamine WT, 20-percent dye at 0500 on August 12, 1991, at river mile 289.43								
6	Left	2.39		12.02		12.85	.60	
	Middle	4.69		11.77		8.63	1.26	
	Right[1]	5.65	4.24	17.13	13.64	9.17	1.44	1.10
7	Left	2.22		16.65		22.12	.70	
	Middle[1]	2.30		16.82		22.22	.72	
	Right	2.24	2.25	17.34	16.94	23.22	.72	.71
8	Middle	1.11		11.47		30.54	.42	
Subreach 3 - Injected 11.81 liters of rhodamine WT, 20-percent dye at 0900 on August 5, 1991, at river mile 277.49								
8	Left	4.94		22.50		7.74	1.65	
	Middle[1]	8.12		21.03		6.37	2.26	
	Right	6.47	6.51	14.46	19.33	6.04	1.94	1.95
9	Left	2.13		18.15		20.48	.69	
	Middle	2.13		15.94		19.04	.69	
	Right[1]	2.18	2.15	16.82	16.97	19.42	.70	.69
10	Right	1.52		15.05		30.78	.51	
11	Middle	1.06		14.89		43.53	.36	
Subreach 4A - Injected 10.31 liters of rhodamine WT, 20-percent dye at 0700 on August 5, 1991, at river mile 254.73								
11	Left	3.29		13.04		11.15	.95	
	Middle[1]	3.42		13.49		10.94	1.03	
	Right	2.99	3.23	15.31	13.95	12.24	.86	.95
12	Left	1.16		12.29		29.17	.37	
	Middle[1]	1.16		11.81		27.04	.40	
	Right	1.10	1.14	11.03	11.71	28.07	.36	.38
13	Middle	.82		11.43		45.01	.29	
Subreach 4B - Injected 10.31 liters of rhodamine WT, 20-percent dye at 0500 on August 5, 1991, at river mile 231.97								
13	Left	3.61		13.24		8.29	1.00	
	Middle[1]	4.69		15.62		7.30	1.30	
	Right	4.05	4.12	13.06	13.97	7.48	1.10	1.13
14	Left	1.00		13.00		29.45	.32	
	Middle[1]	1.13		13.32		26.46	.38	
	Right	1.17	1.10	13.52	13.28	26.13	.38	.36
15	Middle	.71		12.16		40.13	.24	

[1] Site selected for traveltime analyses.

Table 5. Time-concentration curve peak concentrations, areas, and centroids for the August surge-wave studies on the Delaware River

[µg/L, microgram per liter; hr, hour]

Site number	Transect location	Peak concentration (µg/L)	Average peak concentration (µg/L)	Area under time-concentration curve (µg/L)*hr	Average time-concentration area (µg/L)*hr	Time-concentration-curve centroid: Time since injection (hr)	Time-concentration-curve centroid: Time-averaged concentration (µg/L)	Time-concentration-curve centroid: Average concentration (µg/L)
Cannonsville Reservoir release -Injected 5.00 liters of rhodamine WT, 20-percent dye at 0500 on August 14, 1991, at river mile 330.50								
1	Left[1]	5.54		15.69		10.00	1.86	
	Middle	5.38		15.27		9.81	1.89	
	Right	5.49	5.47	15.46	15.47	10.02	1.93	1.89
2	Left	1.30		8.85		26.89	.43	
	Middle[1]	1.47		8.41		25.86	.48	
	Right	1.30	1.36	9.16	8.81	27.08	.44	.45
Lake Wallenpaupack release - Injected 5.00 liters of rhodamine WT, 20-percent dye at 0630 on August 8, 1991, at river mile 275.50								
8	Left	2.87		5.60		3.77	.93	
	Middle[1]	11.80		6.92		2.62	3.53	
	Right	5.54	6.74	7.73	6.75	3.66	1.29	1.92
9	Left	1.13		5.72		16.25	.29	
	Middle[1]	1.39		4.98		14.45	.35	
	Right	1.13	1.22	5.21	5.30	15.78	.29	.31
Rio Reservoir release - Injected 5.00 liters of rhodamine WT, 20-percent dye at 1030 on August 7, 1991, at river mile 257.05								
10	Left	2.30		6.32		4.87	.70	
	Middle[1]	8.48		4.53		2.57	2.36	
	Right	7.16	5.98	5.01	5.29	2.65	1.94	1.67
11	Left[1]	.79		4.46		13.27	.26	
	Middle	.74		4.75		13.31	.26	
	Right	.65	.73	4.64	4.62	14.40	.22	.25

[1] Site selected for traveltime analyses.

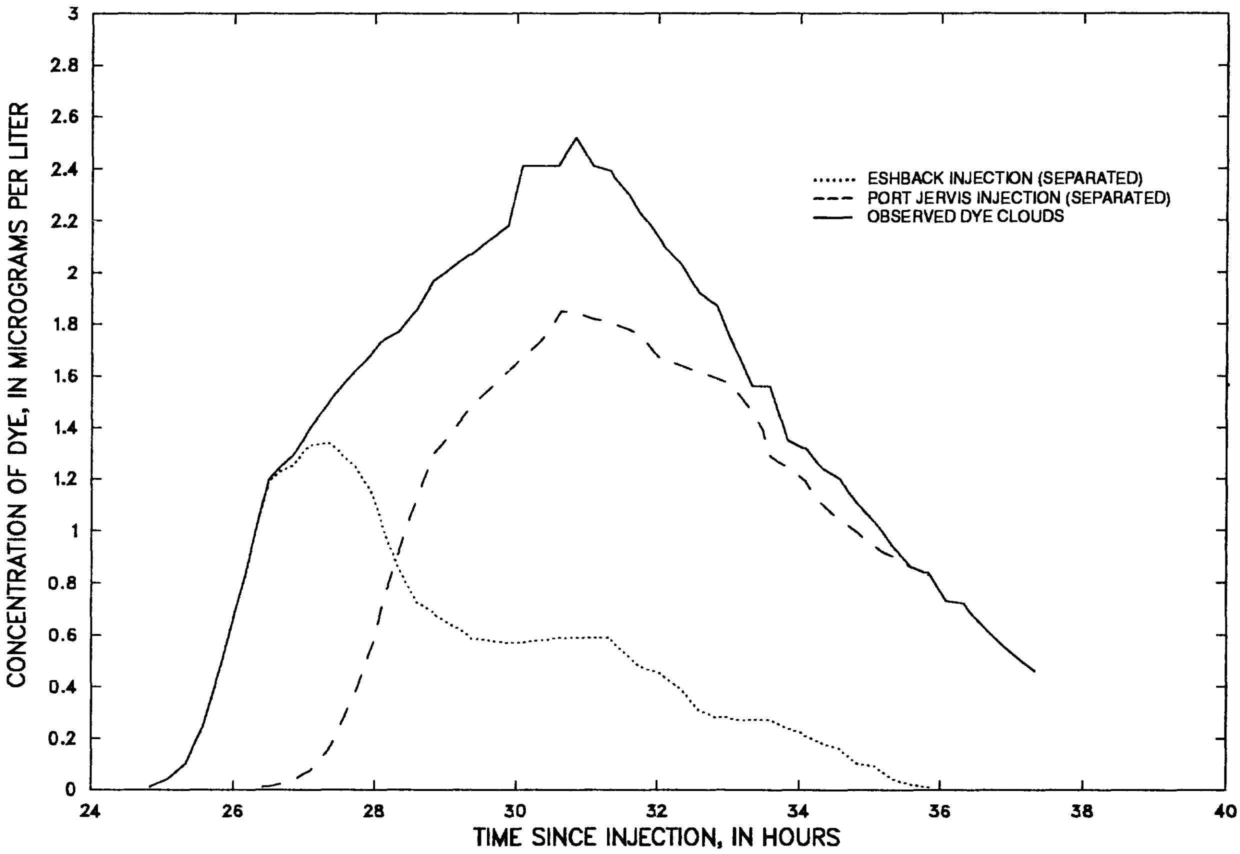


Figure 5. Separation of time-concentration curve for the Eshback Access and Port Jervis dye injection, May 6, 1991.

RIVER DISCHARGE

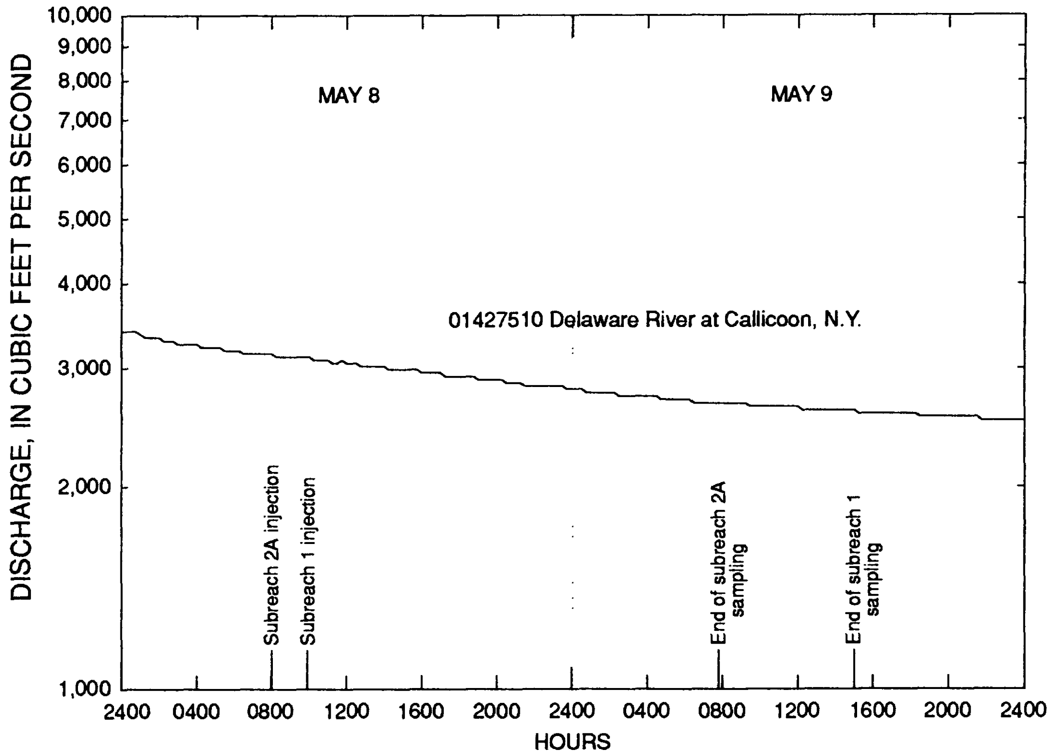
Knowledge of streamflow is essential when attempting to predict how a spill will move. Five continuous-record streamflow-measurement stations are operated within the study reach. These stations were used to monitor discharge during the study and are to be used as index stations when estimating the traveltime of a contaminant spill. Because the subreaches overlap, each subreach includes at least one index station where stage is recorded (and discharge can be calculated) at 15-minute intervals. The streamflow-measurement stations are operated by the USGS offices located in Albany, N.Y., and West Trenton, N.J., and are listed in table 1.

Discharges for each streamflow-gaging station for the medium-flow and low-flow studies are given in figures 6-10. Discharge generally was decreasing during the studies except during the medium-flow study when a rainstorm caused an increase in discharge in the lower part of the study reach. Most of the hydrographs of discharges during the low-flow studies show a sharp increase on August 7 or 15. This "jump" marks the arrival of the water from the reservoir releases at each streamflow-measurement station.

The hydrograph for the streamflow-gaging station Delaware River near Delaware Water Gap shows a constant discharge during most of the August 5-7 study. This occurred because of instrument malfunction at the station. Comparison of this hydrograph with that for the station at Montague, N.J., and consideration of the inflow between the two stations were used to confirm that the determined discharges during passage of the dye cloud are acceptable estimates.

Traveltime and discharge are inversely related. Traveltime must be related to a site-specific discharge in order to reliably estimate traveltimes at different river locations over a range of discharges. Tributary inflow may have a substantial effect on discharge. Because of the potential for large changes in discharge at different river locations, a method of relating flows throughout the study reach is necessary. Flow duration is a useful index for comparing streamflows at any point along a river. Searcy (1959) defines flow duration as "a cumulative frequency that shows the percentage of time that specified discharges are equalled or exceeded." Flow durations were computed for 1976-91. During the May 1991 medium-flow study, the average discharge was at about the 25-30-percent flow duration for all stations. The flow duration for the August low-flow study was at the 85-95-percent flow duration. Figure 11 shows the relation between flow duration and discharge for the five streamflow stations in the study reach.

Each of the index stations is equipped with phone access capability, which permits access to real-time discharge data for those responsible for responding to a contaminant spill.



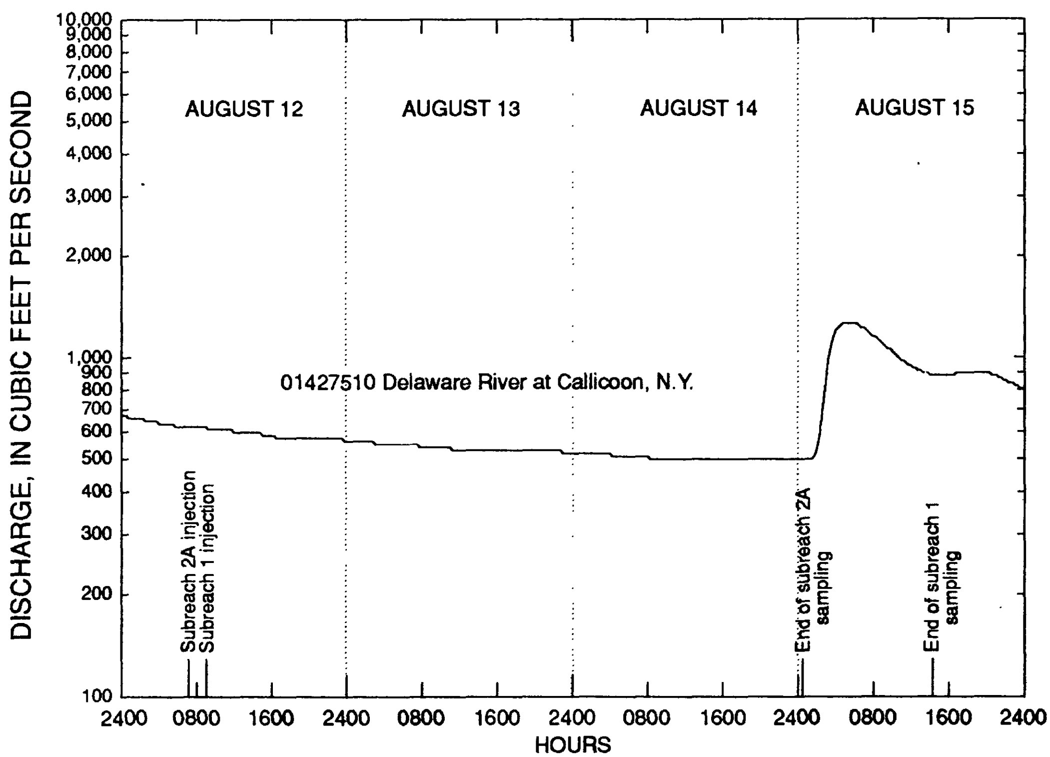


Figure 6. Discharge of Delaware River at Callicoon, N.Y., May 8-9 and August 12-15, 1991.

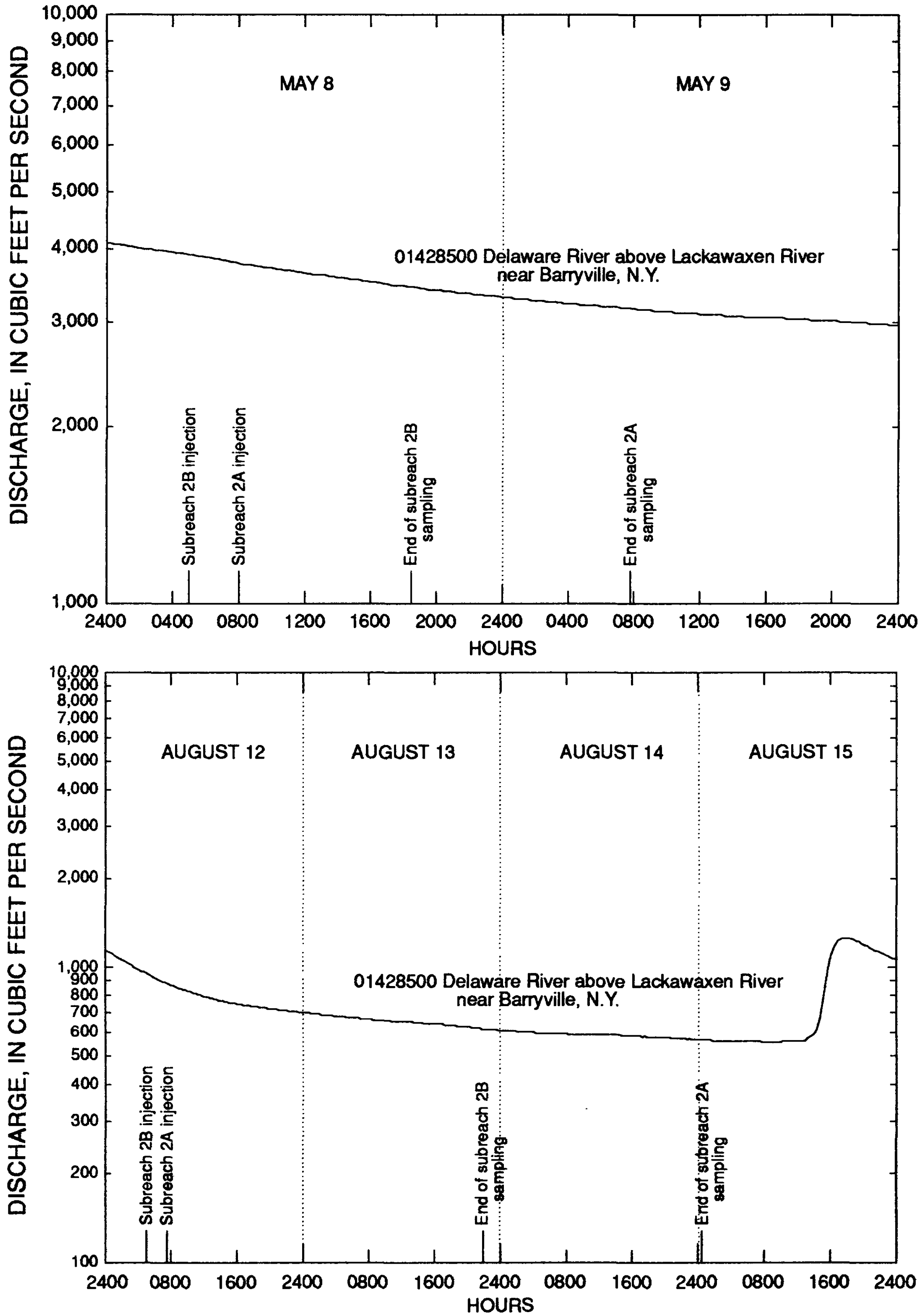


Figure 7. Discharge of Delaware River above Lackawaxen River near Barryville, N.Y., May 8-9 and August 12-15, 1991.

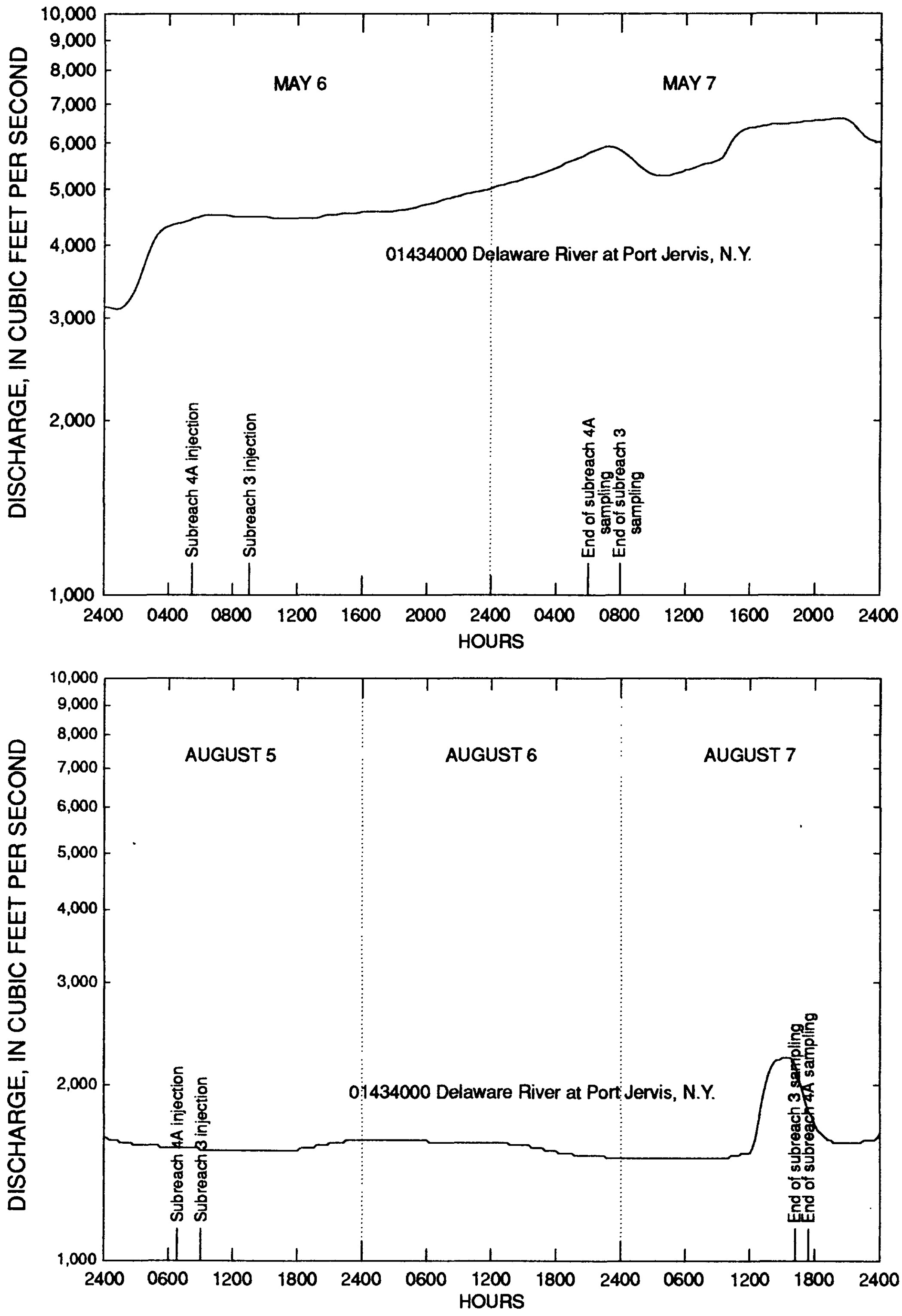


Figure 8. Discharge of Delaware River at Port Jervis, N.Y., May 6-7 and August 5-7, 1991.

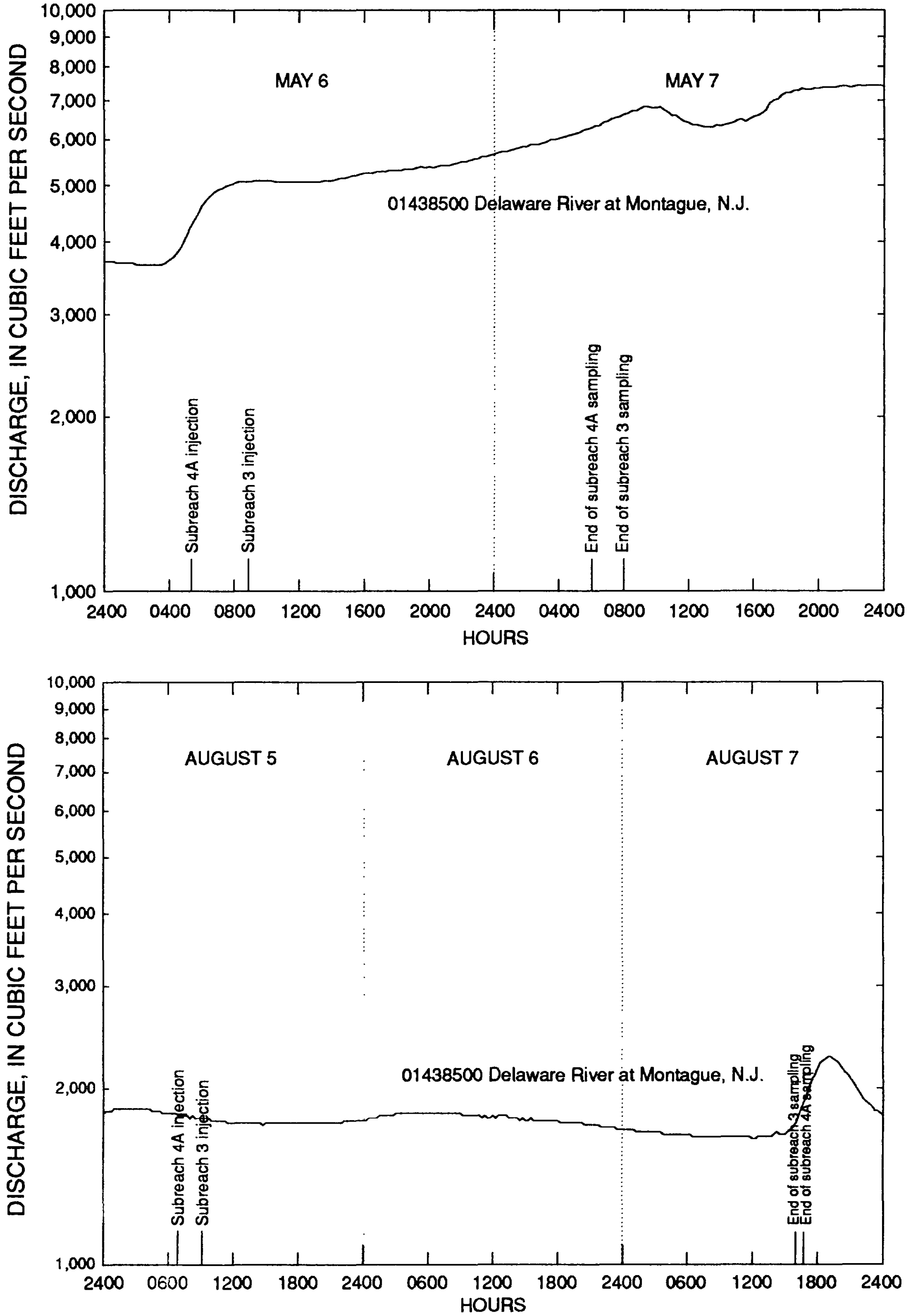


Figure 9. Discharge of Delaware River at Montague, N.J., May 6-7 and August 5-7, 1991.

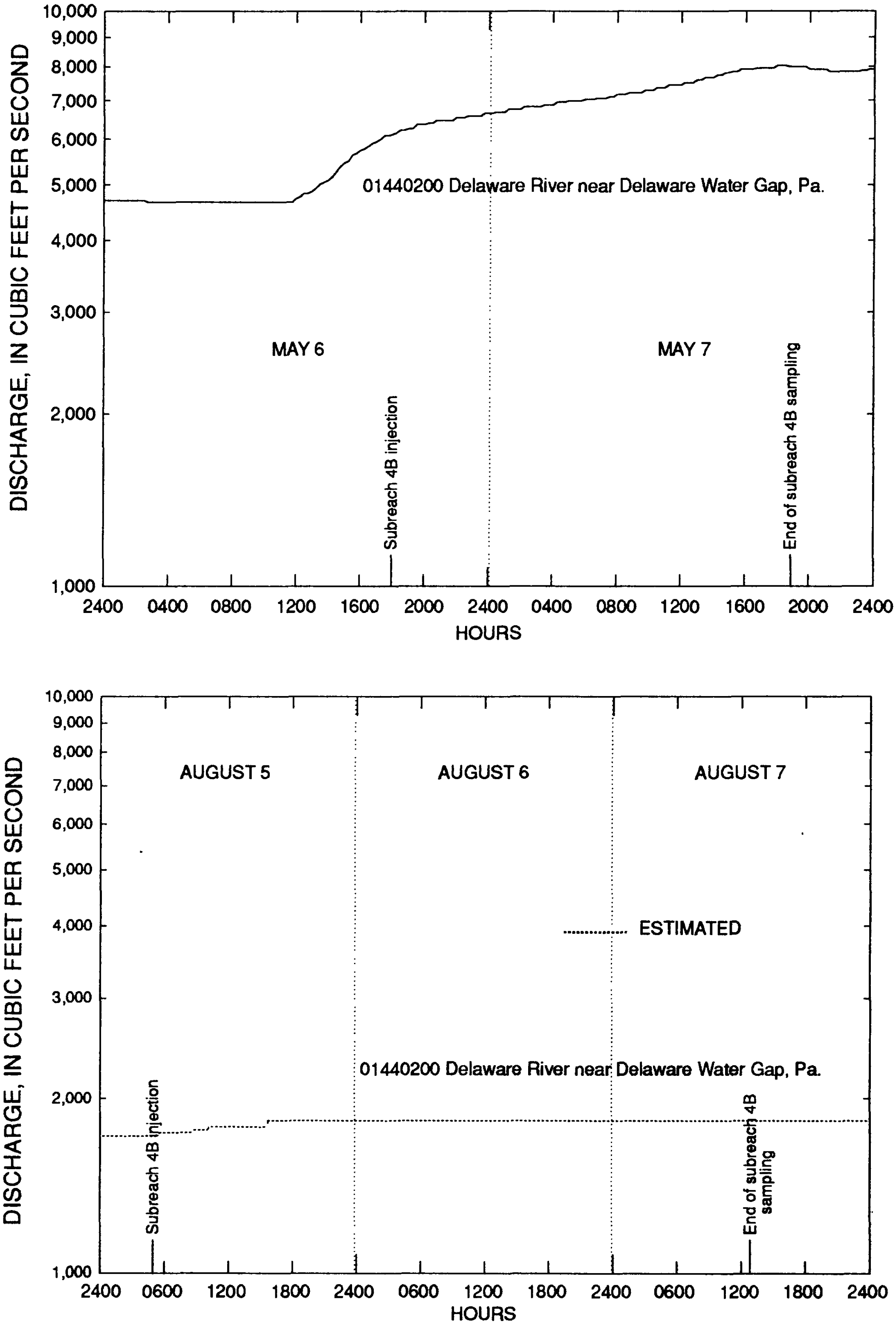


Figure 10. Discharge of Delaware River below Tocks Island Damsite, near Delaware Water Gap, Pa., May 6-7 and August 6-7, 1991.

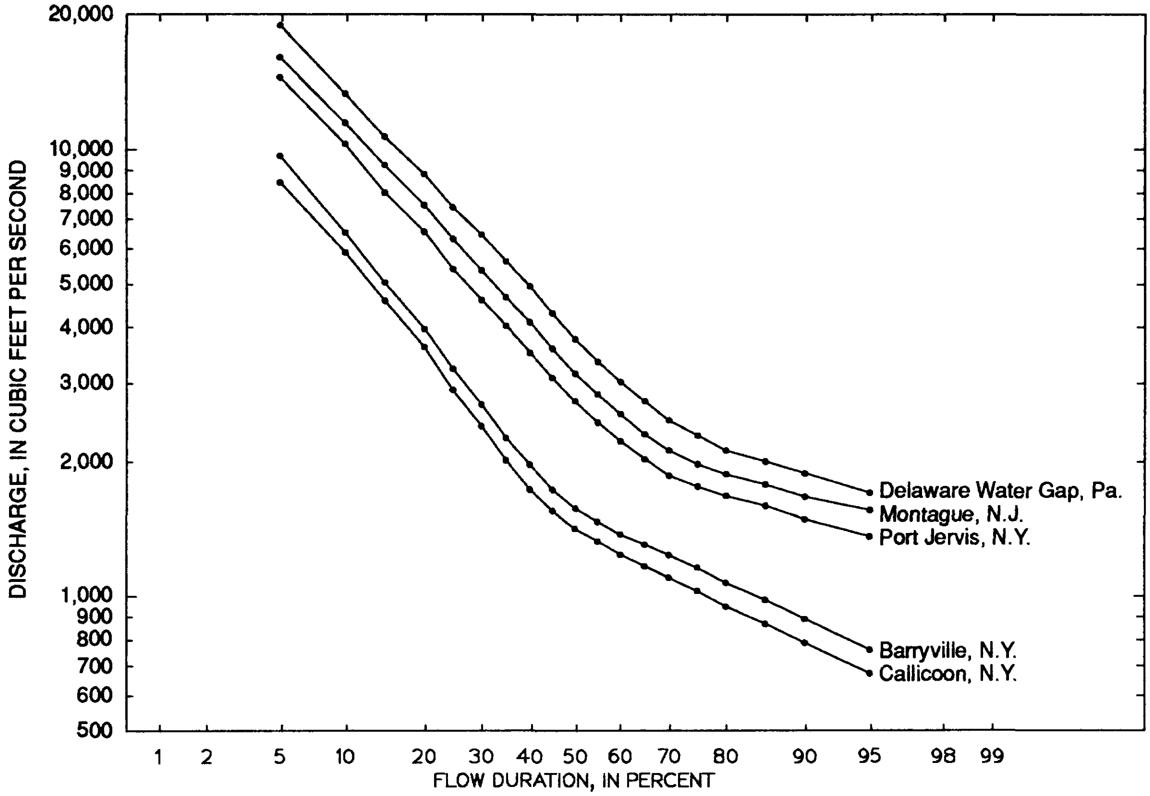


Figure 11. Relation between discharge and flow duration at index streamflow-measurement stations on the Delaware River.

TRAVELTIME

Measured

Curves of the dye concentrations as a function of time since dye injection were used to determine the traveltimes of the leading edge, peak concentration, and trailing edge of the dye cloud. The medium-flow and low-flow time-concentrations curves for each sampling site are shown in figures 12 and 13, respectively. The trailing edge is the point at which the dye concentration has decreased to 10 percent of the peak concentration at each sampling site. Figure 14 shows the accumulated traveltimes of each of the three dye cloud components for both the May and August dye studies. Tables 6 and 7 summarize the traveltimes for the two studies.

Irregularities in the time-concentration curves are attributed to the incomplete mixing of the dye. Some factors that affect mixing are eddy zones, curves, pools, riffles, bridge piers and flow regulation. The curves representing the Bushkill to Kittatinny subreach (subreach 4B) illustrate the overlap of the dye clouds resulting from the Port Jervis and Eshback injections.

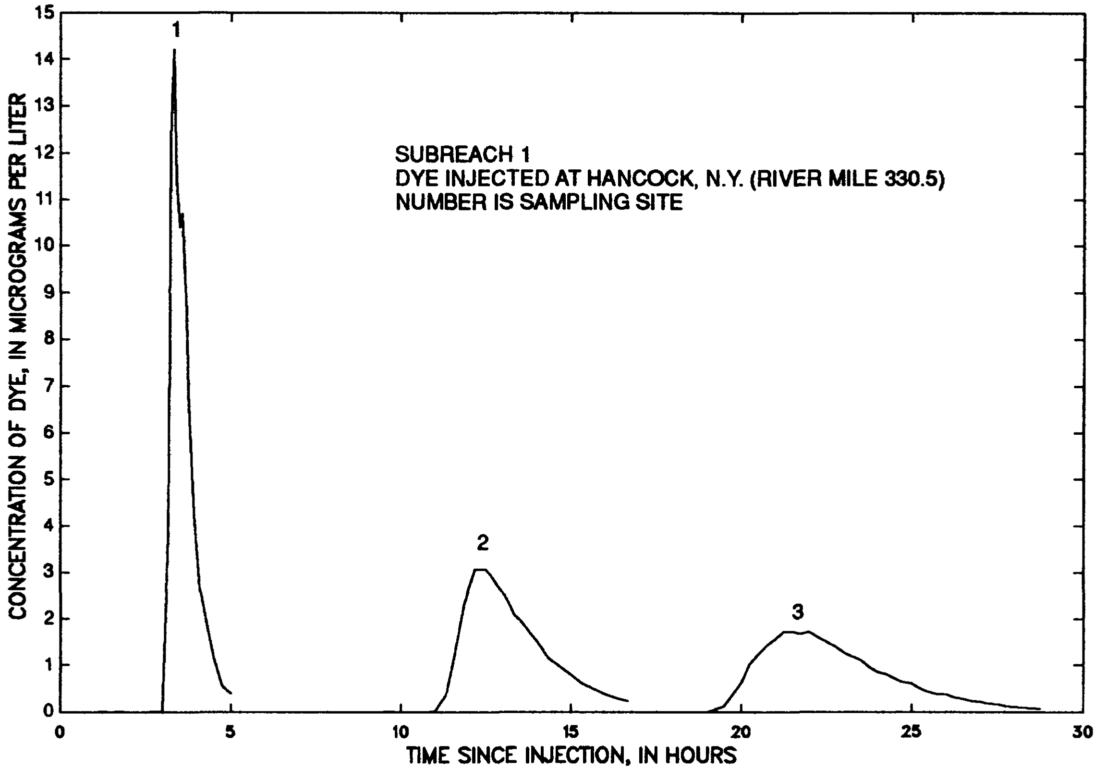
Dye-cloud velocities and stream discharge, determined under medium- and low-flow conditions, were used to estimate dye-cloud velocities for flow durations ranging from 30 to 95 percent. The relation between velocity and discharge is typically linear when plotted on logarithmic paper (Hubbard and others, 1982, p. 30). The velocities of the leading edge, peak concentration, and trailing edge of the dye cloud between successive sampling sites were calculated for both dye studies by dividing the segment length by the traveltimes. The representative discharge for each stream segment was calculated using the time-weighted average discharge measured at the nearest index station(s). The representative discharges were determined for the traveltime of the dye cloud between adjacent sites for each of the three dye-cloud components. Table 8 shows the velocities and representative discharges for each dye-cloud component during the August and May studies for the river reach between Cochecton, N.Y., and Narrowsburg, N.Y. For example, figure 15 shows the dye-cloud velocities as a function of the average discharges at the streamflow-measurement stations at Callicoon and above Lackawaxen near Barryville. Dye-cloud velocities at discharges corresponding to flow duration of 30, 40, 50, 60, 70, 75, 80, 85, 90, and 95 percent were determined assuming a linear relation and are shown in table 9 for the river reach between Cochecton, N.Y., and Narrowsburg, N.Y. In this manner, incremental velocities for each dye-cloud component were determined over the range of flow durations for all 15 stream segments. Where two index stations are included in a particular subreach, plots were made for both, and the results were averaged.

Adjusting the estimated discharge at Delaware River near Delaware Water Gap during the August 5-7 study by 5 percent resulted in changes in velocity of less than 3 percent over the range of flow durations. The estimated discharge for August 5-7 as shown in figure 10 was used in the velocity computations with little loss of accuracy.

Each segment length was divided by each of the 10 incremental velocities to determine the traveltime of the leading edge, peak concentration, and the trailing edge over the range of discharges. The resulting traveltimes were cumulated from Hancock, N.Y., to the Delaware Water Gap. The traveltimes for the entire study reach for the leading edge, peak concentration, and trailing edge are given in tables 10, 11, and 12, respectively, and in figures 16, 17, and 18, respectively. Use of these tables and figures provides the reader with a method of estimating the time for a soluble substance to travel between two points in the study reach over a range of flows.

The sampling point at Dingmans during the May study was 0.5 mi upstream from the August sampling location. The different segment lengths result in different cumulative traveltimes from the Dingmans site down to Kittatinny. Because the variation in traveltimes was within 1 percent, the average of the two traveltimes was used.

Duration is the time it takes for the entire dye cloud to move past a point in the river. Duration can be determined by subtracting the leading-edge traveltime from the trailing-edge traveltime. This calculation was done for the 10 flow durations for each stream segment. The results of these calculations are given in table 13 and are graphically presented in figure 19.



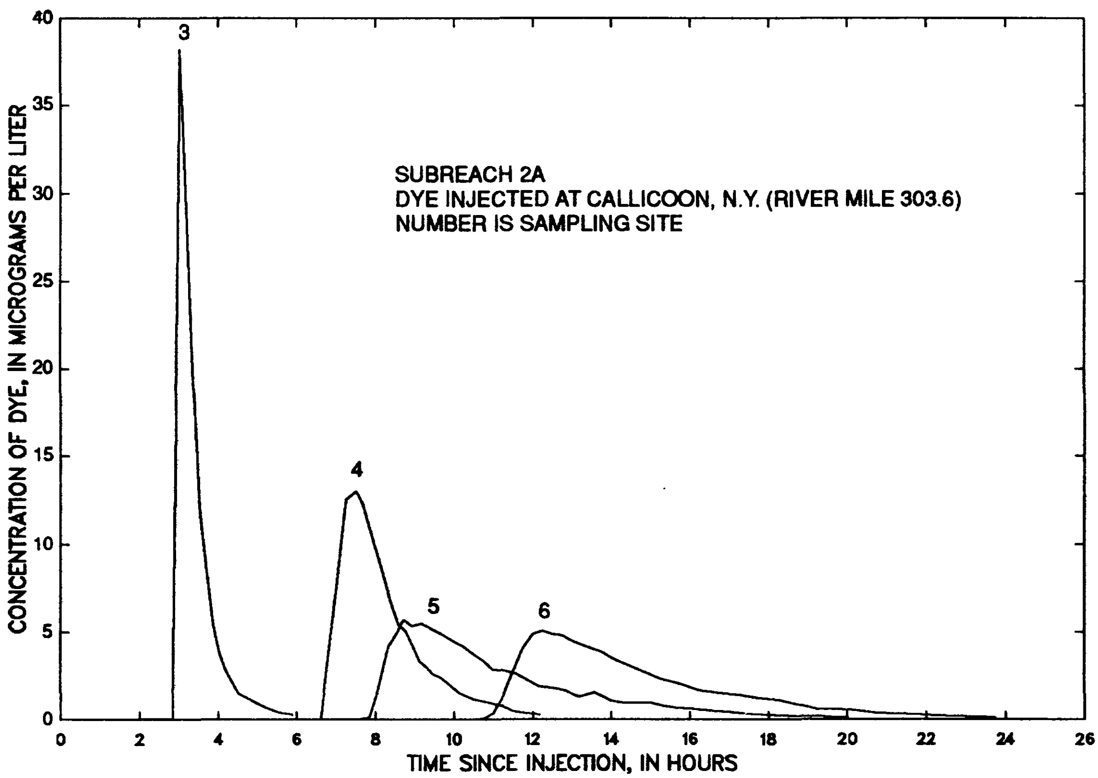


Figure 12A. Observed time-concentration curves from the May 1991 medium-flow study for subreach 1 and subreach 2A.

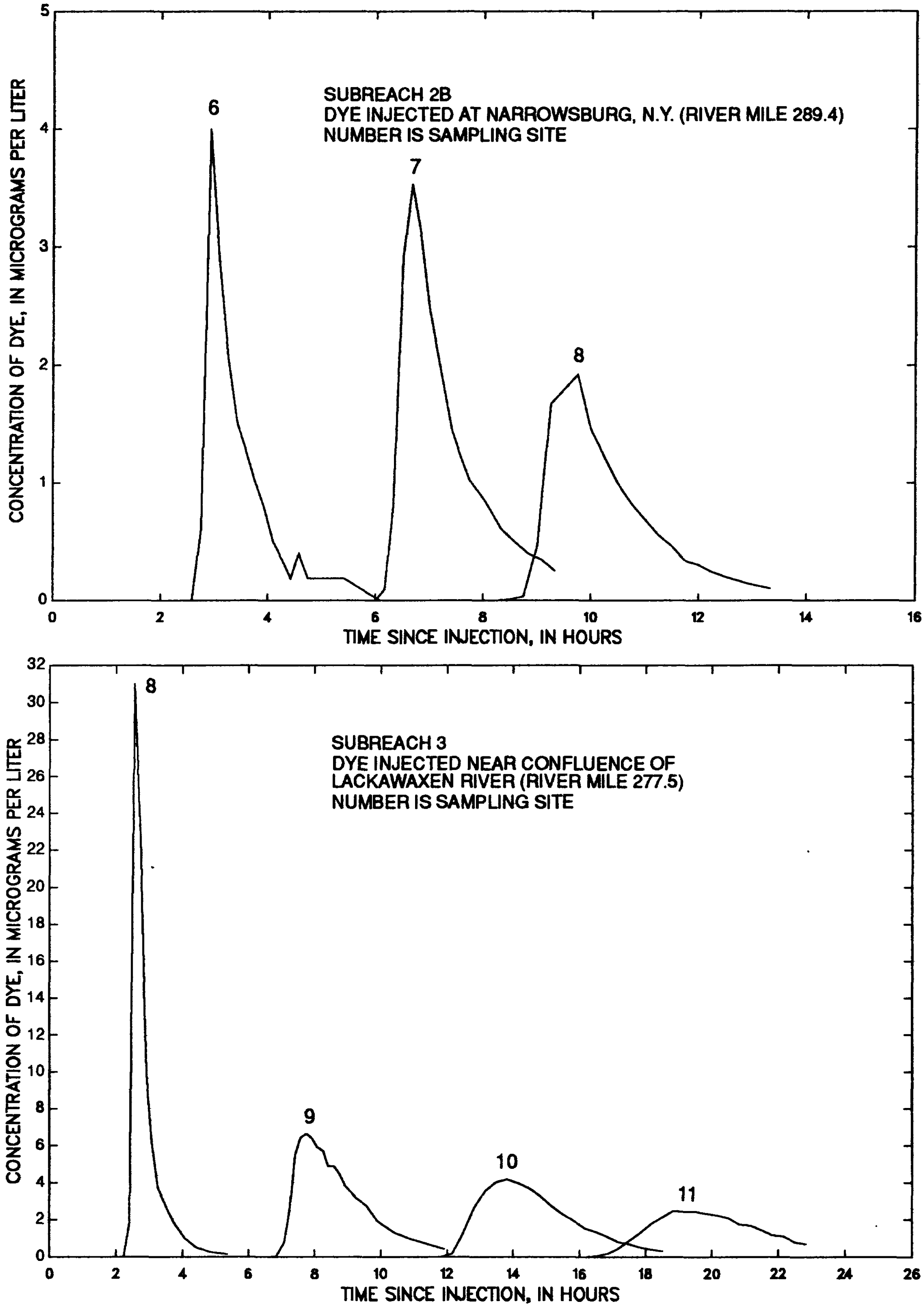
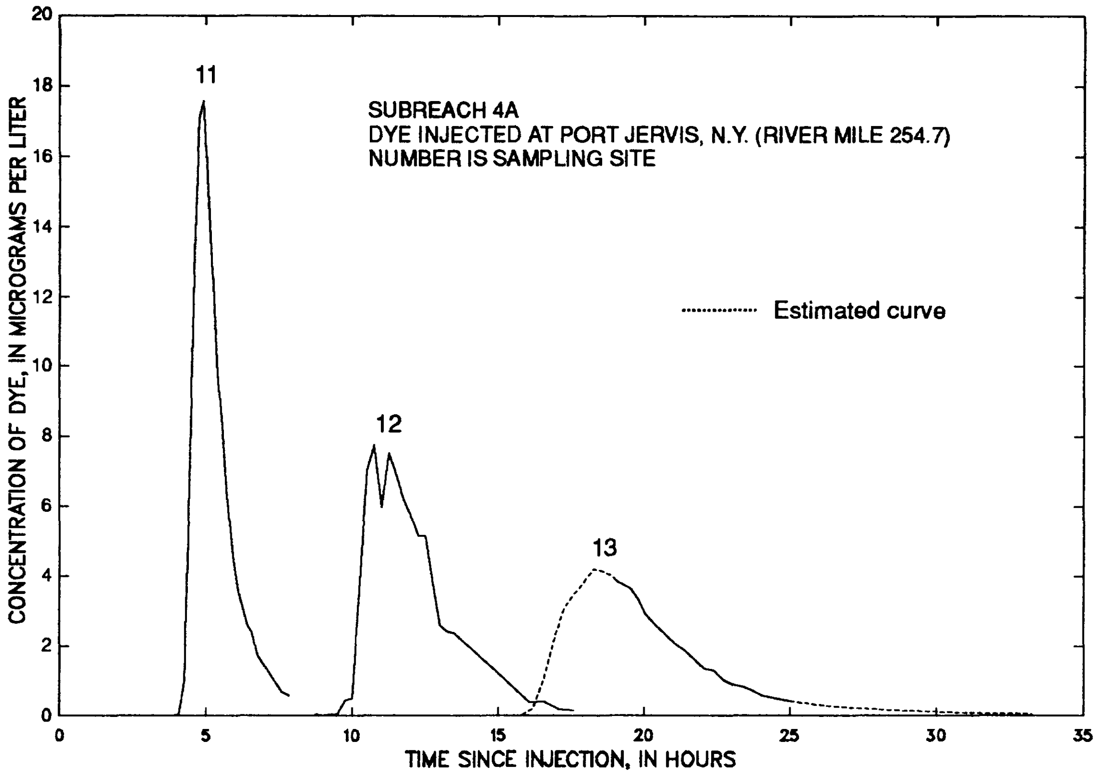


Figure 12B. Observed time-concentration curves from the May 1991 medium-flow study for subreach 2B and subreach 3.



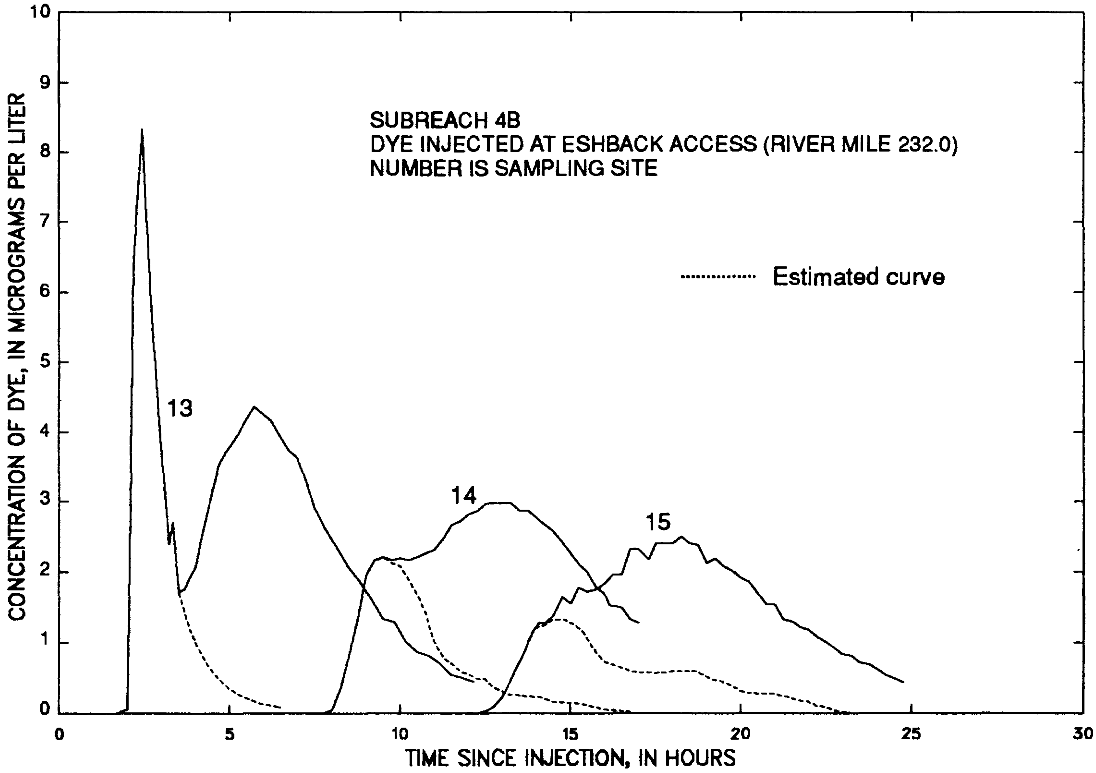


Figure 12C. Observed time-concentration curves from the May 1991 medium-flow study for subreach 4A and subreach 4B.

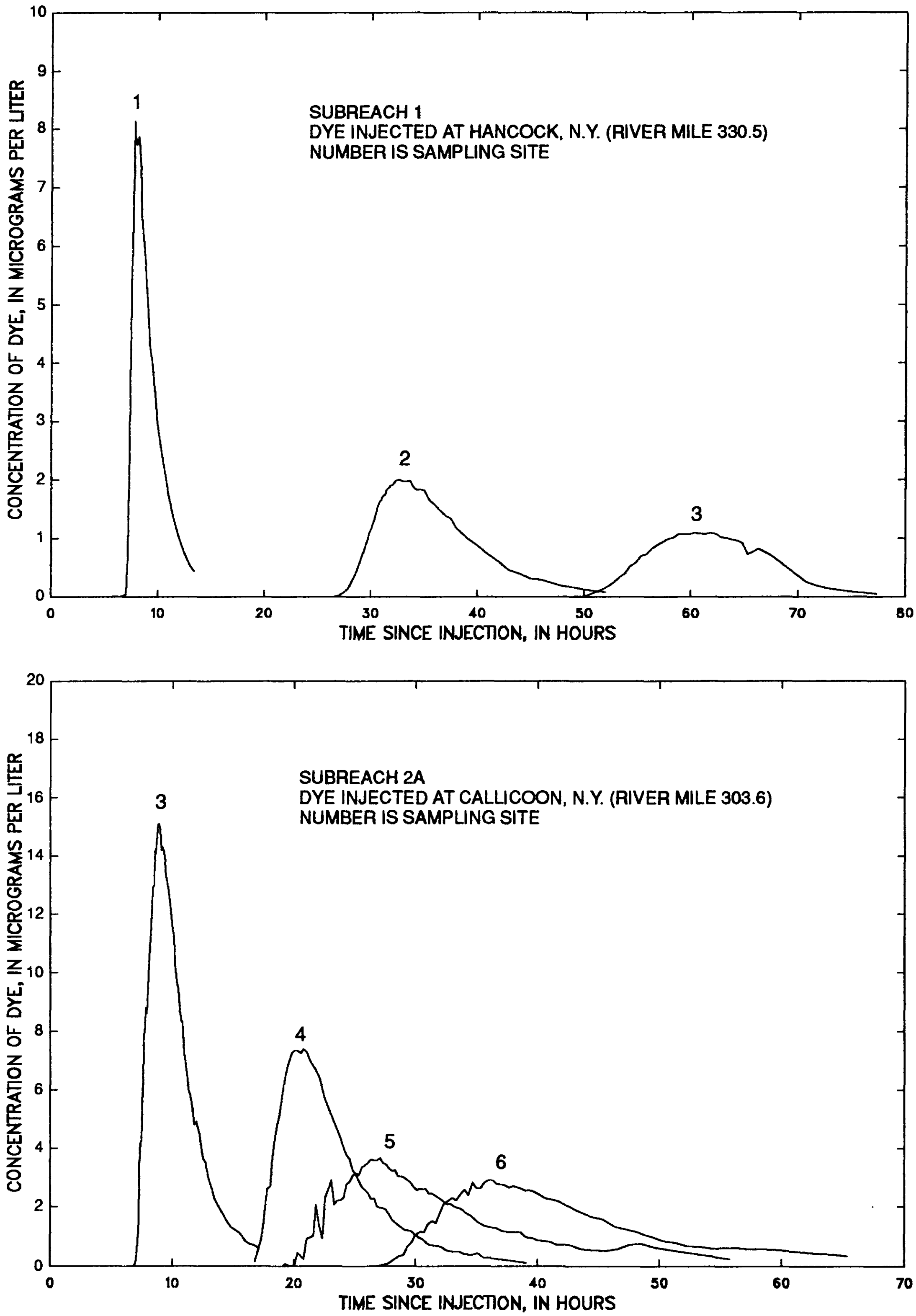
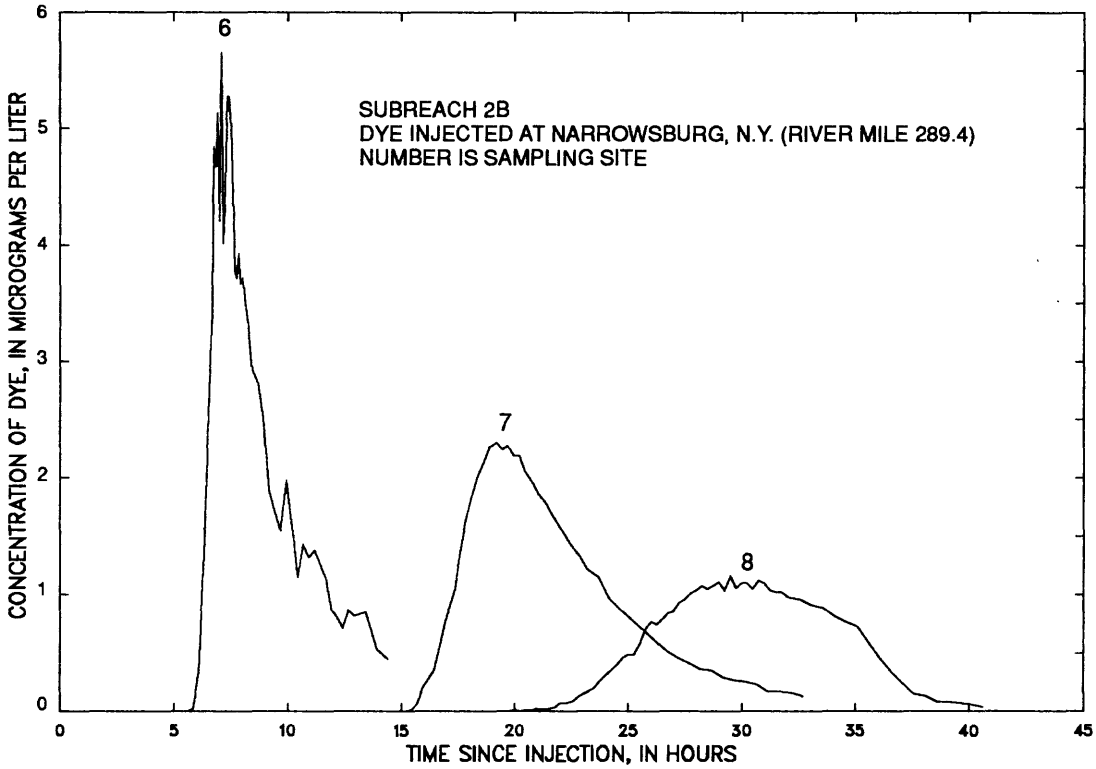


Figure 13A. Observed time-concentration curves from the August 1991 low-flow study for subreach 1 and subreach 2A.



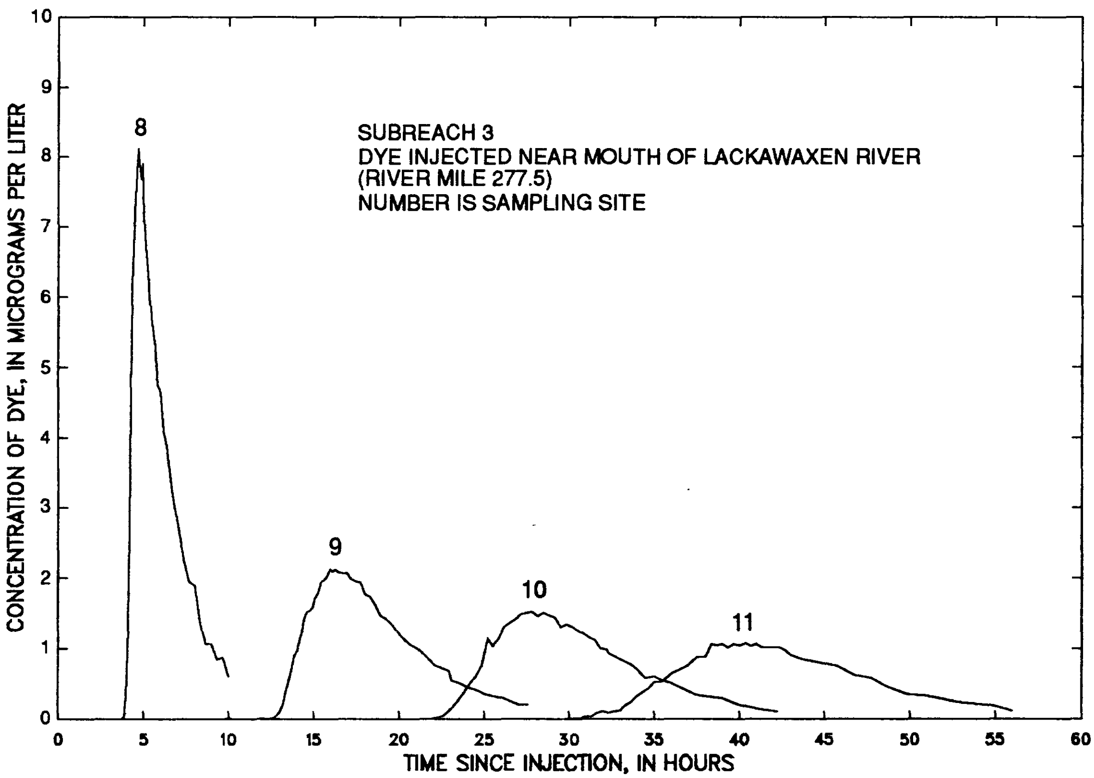
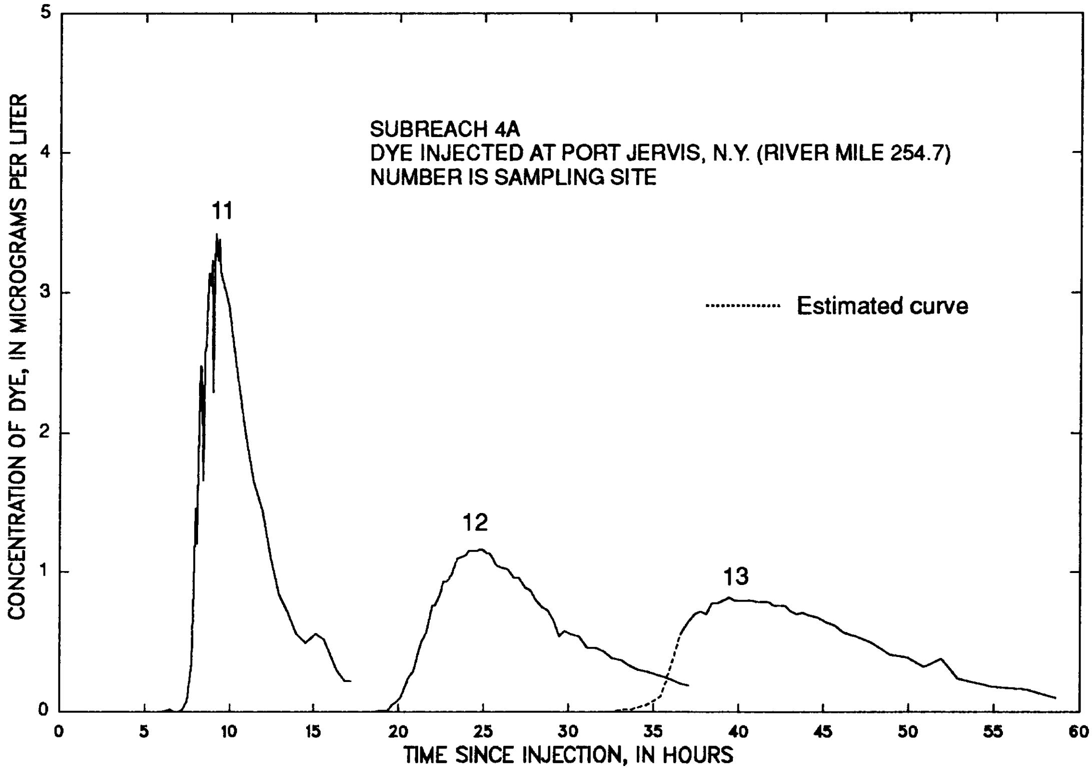


Figure 13B. Observed time-concentration curves from the August 1991 low-flow study for subreach 2B and subreach 3.



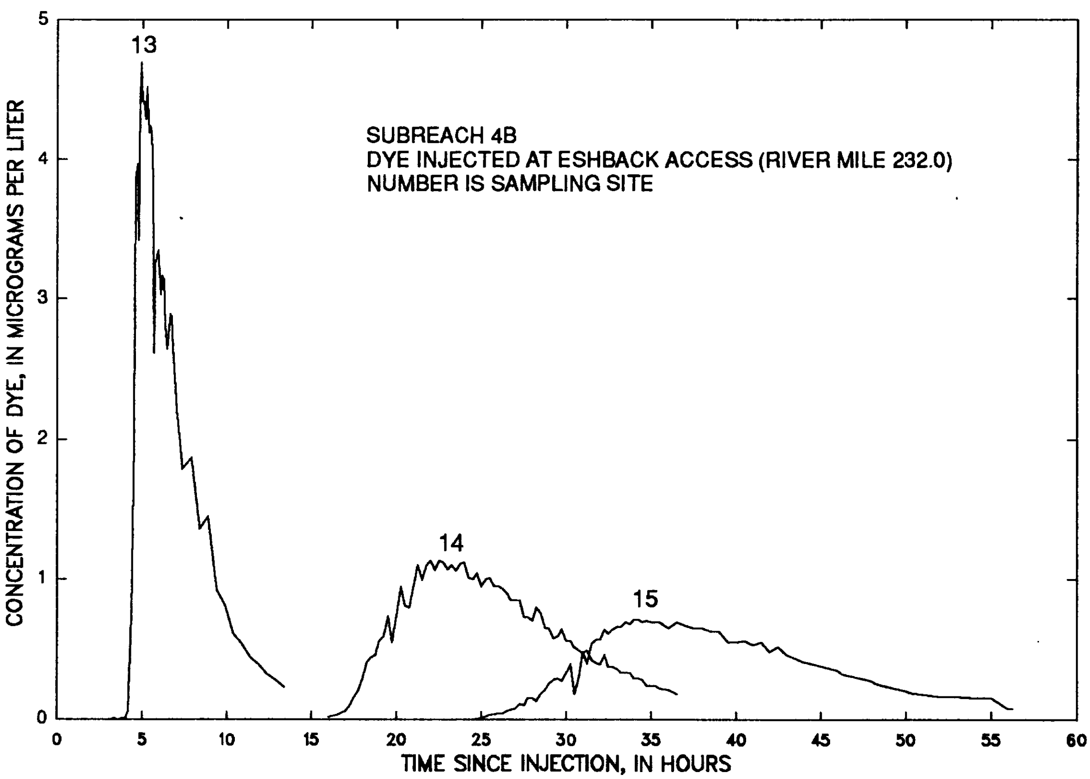


Figure 13C. Observed time-concentration curves from the August 1991 low-flow study for subreach 4A and subreach 4B.

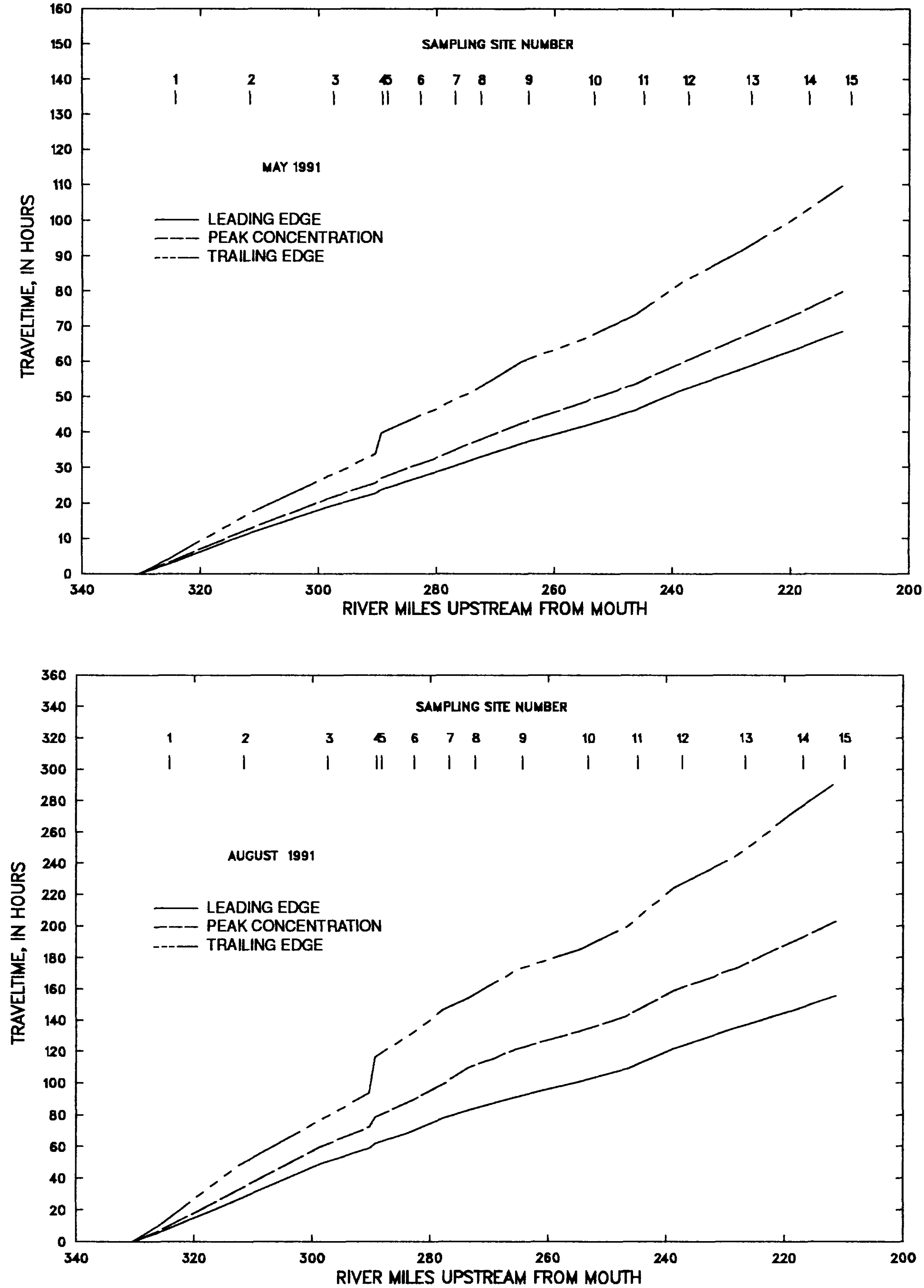


Figure 14. Cumulated traveltime for May and August 1991 medium- and low-flow dye injections, Delaware River, Hancock, N.Y., to the Delaware Water Gap.

Table 6. Traveltimes for the May medium-flow dye study, Delaware River, Hancock, N.Y., to the Delaware Water Gap
[All times are in hours.]

Site number	Leading edge			Peak concentration			Trailing edge		
	Time since injection	Travel-time between sites	Cumul-ative travel-time	Time since injection	Travel-time between sites	Cumul-ative travel-time	Time since injection	Travel-time between sites	Cumul-ative travel-time
Subreach 1									
1	3.00	3.00	3.00	3.33	3.33	3.33	4.43	4.43	4.43
2	11.00	8.00	11.00	12.33	9.00	12.33	16.32	11.89	16.32
3	19.00	8.00	19.00	21.25	8.92	21.25	27.62	11.30	27.62
Subreach 2A									
3	2.85	2.85	21.85	3.02	3.02	24.27	4.03	4.03	31.65
4	6.58	3.73	25.58	7.50	4.48	28.75	10.35	6.32	37.97
5	7.58	1.00	26.58	8.72	1.22	29.97	16.43	6.08	44.05
6	10.25	2.67	29.25	12.25	3.53	33.50	20.44	4.01	48.06
Subreach 2B									
6	2.43	2.43	31.68	2.93	2.93	36.43	4.24	4.24	52.30
7	6.00	3.57	35.25	6.67	3.74	40.17	9.09	4.85	57.15
8	8.25	2.25	37.50	9.75	3.08	43.25	12.68	3.59	60.74
Subreach 3									
8	2.23	2.23	39.73	2.57	2.57	45.82	3.43	3.43	64.17
9	6.99	4.76	44.49	8.00	5.43	51.25	11.34	7.91	72.08
10	11.82	4.83	49.32	13.82	5.82	57.07	18.14	6.80	78.88
11	16.17	4.35	53.67	18.83	5.01	62.08	24.87	6.73	85.61
Subreach 4A									
11	3.93	3.93	57.60	4.92	4.92	67.00	6.70	6.70	92.31
12A	9.57	5.64	63.24	10.83	5.91	72.91	15.48	8.78	101.09
13	15.84	6.27	69.51	18.28	7.45	80.36	25.01	9.53	110.62
14	21.92	6.08	75.59	25.53	7.25	87.61	35.13	10.12	120.74
15	26.42	4.50	80.09	30.63	5.10	92.71	41.81	6.68	127.42
Subreach 4B									
13	[1]14.57	1.99	65.23	[1]15.00	2.42	75.33	[1]16.75	4.17	105.26
14	[1]20.33	5.76	70.99	[1]22.08	7.08	82.41	[1]26.77	10.02	115.28
15	[1]24.83	4.50	75.49	[1]27.33	5.25	87.66	[1]34.69	7.92	123.20

[1] Times adjusted to reflect injection at river mile 254.73 (subreach 4A).

Table 7. Traveltimes for the August low-flow dye study, Delaware River, Hancock, N.Y., to the Delaware Water Gap

[All times are in hours.]

Site number	Leading edge			Peak concentration			Trailing edge		
	Time since injection	Travel-time between sites	Cumulative travel-time	Time since injection	Travel-time between sites	Cumulative travel-time	Time since injection	Travel-time between sites	Cumulative travel-time
Subreach 1									
1	7.00	7.00	7.00	7.75	7.75	7.75	12.33	12.33	12.33
2	26.50	19.50	26.50	32.67	24.92	32.67	47.67	35.34	47.67
3	49.33	22.83	49.33	60.33	27.66	60.33	74.16	26.49	74.16
Subreach 2A									
3	6.75	6.75	56.08	8.83	8.83	69.16	14.50	14.50	88.66
4	16.25	9.50	65.58	20.83	12.00	81.16	31.02	16.52	105.18
5	19.08	2.83	68.41	27.08	6.25	87.41	53.50	22.48	127.66
6	26.00	6.92	75.33	36.00	8.92	96.33	66.18	12.68	140.34
Subreach 2B									
6	5.83	5.83	81.16	7.08	7.08	103.41	13.86	13.86	154.20
7	15.43	9.60	90.76	19.18	12.10	115.51	30.68	16.82	171.02
8	20.25	4.82	95.58	29.00	9.82	125.33	38.28	7.60	178.62
Subreach 3									
8	3.70	3.70	99.28	4.65	4.65	129.98	9.70	9.70	188.32
9	12.08	8.38	107.66	16.42	11.77	141.75	27.83	18.13	206.45
10	21.83	9.75	117.41	27.83	11.41	153.16	41.04	13.21	219.66
11	30.33	8.50	125.91	38.35	10.52	163.68	56.17	15.13	234.79
Subreach 4A									
11	7.00	7.00	132.91	9.17	9.17	172.85	16.15	16.15	250.94
12B	19.10	12.10	145.01	24.77	15.60	188.45	39.64	23.49	274.43
13	32.80	13.70	158.71	39.42	14.65	203.10	60.50	20.86	295.29
Subreach 4B									
13	4.00	4.00	162.71	4.93	4.93	208.03	11.22	11.22	306.51
14	15.18	11.18	173.89	22.00	17.07	225.10	39.20	27.98	334.49
15	24.50	9.32	183.21	34.00	12.00	237.10	57.59	18.39	352.88

Table 8. Dye-cloud velocities and representative stream discharges for leading edge, peak, and trailing edge of dye cloud for reach of the Delaware River between Cochecton, N.Y., and Narrowsburg, N.Y.

[ft^3/s, cubic foot per second]

	Date	Velocity (miles per hour)	Discharge at Callicoon (ft^3/s)	Discharge above Lackawaxen (ft^3/s)
Peak	Aug. 12	0.67	571	713
	May 8	1.80	3,023	3,602
Leading edge	Aug. 12-13	.82	580	732
	May 8	2.14	3,037	3,621
Trailing edge	Aug. 12-13	.46	550	687
	May 8	1.28	2,980	3,541

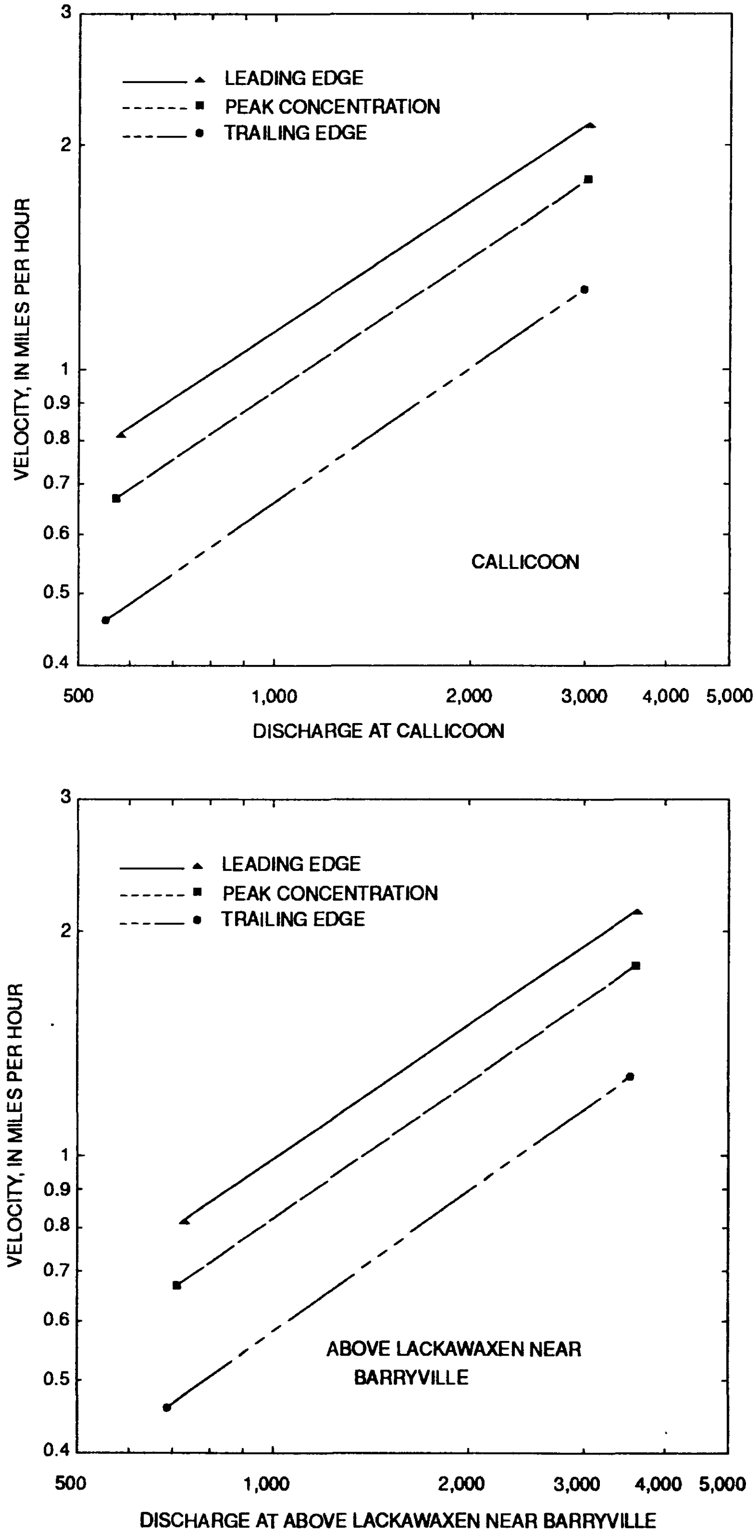


Figure 15. Dye-cloud velocity as a function of average discharges at streamflow-measurement stations Delaware River at Callicoon, N.Y., and above Lackawaxen near Barryville, N.Y.

Table 9. Dye-cloud velocities at discharges corresponding to various flow durations at Delaware River at Callicoon, N.Y., and Delaware River above Lackawaxen River near Barryville, N.Y.

[ft³/s, cubic foot per second; Cal, Callicoon; Lack, Lackawaxen; Avg., average]

Flow duration			Velocity (miles per hour)								
Percent	Discharge (ft³/s)		Peak			Leading edge			Trailing edge		
	Cal	Lack	Cal	Lack	Avg.	Cal	Lack	Avg.	Cal	Lack	Avg.
30	2,400	2,690	1.56	1.50	1.53	1.87	1.75	1.81	1.13	1.08	1.10
40	1,730	1,970	1.29	1.25	1.27	1.56	1.47	1.52	.925	.890	.908
50	1,420	1,580	1.15	1.09	1.12	1.38	1.30	1.34	.815	.770	.792
60	1,240	1,380	1.06	1.00	1.03	1.28	1.20	1.24	.755	.710	.732
70	1,100	1,240	.990	.940	.965	1.20	1.13	1.16	.700	.665	.682
75	1,030	1,160	.950	.900	.925	1.16	1.08	1.12	.670	.640	.655
80	947	1,070	.900	.860	.880	1.11	1.04	1.08	.640	.610	.625
85	868	980	.860	.820	.840	1.05	.990	1.02	.605	.575	.590
90	789	890	.810	.770	.790	.990	.940	.965	.572	.540	.556
95	674	760	.740	.700	.720	.910	.860	.885	.510	.490	.500

Table 10. Traveltimes for leading edge of dye cloud at selected flow durations on the Delaware River, Hancock, N.Y. to the Delaware Water Gap

Site number	Site name	River mile[1]	Distance between sampling sites (miles)	Traveltime (hours) of leading edge of dye cloud from river mile 330.50 for the indicated flow duration (percent)									
				30	40	50	60	70	75	80	85	90	95
Inject	Hancock wastewater treatment plant	330.50	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	Buckingham Access	325.14	5.36	3.4	4.1	4.5	4.8	5.2	5.4	5.6	5.8	6.2	6.7
2	Kellam's Bridge	312.59	12.55	12.3	14.8	16.2	17.6	18.8	19.6	20.3	21.3	22.5	24.4
3	Cochecton Bridge	298.40	14.19	21.1	25.7	28.7	31.2	33.4	34.9	36.5	38.4	40.6	44.6
4	Narrowsburg (N.Y. access)	290.34	8.06	25.5	31.0	34.7	37.6	40.4	42.1	43.9	46.3	49.0	53.8
5	Narrowsburg (Pa. access)	289.43	.91	26.7	32.4	36.3	39.4	42.3	44.1	46.0	48.5	51.4	56.4
6	Tenmile River confluence	284.15	5.28	29.8	36.3	40.6	44.0	47.1	49.2	51.2	54.0	57.1	62.6
7	Lackawaxen River confluence	277.81	6.34	33.9	41.3	46.4	50.4	53.8	56.4	58.9	62.0	65.7	72.2
8	Barryville Bridge	273.50	4.31	36.7	44.5	49.9	54.1	57.6	60.3	63.0	66.2	70.1	76.9
9	Pond Eddy Bridge	265.50	8.00	41.1	49.8	55.8	60.8	65.0	68.0	70.8	74.4	78.6	85.8
10	Port Jervis Bridge	254.75	10.75	46.1	55.7	62.8	68.7	73.9	77.3	80.4	84.2	88.9	96.6
11	Milford Beach	246.31	8.44	50.6	61.0	69.0	75.6	81.7	85.3	88.7	92.7	97.8	106
12	Dingmans[2]	238.98	7.33	56.0	67.6	76.8	84.6	82.0	96.0	99.8	104	110	119
13	Bushkill Access	228.11	10.87	62.2	75.0	85.9	95.3	104	109	113	118	124	134
14	Smithfield Beach	218.34	9.77	68.2	82.0	93.8	104	114	119	123	128	135	146
15	Kittatinny Access	211.37	6.97	73.0	87.4	100	111	122	127	132	138	145	155

[1] River mile zero is located at the mouth of the Delaware Bay.

[2] The relocation of the Dingmans site is reflected in reach-segment average velocities from Dingmans through Kittatinny Access which, in turn, present a slight variation in trave times. Analyses in this report use the average of these traveltimes.

Table 11. Traveltimes for peak concentration of dye cloud at selected flow durations on the Delaware River, Hancock, N.Y., to the Delaware Water Gap

Site number	Site name	River mile[1]	Distance between sampling sites (miles)	Traveltime (hours) for peak concentration of dye cloud from river mile 330.50 for the indicated flow duration (percent)									
				30	40	50	60	70	75	80	85	90	95
Inject	Hancock wastewater treatment plant	330.50	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	Buckingham Access	325.14	5.36	3.8	4.6	5.1	5.5	5.8	6.1	6.3	6.6	7.0	7.7
2	Kellam's Bridge	312.59	12.55	14.1	17.1	19.2	20.8	22.1	23.1	24.2	25.4	27.0	29.6
3	Cochecton Bridge	298.40	14.19	23.8	29.3	33.1	35.9	38.6	40.4	42.4	44.8	47.5	52.6
4	Narrowsburg (N.Y. access)	290.34	8.06	29.1	35.6	40.3	43.7	47.0	49.1	51.6	54.4	57.7	63.8
5	Narrowsburg (Pa. access)	289.43	.91	30.6	37.7	43.0	46.6	50.3	52.7	55.5	58.7	62.5	69.3
6	Tenmile River confluence	284.15	5.28	34.6	42.5	48.3	52.4	56.5	59.1	62.1	65.6	69.8	77.3
7	Lackawaxen River confluence	277.81	6.34	39.4	48.4	55.3	60.2	64.6	67.8	71.4	75.6	80.5	89.3
8	Barryville Bridge	273.50	4.31	43.2	53.1	60.8	66.2	71.1	74.6	78.6	83.12	88.6	98.5
9	Pond Eddy Bridge	265.50	8.00	48.3	59.4	68.5	75.2	81.4	85.5	89.7	94.7	101	112
10	Port Jervis Bridge	254.75	10.75	54.4	66.6	76.9	84.6	91.8	96.3	101	106	113	124
11	Milford Beach	246.31	8.44	59.6	72.8	84.3	93.0	101	106	111	117	124	135
12	Dingmans[2]	238.98	7.33	65.6	80.4	93.6	104	114	120	125	132	140	152
13	Bushkill Access	228.11	10.87	73.0	89.0	104	116	128	134	140	147	155	170
14	Smithfield Beach	218.34	9.77	80.2	98.0	114	128	142	148	155	163	172	188
15	Kittatinny Access	211.37	6.97	86.4	105	123	137	152	159	166	174	184	200

[1] River mile zero is located at the mouth of the Delaware Bay.

[2] The relocation of the Dingmans site is reflected in reach-segment average velocities from Dingmans through Kittatinny Access which, in turn, present a slight variation in traveltimes. Analyses in this report use the average of these traveltimes.

Table 12. Traveltimes for trailing edge of dye cloud at selected flow durations on the Delaware River, Hancock, N.Y., to the Delaware Water Gap

Site number	Site name	River mile[1]	Distance between sampling sites (miles)	Traveltime (hours) for trailing edge of dye cloud from river mile 330.50 for the indicated flow duration (percent)									
				30	40	50	60	70	75	80	85	90	95
Inject	Hancock wastewater treatment plant	330.50	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	Buckingham Access	325.14	5.36	5.2	6.3	7.0	7.7	8.2	8.6	9.1	9.6	10.1	11.4
2	Kellam's Bridge	312.59	12.55	18.5	22.8	25.8	27.9	30.3	31.9	33.2	35.2	37.4	41.3
3	Cochecton Bridge	298.40	14.19	30.5	37.4	42.3	45.5	48.9	51.9	53.9	57.0	60.6	66.6
4	Narrowsburg (N.Y. access)	290.34	8.06	37.8	46.2	52.5	56.6	60.8	64.2	66.8	70.7	75.2	82.7
5	Narrowsburg (Pa. access)	289.43	.91	45.0	55.3	63.2	68.6	73.8	78.0	81.3	86.1	92.0	102
6	Tenmile River confluence	284.15	5.28	49.5	60.9	69.7	75.6	81.3	85.9	89.6	94.9	101	112
7	Lackawaxen River confluence	277.81	6.34	55.3	68.2	78.5	85.2	91.5	97.0	101	108	115	128
8	Barryville Bridge	273.50	4.31	59.3	72.8	83.6	90.6	97.2	103	107	114	122	135
9	Pond Eddy Bridge	265.50	8.00	67.3	82.5	95.5	105	113	120	125	132	141	155
10	Port Jervis Bridge	254.75	10.75	74.2	90.6	105	115	125	132	138	145	154	169
11	Milford Beach	246.31	8.44	81.6	99.4	115	127	138	146	152	160	170	185
12	Dingmans[2]	238.98	7.33	90.6	111	130	144	158	167	174	182	193	211
13	Bushkill Access	228.11	10.87	101	123	145	161	177	187	194	204	216	235
14	Smithfield Beach	218.34	9.77	111	136	160	179	199	210	219	230	243	265
15	Kittatinny Access	211.37	6.97	121	146	172	193	214	226	236	248	262	284

[1] River mile zero is located at the mouth of the Delaware Bay.

[2] The relocation of the Dingmans site is reflected in reach-segment average velocities from Dingmans through Kittatinny Access which, in turn, present a slight variation in trave times. Analyses in this report use the average of these traveltimes.

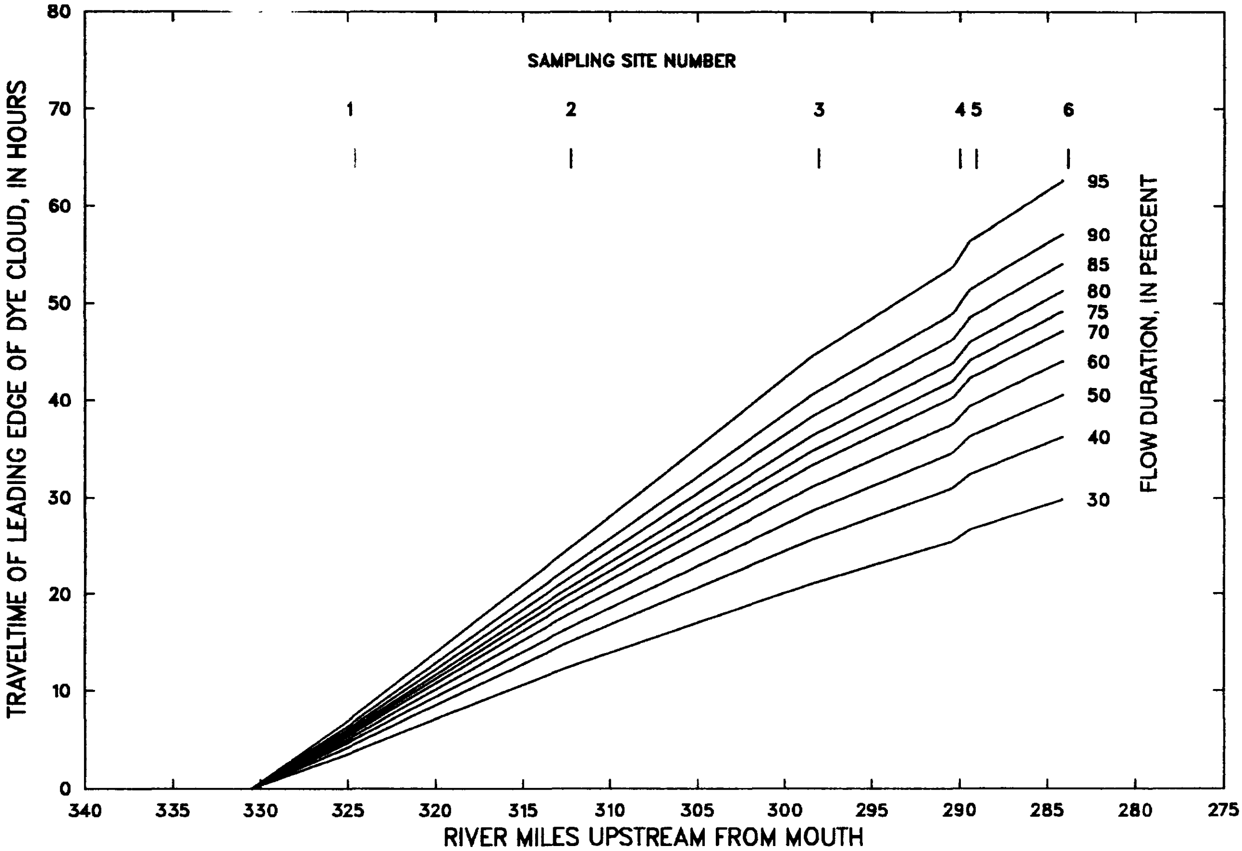


Figure 16A. Relation of traveltime and distance of leading edge of dye cloud at selected flow durations on the Delaware River for sampling sites 1-6, Hancock, N.Y., to 0.1 mile downstream of Tenmile River confluence.

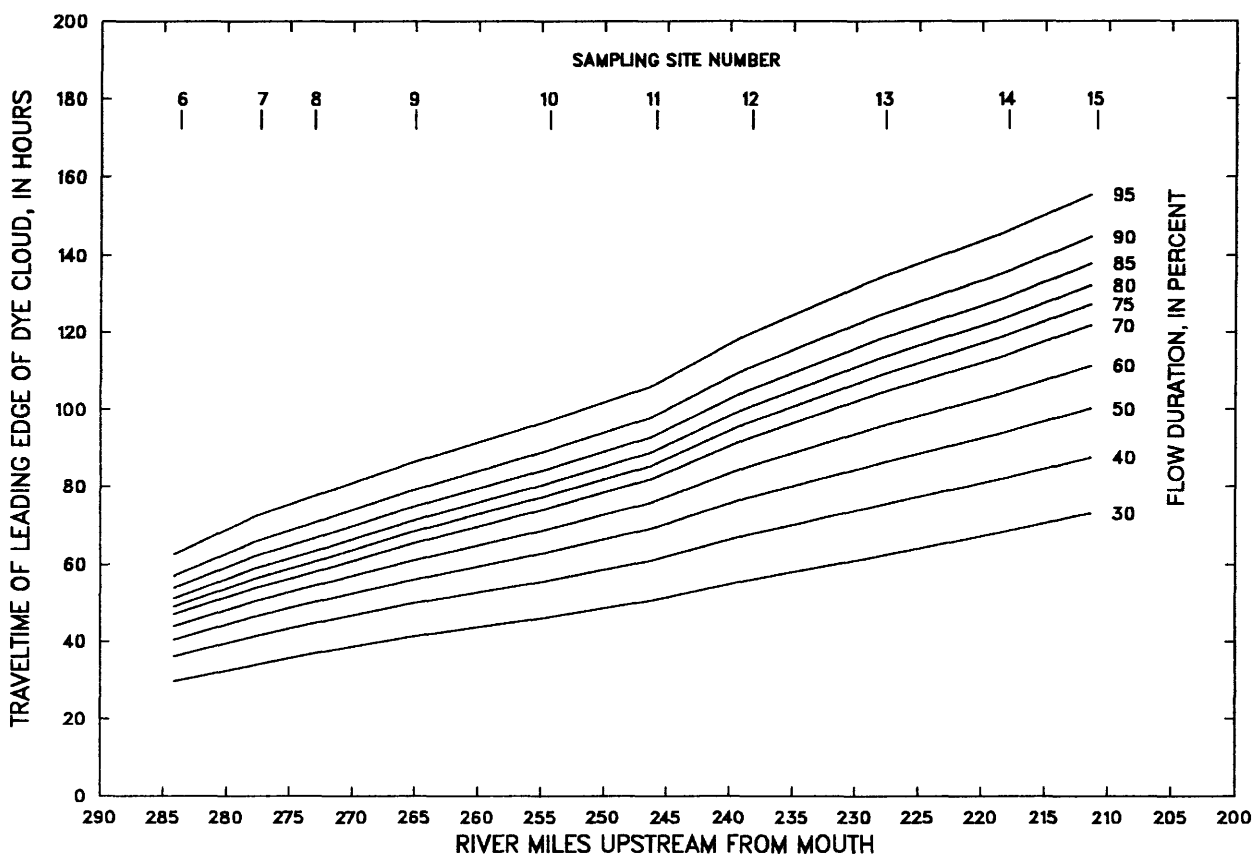


Figure 16B. Relation of traveltime and distance of leading edge of dye cloud at selected flow durations on the Delaware River for sampling sites 6-15, 0.1 mile downstream of Tenmile River confluence to the Delaware Water Gap.

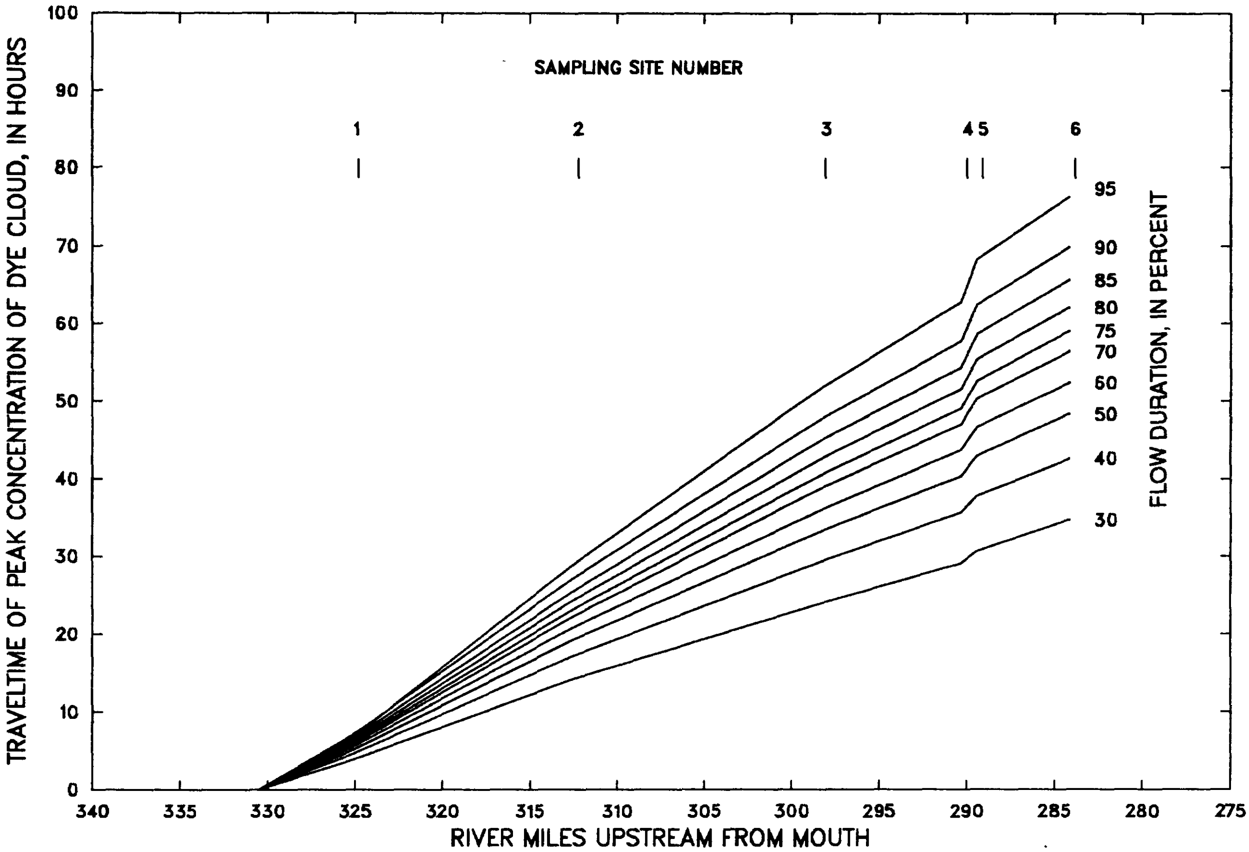


Figure 17A. Relation of traveltime and distance of peak concentration of dye cloud at selected flow durations on the Delaware River for sampling sites 1-6, Hancock, N.Y., to 0.1 mile downstream of Tenmile River confluence.

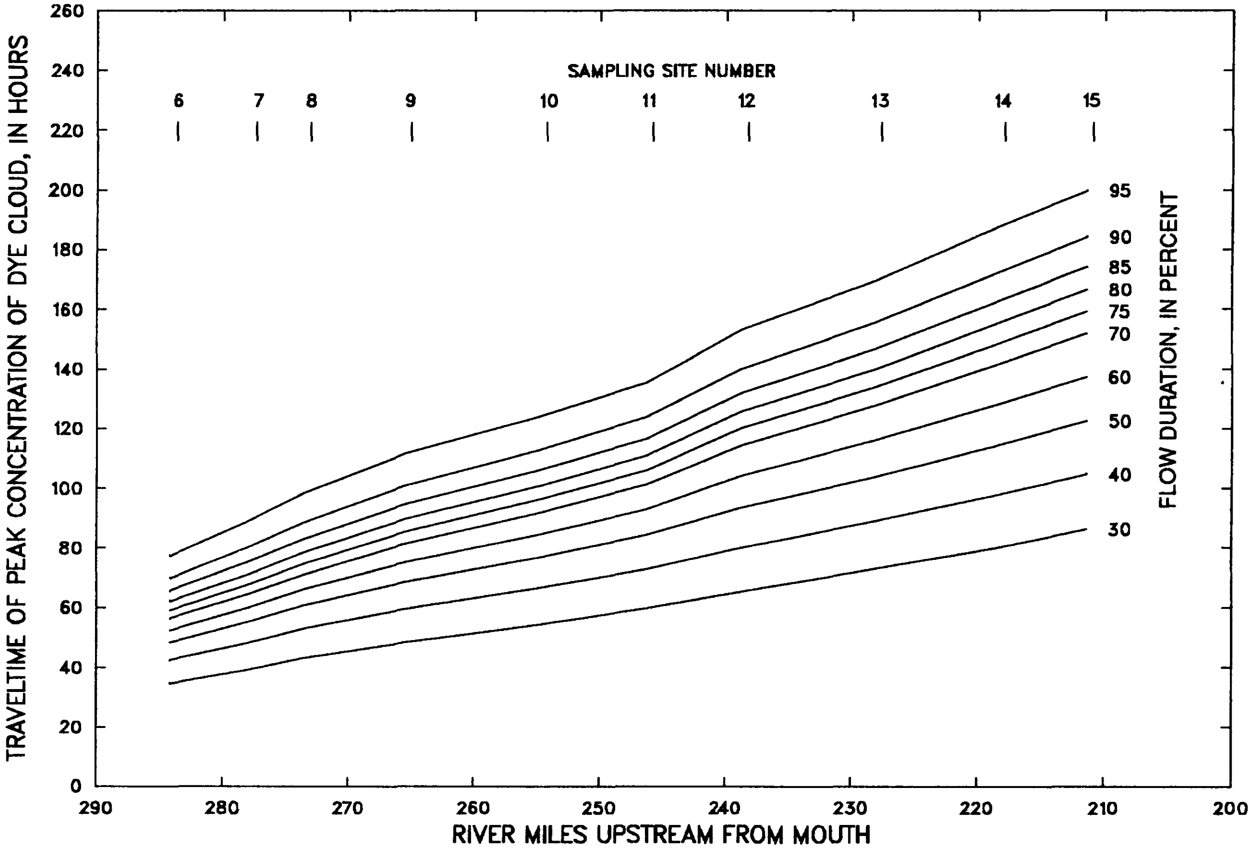


Figure 17B. Relation of traveltime and distance of peak concentration of dye cloud at selected flow durations on the Delaware River for sampling sites 6-15, 0.1 mile downstream of Tenmile River confluence to the Delaware Water Gap.

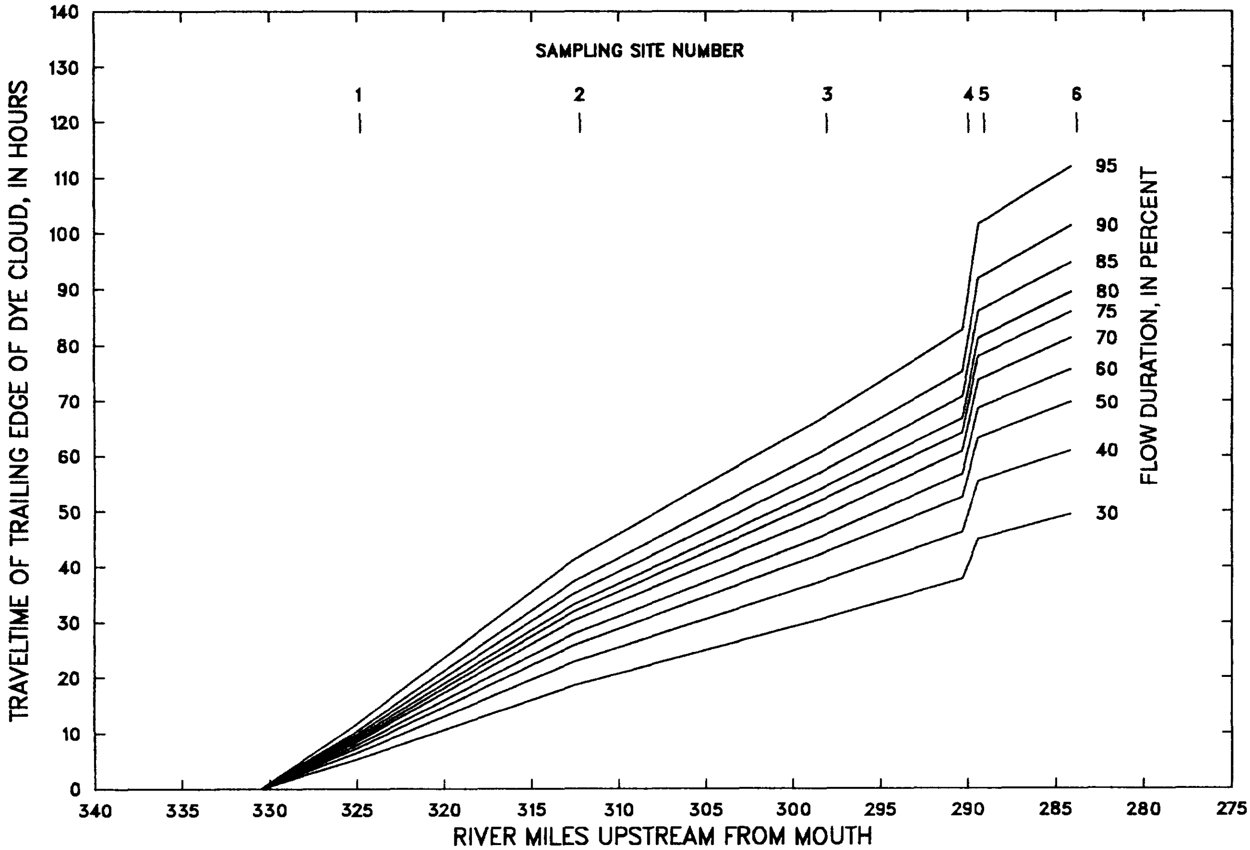


Figure 18A. Relation of traveltime and distance of trailing edge of dye cloud at selected flow durations on the Delaware River for sampling sites 1-6, Hancock, N.Y. to 0.1 mile downstream of Tenmile River confluence.

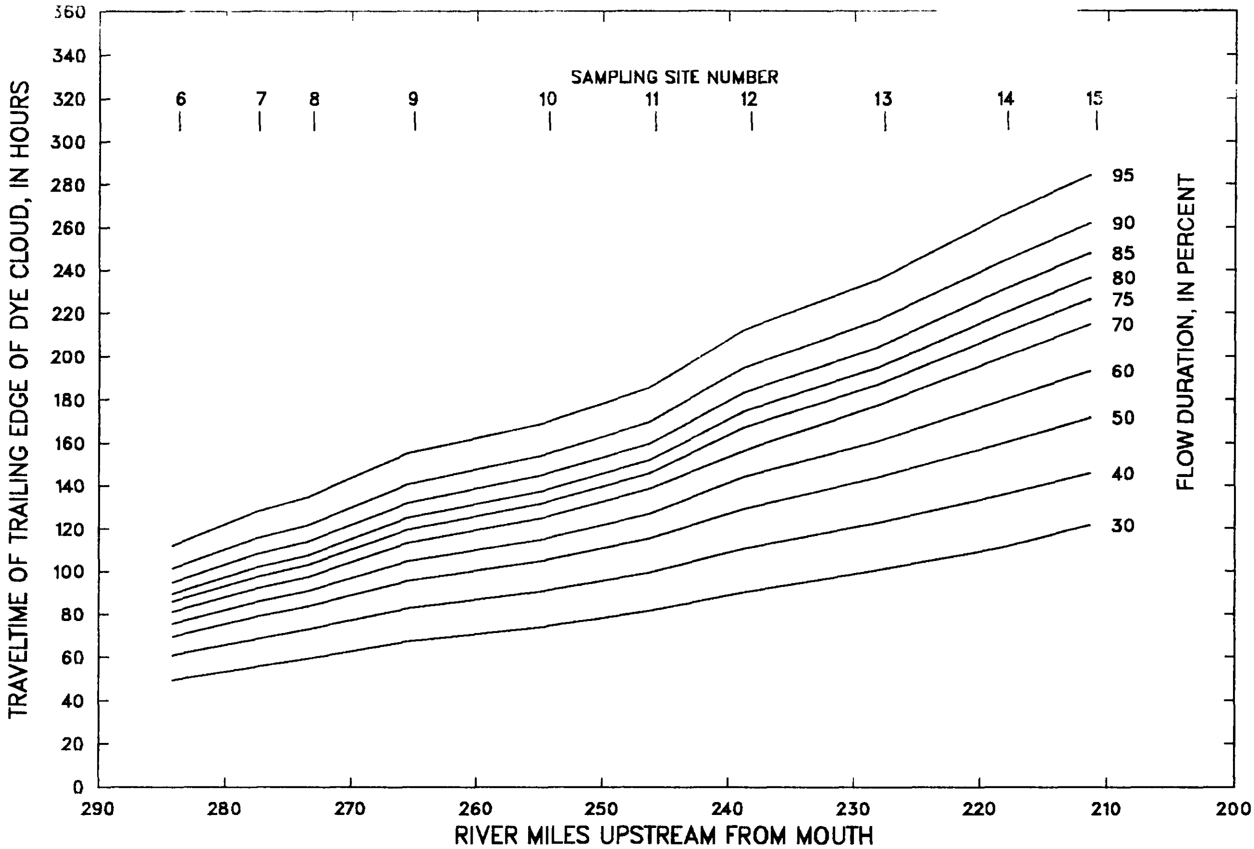


Figure 18B. Relation of traveltime and distance of trailing edge of dye cloud at selected flow durations on the Delaware River for sampling sites 6-15, 0.1 mile downstream of Tenmile River confluence to the Delaware Water Gap.

Table 13. Time durations for dye cloud at selected flow durations on the Delaware River, Hancock, N.Y., to the Delaware Water Gap

Site number	Site name	River mile[1]	Distance between sampling sites (miles)	Traveltime (hours) of dye cloud injected at river mile 330.50 for the indicated flow duration (percent)									
				30	40	50	60	70	75	80	85	90	95
Inject	Hancock wastewater treatment plant	330.50	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	Buckingham Access	325.14	5.36	1.7	2.2	2.6	2.8	3.1	3.3	3.5	3.7	4.0	4.7
2	Kellam's Bridge	312.59	12.55	6.2	8.0	9.6	10.3	11.5	12.3	12.9	13.9	14.9	16.9
3	Cochecton Bridge	298.40	14.19	9.4	11.6	13.6	14.3	15.5	17.0	17.5	18.6	20.0	22.0
4	Narrowsburg (N.Y. access)	290.34	8.06	12.3	15.2	17.8	19.0	20.4	22.1	22.9	24.4	26.2	29.0
5	Narrowsburg (Pa. access)	289.43	.91	18.3	22.9	26.9	29.2	31.5	33.9	35.3	37.6	40.6	45.3
6	Tenmile River confluence	284.15	5.28	19.7	24.6	29.2	31.6	34.2	36.8	38.3	40.9	44.3	49.5
7	Lackawaxen River confluence	277.81	6.34	21.4	26.9	32.0	34.8	37.7	40.6	42.5	45.6	49.4	55.4
8	Barryville Bridge	273.50	4.31	22.5	28.3	33.6	36.6	39.5	42.4	44.5	47.6	51.5	57.7
9	Pond Eddy Bridge	265.50	8.00	26.2	32.8	39.6	43.8	48.2	51.6	54.2	57.6	62.2	69.2
10	Port Jervis Bridge	254.75	10.75	28.1	34.9	42.1	46.4	51.1	54.6	57.3	60.8	65.3	72.6
11	Milford Beach	246.31	8.44	31.0	38.4	46.2	51.4	56.7	60.4	63.3	67.0	71.9	79.5
12	Dingmans[2]	238.98	7.33	39.6	43.2	53.3	59.2	66.2	70.6	74.0	78.2	83.6	92.8
13	Bushkill Access	228.11	10.87	38.4	47.8	58.8	65.3	73.0	77.8	81.4	85.9	91.8	101
14	Smithfield Beach	218.34	9.77	42.8	53.6	66.6	75.4	85.4	91.2	95.9	101	108	119
15	Kittatinny Access	211.37	6.97	48.0	58.3	72.2	81.8	82.8	98.8	104	110	117	128

[1] River mile zero is located at the mouth of the Delaware Bay.

[2] The relocation of the Dingmans site is reflected in reach-segment average velocities from Dingmans through Kittatinny Access which, in turn, present a slight variation in traveltimes. Analyses in this report use the average of these traveltimes.

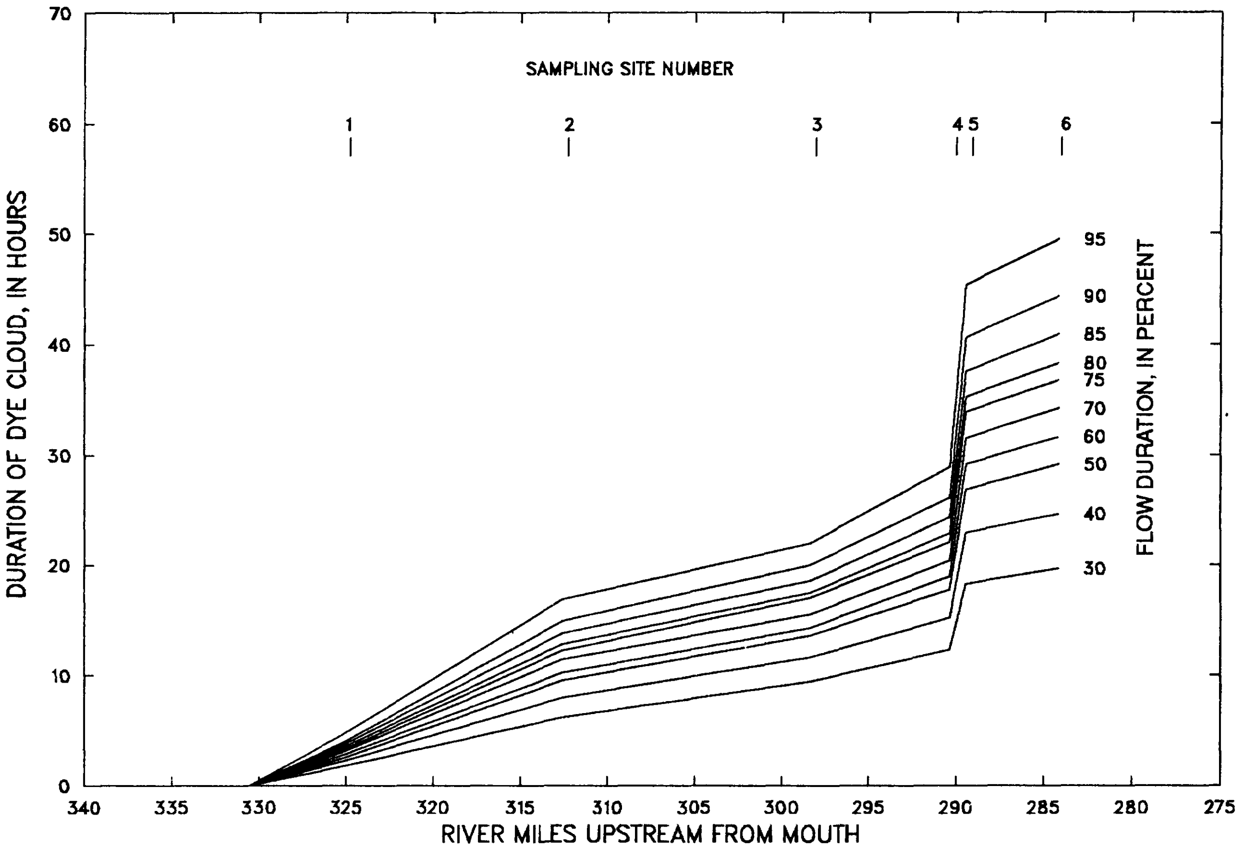


Figure 19A. Relation between dye cloud duration and distance at selected flow durations on the Delaware River for sampling sites 1-6, Hancock, N.Y., to 0.1 mile downstream of Tenmile River confluence.

The data presented in figures 16-19 and tables 9-12 indicate that the traveltime for the leading edge of a spill at Buckingham Access (site 1) to reach the Delaware Water Gap would be about 70 hours if flows were at the 30-percent flow duration and 155 hours if flows were at the 95-percent flow duration. Traveltimes for the peak concentration would be about 85 hours and 200 hours for the 30-percent and 95-percent flow durations, respectively. The trailing edge would take about 120 hours at the 30-percent flow duration and about 290 hours at the 95-percent flow duration to travel the same distance. The duration of this hypothetical spill at the Water Gap would be about 45 hours and 130 hours at the 30-percent and 95-percent flow durations, respectively. The duration of the spill is directly related to the time since the spill occurred, location of the spill, flow, and dispersion characteristics.

Figures 16 to 19 show a large increase in dye-cloud traveltime between sampling sites 4 and 5, a segment of less than 1 mi containing the Narrowsburg pool and eddy. At the pool and eddy, depths range from about 20 ft to over 110 ft and then recover within a distance of less than 3,000 ft. During the Narrowsburg dye injection, three points in the transect entering the pool were sampled, three locations within the eddy were sampled (one of which involved vertical sampling to a depth of 85 ft), and one point downstream of the pool was sampled. This sampling was done to determine the effect of the pool on the dye clouds for the two subsequent dye injections. A vertical temperature profile was taken in the pool to determine the presence of stratification in the water column that might affect the movement of dye. This profile showed a difference of less than 0.5°C between the surface temperature and the temperature at 110 ft. Vertical dye sampling at depths of 1, 15, 30, 45, and 85 ft showed that with time the dye concentrations

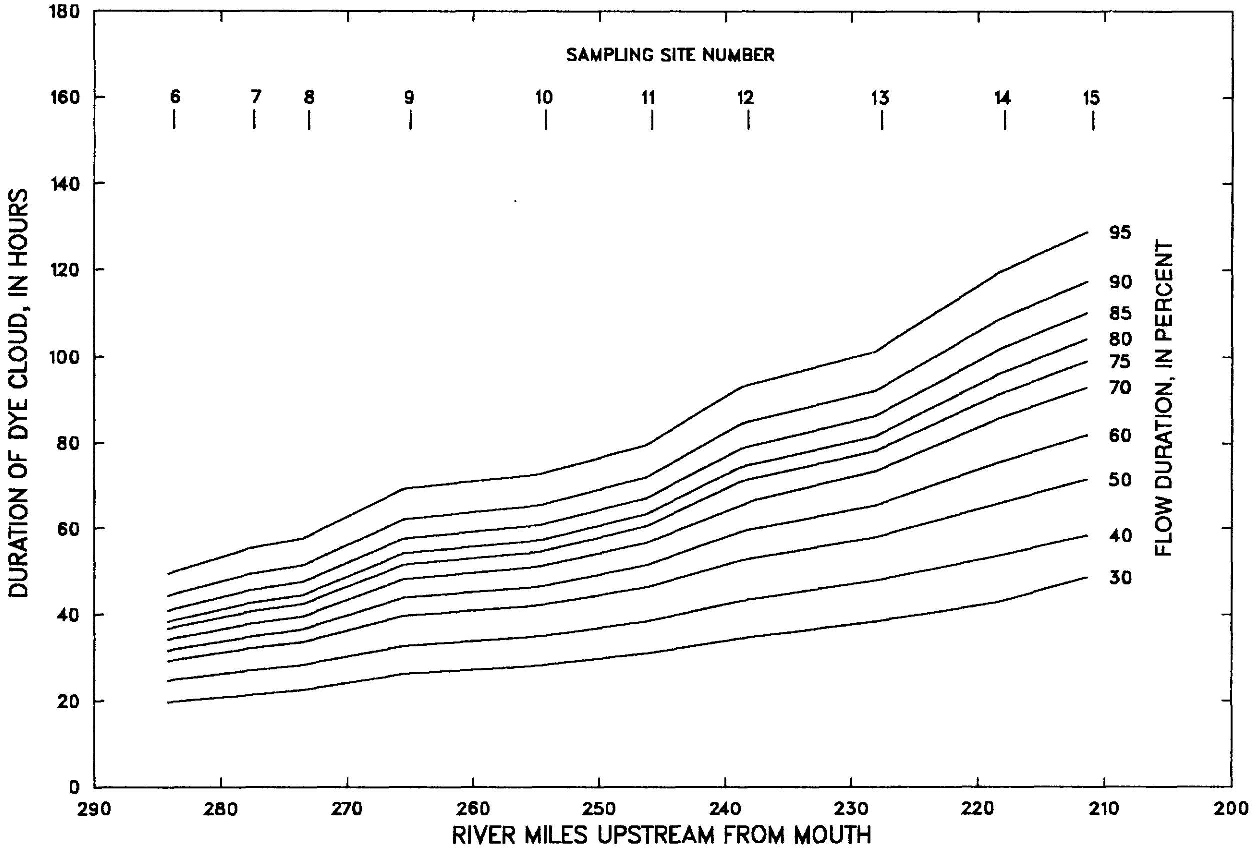


Figure 19B. Relation between dye cloud duration and distance at selected flow durations on the Delaware River for sampling sites 6-15, 0.1 mile downstream of Tenmile River confluence to the Delaware Water Gap.

increased with depth, while decreasing on the surface. This indicates continued vertical mixing, surface velocity stripping of the upper layers of the dye cloud, and, to some degree, the vortex of the eddy at this location. Tables 14 and 15 show the effect of the pool on traveltime of the dye cloud. The peak concentration exiting the pool was reduced by a ratio of about 4:1. A comparison of dye-cloud durations at the upstream and downstream end of the pool show an increase of over 50 percent in the time required for passage of the dye cloud. Figure 20 illustrates the elongation of the trailing edge of the dye cloud after passing through the pool.

Table 14. Traveltimes, areas, and centroids of the dye cloud for the Delaware River at Narrowsburg pool study, May 1, 1991

Site number	Transect location	River mile	Time since injection (hour): Leading edge	Time since injection (hour): Peak concentration	Time since injection (hour): Trailing edge	Peak concentration	Area under time concentration curve	Dye-cloud centroid: Time since injection	Dye-cloud centroid: Concentration
Injected 10.31 liters of 20 percent Rhodamine WT dye at 0626 hours on May 1, 1991, at river mile 295.33									
4	Left		2.43	2.85	4.10	14.40	8.50	3.26	3.54
	Middle		2.42	2.83	3.27	16.05	6.38	2.90	4.46
	Right	290.34	2.40	3.15	4.13	6.69	5.20	3.28	2.04
5	Middle	289.43	3.57	4.07	8.06	4.15	7.67	6.21	.88

Table 15. Dye-cloud velocities and durations for the Delaware River at Narrowsburg pool study, May 1, 1991

Location	Distance			Leading edge			Peak concentration			Trailing edge				
Site number	River miles	Between sites	From point of injection (mile)	Time since injection (hour)	Traveltime between sites (hours)	Velocity (miles per hour)	Time since injection	Traveltime between sites (hours)	Velocity (miles per hour)	Time since injection	Traveltime between sites (hours)	Velocity (miles per hour)	Reach-specific discharge, Q (ft^3/s)	Duration of dye cloud (hours)
Injected 10.50 liters of 20 percent Rhodamine WT dye at 0626 hours on May 1, 1991, at river mile 295.33														
4	290.34	4.99	4.99	2.42	2.42	2.06	2.83	2.83	1.76	3.27	3.27	1.53	2,813	0.85
5	289.43	.91	5.90	3.57	1.15	.79	4.07	1.24	.73	8.06	4.79	.19	2,825	4.49

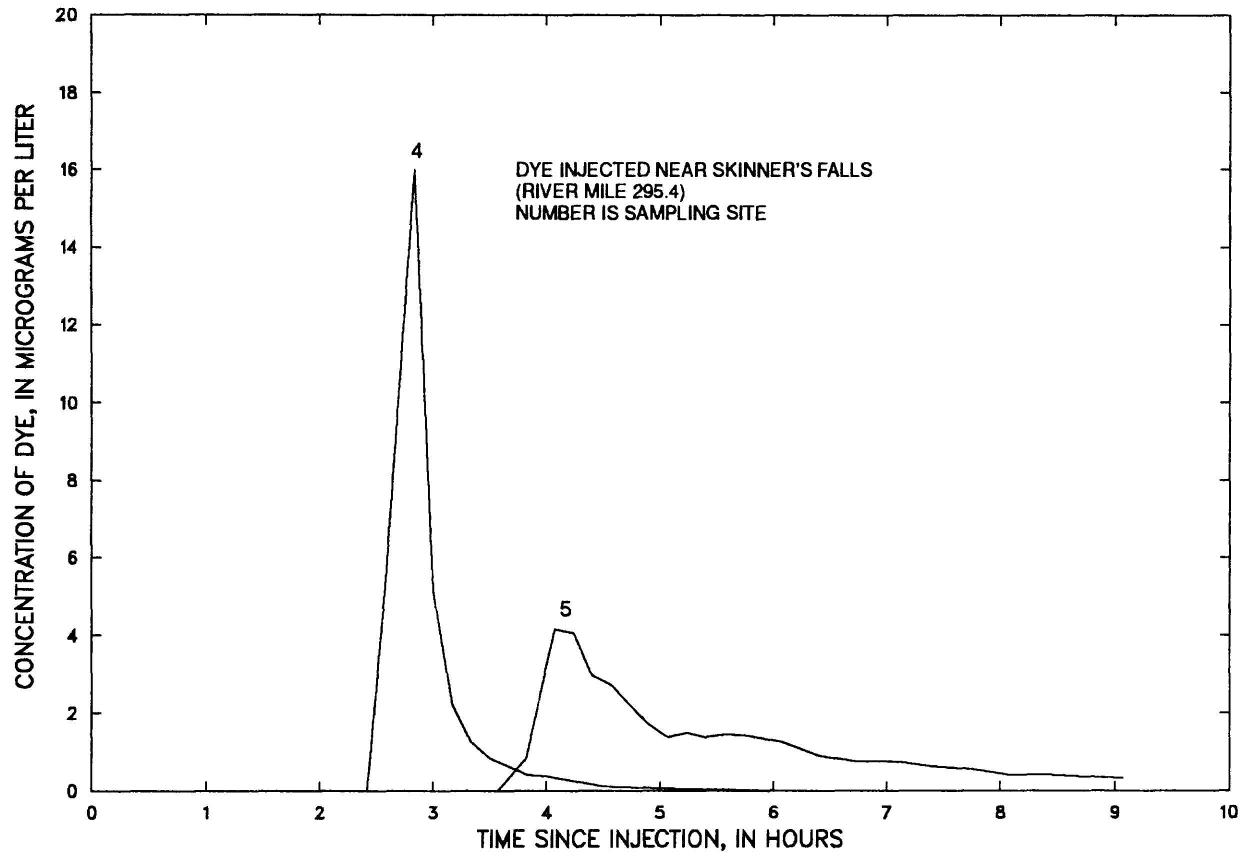


Figure 20. Time-concentration curves for the Delaware River at Narrowsburg pool, May 1, 1991.

Subsequent to the low-flow study, three stream segments were injected with dye and sampled during reservoir releases. Time-concentration curves were developed for the upstream and downstream sampling points in each segment. Preceding flows were similar to those during the low-flow study. The stream segment between Buckingham Access and Kellams Bridge was sampled following a 12-hour release from Cannonsville Reservoir. The preceding discharge at the streamflow-measurement station at Callicoon, N.Y., was 497 ft^3/s. The maximum flow discharge from Cannonsville Reservoir was 1,200 ft^3/s. The segment between Barryville and Pond Eddy was sampled after a 4-hour release from Lake Wallenpaupack. The preceding discharges at streamflow-measurement stations at Port Jervis and Montague were 1,530 and 1,670 ft^3/s, respectively. The maximum flow discharge from Lake Wallenpaupack was 1,420 ft^3/s. The segment between Port Jervis and Milford Beach was sampled following a 4-hour release from the Mongaup Reservoir System. The preceding discharges at Port Jervis and Montague were 1,500 and 1,670 ft^3/s, respectively. The maximum flow discharge from the Mongaup Reservoir System was 720 ft^3/s. Each dye injection was timed so that the surge wave passed through the dye cloud between the upstream and downstream sampling sites of each stream segment. Figures 21-23 compare the time-concentration curves developed from data collected during the low-flow and surge-wave studies at Kellam's Bridge, Pond Eddy, and Milford Beach to illustrate the effect of a sudden infusion of water on a contaminant spill. These time-concentration curves were normalized for differences in the volume of dye injected, not for the differences in stream discharge in each study. Less dye was injected for the surge-wave studies, which explains, in part, the reduced peak concentrations during the surge-wave studies. The additional volume of water is another reason for the dilution of the dye resulting in a reduced peak concentration. The most apparent effect of the surge waves on the dye clouds is the decreased traveltime from Buckingham to Kellam's Bridge and from Port Jervis to Milford Beach. The increase in flow results in an increase in the velocity of the water and the dye cloud. The surge wave did not reach Pond Eddy until after sampling had begun, which explains the similar traveltimes of the leading edge for the low-flow and surge-wave study from Barryville.

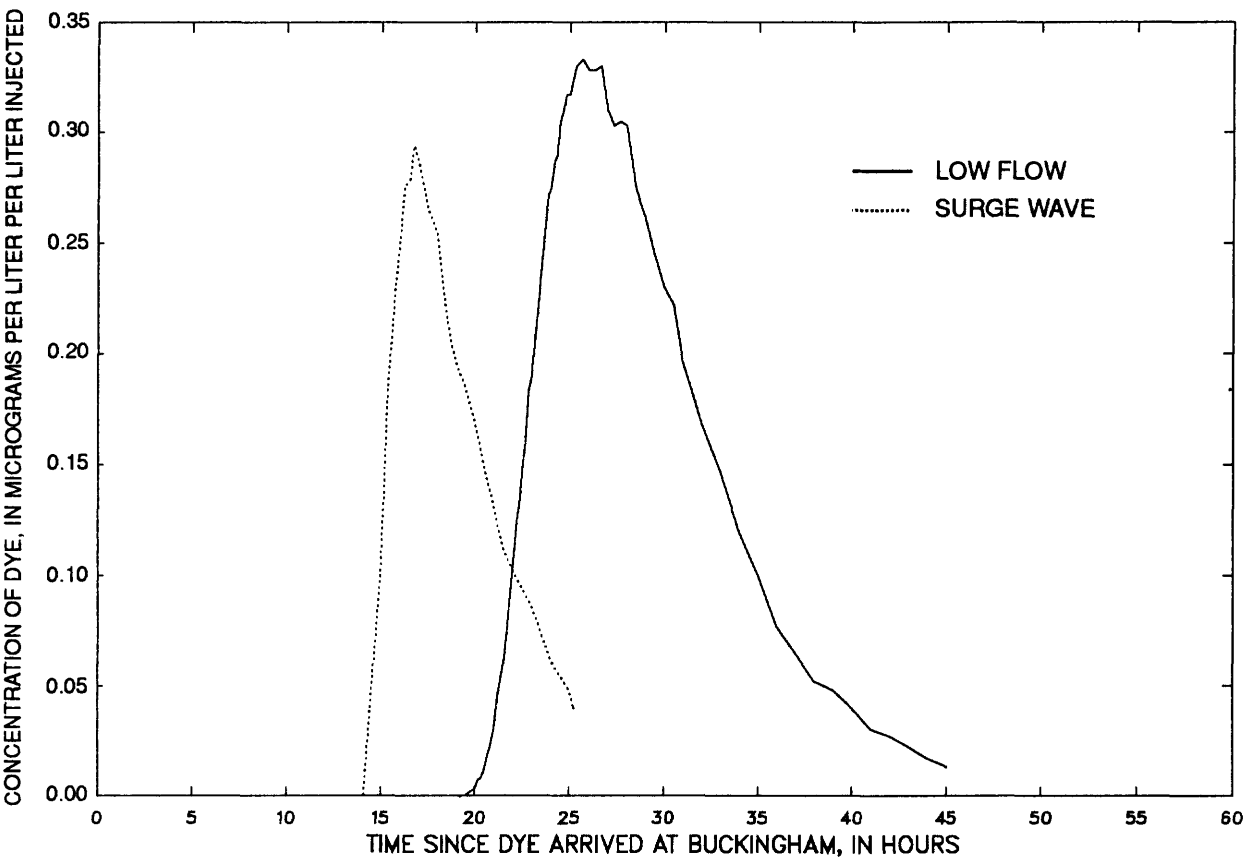


Figure 21. Time-concentration curves from Kellam's Bridge for the low-flow and surge-wave studies on the Delaware River.

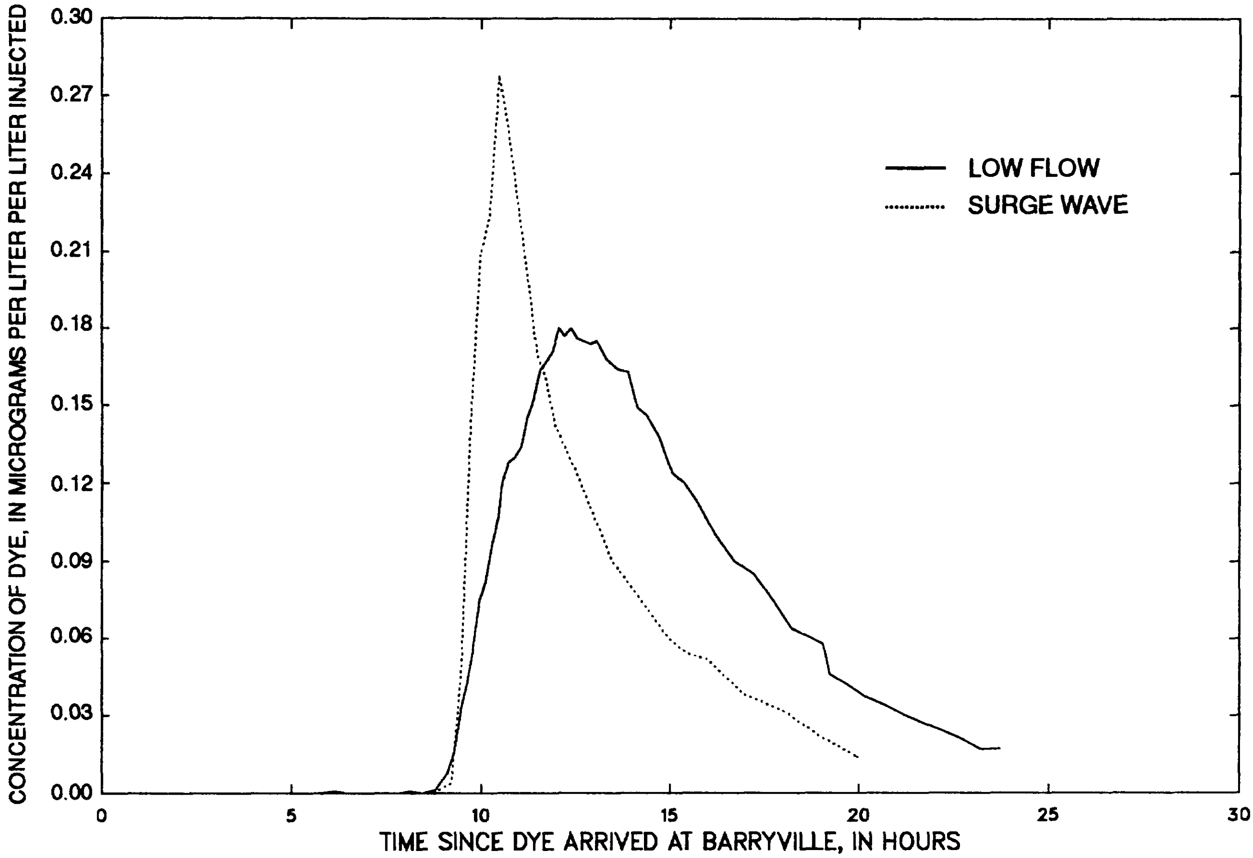


Figure 22. Time-concentration curves from Pond Eddy for the low-flow and surge-wave studies on the Delaware River.

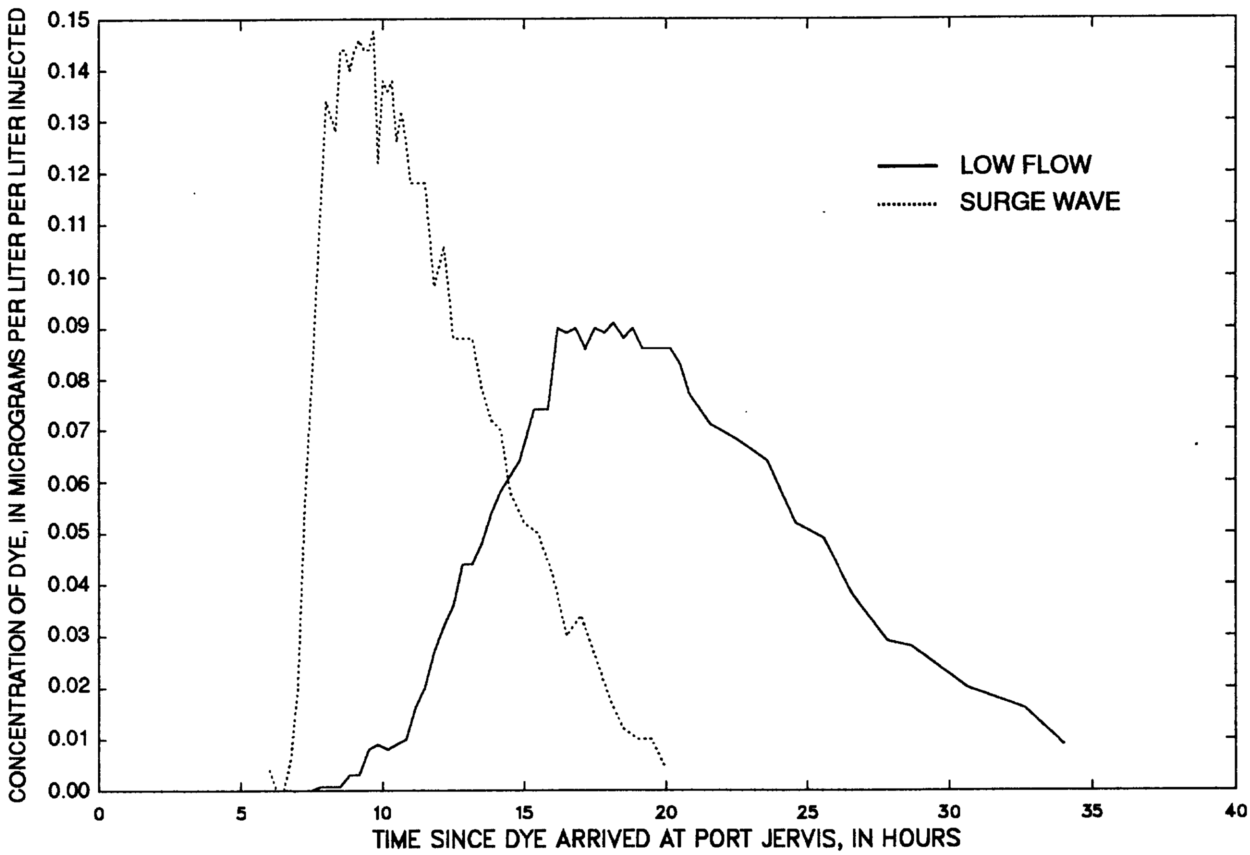


Figure 23. Time-concentration curves from Milford Beach for the low-flow and surge-wave studies on the Delaware River.

Predicted

This report can be used to calculate traveltime by: (1) Use table 1 to determine the river miles in the study reach where the spill was introduced into the river and for the downstream location of concern. (2) Use table 1 to locate the nearest USGS streamflow-measurement station. (3) Determine the discharge at the streamflow-measurement station. Each station can be accessed by phone to determine the current stream gage height. This value can then be applied to a gage height/discharge rating table, created by the USGS, which will provide the corresponding discharge. (4) Use figure 11 to determine the flow duration that most closely corresponds to the discharge at the streamflow-measurement station. (5) Use tables 8-10 or figures 16A-18B to estimate the traveltime (leading edge, peak, and trailing edge) of the spill in that stream segment. When the flow duration is between two of the values provided, interpolate between the values. (6) Use table 11 or figures 19A-19B to determine the duration of the pollutant cloud.

This procedure will provide an estimate of when a water-soluble pollutant will reach a site, when the peak concentration will occur, and when the concentration will fall below 10 percent of the peak concentration. It should be repeated for all downstream locations that will be affected by the spill.

The user of this report should be aware that an immiscable substance may behave differently than the water-soluble dye used in this study.

SUMMARY

Traveltime and dispersion studies were made in May and August of 1991 on a 120-mi reach of the Delaware River from the confluence of the East Branch Delaware River and West Branch Delaware River at Hancock, N.Y., to the Delaware Water Gap. This section of the river, most of which is National Park and designated a Scenic and Recreational River, is used extensively for recreation. Introduction of a soluble contaminant could severely effect the water quality. Information on traveltime of water soluble substances is essential for resource managers and health agencies to make informed decisions on a proper response to a spill.

Dye was injected at six locations along the river when discharges were at the 85- to 95-percent and 25- to 30-percent flow durations. Time-concentration curves were developed from data collected at 15 sampling locations. These curves were used to determine traveltime of the dye cloud between adjacent sampling points and to determine cumulative traveltimes for the entire reach at 10 flow durations. The data indicate that a spill at Buckingham Access (river mile 325.1) would reach the Delaware Water Gap in about 70 hours when flow was at the 30-percent flow duration. The peak concentration can be expected about 85 hours after the spill occurred at Buckingham Access. Solute concentration would decrease to 10 percent of the peak concentration about 120 hours after introduction of the spill.

The Narrowsburg pool and eddy dramatically affect the movement of dye in that section of the river. Prolonged vertical mixing, caused by depths which exceed 100 ft, increases the duration of the dye cloud. A comparison of dye cloud durations at the upstream and downstream end of the pool show an increase of over 50 percent in the time required for passage of the dye cloud at the downstream site.

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