Traveltime and Dispersion in the Potomac River, Cumberland, Maryland, to Washington, D.C.

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Prepared in cooperation with the District of Columbia Department of Environmental Services, Fairfax County Water Authority, Interstate Commission on the Potomac River Basin, Maryland Department of Natural Resources, and the Washington Suburban Sanitary Commission

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CONTENTS

Abstract 1
Introduction 1
Description of the study reach 3
Field procedures 3
Data analysis 5
  Traveltimes 5
  Dispersion 9
Use of data 21
Discussion 27
Summary 28
Selected references 28
Conversion of measurement units 30

FIGURES

1. Map showing location of study reach 2

2, 3. Graphs showing observed time-concentration curves for 1981 study for
  2. Cumberland-to-Hancock subreach 8
  3. Hancock-to-Williamsport subreach 8

4. Graph showing relation between flow duration and mean-daily discharge at Potomac River gaging stations 9
5. Example of typical computation of velocities for 5-percent increments of flow duration 10

6–8. Graphs showing traveltime-distance relation of dye cloud at selected flow durations for
  6. Leading edge 13
  7. Peak concentration 14
  8. Trailing edge 15

9. Graph showing relation between unit peak concentration and traveltime of peak concentration for dye studies on the Potomac River 18
10. Definition sketch of relation between time-concentration curve and scalene triangle 19
11. Graph showing relation between true area of time-concentration curve and area computed by triangle approach 20
12. Graph showing relation among dye-cloud duration, flow duration, and distance for dispersion studies on the Potomac River 22
13. Graph showing relation between unit peak concentrations and traveltimes of the peak concentrations at the 50-, 70-, and 90-percent flow durations for a spill at Cumberland, Maryland 23
14. Graph showing relation between drainage areas at index gages and drainage areas upstream and downstream from index gages 24

TABLES

1. River mileage for selected tributaries, bridge crossings, and other identifiable landmarks 4
2. Traveltime, dispersion, and related data for dye study of May 1964 6
3. Traveltime, dispersion, and related data for dye study of September and October 1981 7
4. Traveltimes for leading edge of dye cloud at selected flow durations 11
5. Traveltimes for peak concentration of dye cloud at selected flow durations 11
6. Traveltimes for trailing edge of dye cloud at selected flow durations 12
7. Duration of dye cloud at selected flow durations 21

Traveltime and Dispersion in the Potomac River, Cumberland, Maryland, to Washington, D.C.

By K. R. Taylor, R. W. James, Jr., *and* B. M. Helinsky

Abstract

A traveltime and dispersion study using rhodamine dye was conducted on the Potomac River between Cumberland, Maryland, and Washington, D.C., a distance of 189 miles. The flow during the study was at approximately the 90-percent flow-duration level. A similar study was conducted by Wilson and Forrest in 1964 at a flow duration of approximately 60 percent.

The two sets of data were used to develop a generalized procedure for predicting traveltimes and downstream concentrations resulting from spillage of water-soluble substances at any point along the river. The procedure will allow the user to calculate traveltime and concentration data for almost any spillage problem that occurs during periods of relatively steady flow between 50- and 95-percent flow duration.

A new procedure for calculating unit peak concentration was derived. The new procedure depends on an analogy between a time-concentration curve and a scalene triangle. As a result of this analogy, the unit peak concentration can be expressed in terms of the length of the dye or contaminant cloud. The new procedure facilitates the calculation of unit peak concentration for long reaches of river. Previously, there was no way to link unit peak concentration curves for studies in which the river was divided into subreaches for study. Variable dispersive characteristics caused mainly by low-head dams precluded useful extrapolation of the unit peak-concentration attenuation curves, as has been done in previous studies.

The procedure is applied to a hypothetical situation in which 20,000 pounds of contaminant is spilled at a railroad crossing at Magnolia, West Virginia. The times required for the leading edge, the peak concentration, and the trailing edge of the contaminant cloud to reach Point of Rocks, Maryland (110 river miles downstream), are 295, 375, and 540 hours respectively, during a period when flow is at the 80-percent flow-duration level. The peak conservative concentration would be approximately 340 micrograms per liter at Point of Rocks.

INTRODUCTION

The purposes of this report are to describe the movement of a soluble material in the Potomac River from Cumberland, Md., to Washington, D.C. (fig. 1), and to present techniques for predicting traveltimes and concentration attenuation at downstream locations resulting from the spillage of any amount of soluble contaminant at any point along the river.

In May 1964, the U.S. Geological Survey made a time-of-travel and dispersion study of the Potomac River between Cumberland and Washington using rhodamine dye as a tracer (Wilson and Forrest, 1965). The average daily flow during the 5-day study period was about 3,900 ft^3/s at Point of Rocks, Md., which is a flow exceeded approximately 60 percent of the time (60-percent flow duration). This single study of time of travel and dispersion is useful in predicting the behavior of other soluble substances introduced into the river. The usefulness of this initial study, however, is dependent on the flow of the river being reasonably close to the flow existing at that time.

A tanker truck accidentally spilled a toxic substance (aniline) into the Potomac River upstream from Shepherdstown, W. Va., in June 1981. This accident called attention to the need for additional time-of-travel and dispersion data on the Potomac River. Owing to the small quantity and volatile nature of the aniline, the spill did not constitute a real hazard to downstream water users. The concern, however, provided the impetus for additional work, so that in the event of a real threat, there would be sufficient information to respond effectively to the situation.

Developing a generalized method for predicting traveltime and concentrations of a soluble substance requires a minimum of two studies. The objectives of this study were to collect traveltime and dispersion data for a flow rate substantially different from that during the 1964 study, and to interpolate and extrapolate the information from the two studies to provide a general method for the Potomac River that would enable water-supply managers and water-regulatory agencies to make necessary calculations in case of a spill of a toxic, soluble substance in the river. The method was to be sufficiently general to permit predictions of traveltime and concentration at any location resulting from a spill at any upstream point over a wide range of flow conditions.

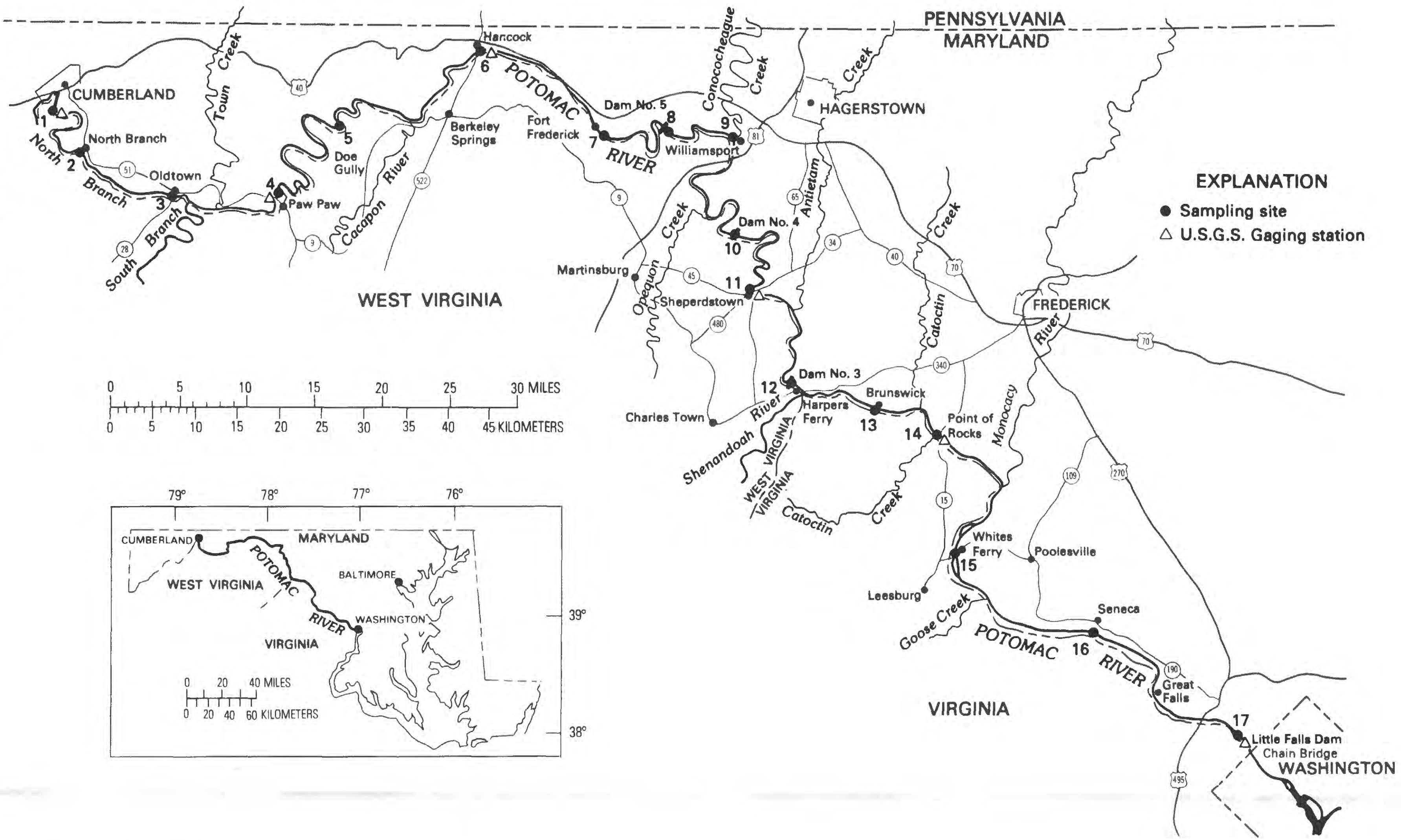

Figure 1. Location of study reach.

The kinds of predictions needed are as follows:

1. The time of arrival of the leading edge of the contaminant,
2. The time of arrival of the peak concentration of the contaminant,
3. The time required for the contaminant cloud to pass a point of interest, and
4. The magnitude of the peak concentration of a conservative contaminant.

A consortium of regulatory and water-supply agencies provided funding for the study through the CO-OP Section, Interstate Commission on the Potomac River Basin. The U.S. Geological Survey provided matching funds for the work.

Special acknowledgment is given to the U.S. Geological Survey field personnel who spent many hours, around the clock, collecting the data used in preparing this report.

DESCRIPTION OF THE STUDY REACH

The Potomac River (fig. 1) is formed by the confluence of the North and South Branches, 21 mi downstream from Cumberland, Md. From this point, the river flows for 287 mi, generally southeasterly, to Chesapeake Bay (Searcy and Davis, 1961, p. 1). The reach selected for this study is between Cumberland and Washington, D.C., the same as that used by Wilson and Forrest in 1964. The 189-mi study reach includes the 21-mi section of the North Branch between Cumberland and the confluence with the South Branch.

In general, the Potomac River is free flowing in the study reach, impeded only by several low-head dams. These dams store little water and, except for Dams No. 4 and No. 5 (fig. 1), have little impact on the movement of water. Dams No. 4 and No. 5 store relatively larger amounts of water and significantly impede the movement of water, particularly during periods of low flow.

The average slope of the study reach is about 3 ft/mi. Between Cumberland and Paw Paw, W. Va., the slope averages about 3.5 ft/mi. The average slope decreases to about 1.9 ft/mi between Hancock, Md., and Shepherdstown, W. Va., and then increases to an average of more than 3.5 ft/mi between Point of Rocks, Md., and Little Falls Dam. Most of the fall in the latter reach occurs in a series of rapids and falls in the last few miles above Little Falls Dam.

For this report, all stream mileages are referenced to Chain Bridge near Washington, D.C. The stream mileage for selected tributary streams, bridge crossings, and other identifiable landmarks is given in table 1.

Six continuous-record gaging stations are operated by the U.S. Geological Survey in the study reach. Because the rate of movement of water is directly related to the magnitude of discharge in the river, discharge information is necessary for both the development of and the subsequent use of the procedures in this report. Discharge information is available for the following gaging stations:

Station No.	Station name	Miles above Chain Bridge	Average slope in reach (ft/ft)	Drainage area (mi²)
01603000	N. Br. Potomac R. near Cumberland, Md.	188.7	-	875
01610000	Potomac River at Paw Paw, W. Va.	160.6	0.0007	3,109
01613000	Potomac River at Hancock, Md.	122.7	.0005	4,073
01618000	Potomac River at Shepherdstown, W.Va.	67.7	.0004	5,936
01638500	Potomac River at Point of Rocks, Md.	43.6	.0006	9,651
01646500	Potomac River near Washington, D.C.	1.2	.0007	11,560

FIELD PROCEDURES

Field procedures for conducting traveltime and dispersion studies on streams using dye tracers are well documented (see Hubbard and others, 1982). In general, the described procedures were followed closely in this study.

Wilson and Forrest, in the 1964 study, divided the total study reach into six subreaches. They injected dye at the head of all the subreaches during a 4-hour period on May 25, 1964. After about 5½ days of sampling at successive downstream locations, the dye had passed the farthest downstream sampling site in each subreach. Owing to the experimental nature of their study, they continued selective sampling of the dye clouds as they moved through successive downstream subreaches. Field operations for the 1964 study are described by Wilson and Forrest (1965, p. 5, 6). The following is a list of the subreaches used in the 1964 study:

Subreach	Length (mi)
1. Cumberland to Paw Paw	28.1
2. Paw Paw to Hancock	37.9
3. Hancock to Williamsport	27.8
4. Williamsport to Shepherdstown	27.1
5. Shepherdstown to Point of Rocks	24.1
6. Point of Rocks to Washington (Chain Bridge)	43.6

In the present study, conducted in 1981, the first and second subreaches were combined into a single subreach. Sampling sites were chosen to coincide with those used in the 1964 study, except that the farthest downstream sampling site was Little Falls Dam rather than Chain Bridge. For each subreach, the dye was injected simultaneously at several points in the cross section of the river. Multiple-point injection greatly reduces the time and distance required for complete lateral and vertical

Table 1. River mileage for selected tributaries, bridge crossings, and other identifiable landmarks

River mile (rounded)	Landmark[1]
189	Wiley Ford Bridge near Cumberland, Md. (USGS gage)
180	C & O Railroad Bridge at North Branch, Md.
178	Mouth Patterson Creek (right bank)
171	Bridge at Oldtown, Md.
169	Confluence South Branch (right bank)
167	Mouth Town Creek (left bank)
165	Mouth L. Cacapon River (right bank)
161	Paw Paw, W. Va. (USGS gage)
154	C & O Railroad Bridge, Magnolia, W. Va.
141	Doe Gully, W. Va.
134	Mouth Sideling Hill Creek (left bank)
132	Mouth Cacapon River (right bank)
123	U.S. Highway 522 at Hancock, Md. (USGS gage 1/2 mi downstream)
117	Mouth Sleepy Creek (right bank)
115	Mouth Licking Creek (left bank)
111	Fort Frederick State Park
102	Dam No. 5
95	Mouth Conococheague Creek (left bank)
95	U.S. Highway 11, Williamsport, Md.
86	Mouth Opequon Creek (right bank)
79	Dam No. 4
68	Bridge at Shepherdstown, W. Va. (USGS gage)
64	Mouth Antietam Creek (left bank)
57	Dam No. 3
56	Mouth Shenandoah River (right bank)
55	U.S. Highway 340, Harpers Ferry, W. Va.
50	Bridge at Brunswick, Md.
44	U.S. Highway 15, at Point of Rocks, Md. (USGS gage)
38	Mouth Monocacy River (left bank)
31	Whites Ferry
26	Mouth Goose Creek (right bank)
18	Mouth Seneca Creek (left bank)
10	Great Falls, Md.
1	Little Falls Dam near Washington, D.C. (USGS gage)
0	Chain Bridge

[1] All landmarks can be found on 1:24,000 (7½ min.) USGS topographic maps.

mixing. In contrast to the 1964 study, the dye was injected upstream from the head of each subreach. This upstream injection allowed time for lateral and vertical mixing prior to the sampling and definition of the dye cloud at the head of each subreach.

Dye was injected upstream from Shepherdstown and Point of Rocks on September 26, 1981. The dye clouds took approximately 5 and 8 days, respectively, to pass through the subreaches. Dye was injected upstream from Cumberland, Hancock, and Williamsport on October 10, 1981. The trailing edges of the dye clouds took approximately 8, 10, and 13 days, respectively, to travel through the subreaches. Storage behind Dam No. 5 reduced the average velocity of the peak concentration to 0.1 mi/h between sampling sites at Fort Frederick and at Dam No. 5.

Flow at the Point of Rocks gaging station, during the 1981 study of the two downstream subreaches, ranged from 1,750 ft^3/s on September 26 to 1,420 ft^3/s on October 3. The average flow during this period was 1,525 ft^3/s, which is a flow duration of 91 percent. Flow at the Hancock gaging station, during the 1981 study of the upstream subreaches, ranged from 575 ft^3/s on October 10 to 491 ft^3/s on October 20. The average flow was 535 ft^3/s, which is a flow duration of about 88 percent.

The dye cloud for each subreach was sampled at a minimum of three cross sections, including the cross section at the head of each subreach. The Cumberland-to-Hancock subreach was sampled at six cross sections. The Williamsport-to-Shepherdstown subreach was sampled at three cross sections, and the other three subreaches were each sampled at four cross sections. At each cross section, samples were collected at one point. The point was visually selected to be representative of the main mass of flow.

The frequency of sampling was varied on the basis of the time since injection of the dye and the appearance of the time-concentration curve at the previous sampling site upstream. In general, sampling was continued at each sampling site until the concentration reached a level of about 10 percent of the peak concentration. Below about 10 percent, the tail of the dye cloud becomes almost asymptotic to the zero-concentration line. Excellent definitions of the time-concentration curves were obtained for each sampling site during the 1981 study. Tables 2 and 3 give the sampling sites, traveltimes, and other pertinent data from the 1964 and 1981 studies, respectively.

DATA ANALYSIS

Traveltimes

All samples collected in the field were analyzed on the fluorometer in the office under controlled temperature conditions. The fluorometer was calibrated from standard solutions prepared from the same dye lot used in the study.

The dye concentrations were plotted versus the time since injection of the dye for each sampling site. The time-concentration curves shown in figure 2 are for the subreach between Cumberland and Hancock, which is a relatively free-flowing section of the river. Figure 3 shows the time-concentration curves for a subreach that is obstructed by one of the low-head dams (Dam No. 5). Note that there are two time-concentration curves for site 6: (1) as the last sampling site in the Cumberland-to-Hancock subreach (fig. 2), and (2) as the first sampling site in the Hancock-to-Williamsport subreach (fig. 3).

The traveltimes of the leading edge, the peak concentration, and the trailing edge of the dye cloud were determined from the time-concentration curve for each sampling site. The traveltime of the trailing edge of the dye cloud is defined in this report as the time between injection and the time the concentration reaches a level of 10 percent of the peak concentration observed at a sampling site.

Time of travel varies inversely with discharge in a stream. To develop a method of predicting traveltimes that can be used over a range of discharges, it is necessary to relate the time of travel in some way to stream discharge. Over a long reach of river, stream discharge generally increases in the downstream direction as the area drained increases. These increases, however, do not occur uniformly with distance along the river. At the points where tributaries enter the river, stream discharge increases abruptly. Depending on the drainage area of the tributary, these increases can be substantial. Usually, however, the river channel has adjusted to these increases in flow, and an increase in velocity commensurate with the increase in flow does not occur. For this reason, absolute discharge in the river is not an ideal parameter for the relationship between traveltime and discharge.

Flow duration is an index of river discharge that is fairly constant throughout a reach of stream, provided there is no flood wave moving through the system. This characteristic makes flow duration a useful index of stream discharge for use in developing a relationship with time of travel. Flow duration, expressed in percent, is defined as the percentage of time the historic mean-daily discharges exceeded a specified discharge. The relations between flow duration and mean-daily discharge for five gaging stations on the Potomac River are shown in figure 4.

Traveltimes for the movement of the dye cloud between sampling sites were obtained from the time-concentration curves for each sampling point. Typical curves are given in figures 2 and 3, and all traveltime data are summarized in tables 2 and 3.

The velocities at which the leading edge, the peak concentration, and the trailing edge of the dye cloud moved between successive sampling sites were calculated by dividing the reach length by the traveltimes. These velocities for the two studies were plotted versus the average of the daily discharges observed at each of two index gaging stations during the time the dye cloud moved between the two sampling sites. Straight lines were drawn through the points derived from the two studies to represent the leading edge, peak concentration, and trailing edge. These plots were done independently for the discharges at the two gaging stations. The relations described above were entered with discharges corresponding to flow-duration values selected at 5-percent intervals between 50 percent and 95 percent for each of the two gaging stations. The resulting velocities for each 5-percent increment of flow duration were averaged for the two index gaging stations for the leading

Table 2. Traveltime, dispersion, and related data for dye study of May 1964

Site No.	Site name	Distance: Upstream from Chain Bridge (mi)	Distance: Sub-reach length (mi)	Distance: From point of injection (mi)	Leading edge (LE): Time since injection (h)	Leading edge (LE): Travel-time (h)	Leading edge (LE): Cumulative travel-time (h)	Leading edge (LE): Velocity (mi/h)	Peak concentration (C_p): Time since injection (h)	Peak concentration (C_p): Travel-time (h)	Peak concentration (C_p): Cumulative travel-time (h)	Peak concentration (C_p): Velocity (mi/h)	Trailing edge (TE) at 0.1 C_p: Time since injection (h)	Trailing edge (TE) at 0.1 C_p: Travel-time (h)	Trailing edge (TE) at 0.1 C_p: Cumulative travel-time (h)	Trailing edge (TE) at 0.1 C_p: Velocity (mi/h)	Discharge at sampling site, Q (ft^3/s)	Observed peak concentration, C_p (µg/L)	Calculated dye recovery, R_p (percent)[1]	Unit peak concentration, C_{up}[2]	Duration of dye cloud (h)
Injected 45.4 liters of 30-percent rhodamine BA dye at mile 188.7 at 1540 on May 25, 1964																					
1	Cumberland	188.7																			
2	North Branch	180.0	8.7	8.7	[3]15.0	15.0	15.0	0.580	19.0	19.0	19.0	0.458	26.0	26.0	26.0	0.335	410	58	92	835	11.0
3	Oldtown	171.3	8.7	17.4	28.0	13.0	28.0	.669	33.0	14.0	33.0	.621	43.5	17.5	43.5	.497	585	33	108	575	15.5
4	Paw Paw	160.6	10.7	28.1	43.5	15.5	43.5	.690	50.5	17.5	50.5	.611	[3]64.0	20.5	64.0	.522	870	12	80	410	20.5
5	Doe Gully	140.8	19.8	47.9	70.0	26.5	70.0	.747	80.5	30.0	80.5	.660	[3]96	32.0	96	.619	860	7.5	58	360	26.0
6	Hancock	122.7	18.1	66.0	92.5	22.5	92.5	.804	106	25.5	106	.710	[3]129	33.0	129	.548	990	4.2	54	250	36.5
Injected 68.1 liters of 30-percent rhodamine BA dye at mile 160.6 at 1405 on May 25, 1964																					
4	Paw Paw	160.6																			
5	Doe Gully	140.8	19.8	19.8	22.0	22.0	22.0	0.900	25.0	25.0	25.0	0.792	32.0	32.0	32.0	0.619	1,010	52	109	1,010	10.0
6	Hancock	122.7	18.1	37.9	44.5	22.5	44.5	804	48.5	23.5	48.5	.770	63.5	31.5	63.5	.575	1,200	14	68	545	19.0
7	Fort Frederick	111.2	11.5	49.4	58.5	14.0	58.5	.821	64.0	15.5	64.0	.742	-	-	-	-	1,280	11	72	405	-
Injected 64.4 liters of 30-percent rhodamine BA dye at mile 122.7 at 1305 on May 25, 1964																					
7	Fort Frederick	111.2	11.5	11.5	12.0	12.0	12.0	0.958	14.0	14.0	14.0	0.821	15.5	15.5	15.5	0.742	1,530	96	131	2,540	3.5
8	Dam No. 5	101.5	9.7	21.2	48.0	36.0	48.0	.269	64.0	50.0	64.0	.194	100	84.5	100	.115	1,200	5.7	77	205	52.0
9	Williamsport	94.9	6.6	27.8	61.0	13.0	61.0	.508	79.0	15.0	79.0	.440	120	20.0	120	.330	1,500	4.5	99	155	59.0
Injected 132 liters of 30-percent rhodamine BA dye at mile 94.9 at 1540 on May 25, 1964																					
10	Dam No. 4	79.4	15.5	15.5	44.0	44.0	44.0	0.352	48.0	48.0	48.0	0.323	91.0	91.0	91.0	0.170	1,840	8.7	91	195	47.0
11	Shepherdstown	67.7	11.7	27.2	[3]58	14.0	58.0	.836	65.0	17.0	65.0	.688	106	15.0	106	.780	1,740	7.2	73	190	48.0
Injected 87.1 liters of 30-percent rhodamine BA dye at mile 67.7 at 1440 on May 25, 1964																					
12	Dam No. 3	57.2	10.5	10.5	28.5	28.5	28.5	0.368	32.0	32.0	32.0	0.328	39.0	39.0	39.0	0.269	2,270	24	90	1,010	10.5
13	Brunswick	49.9	7.3	17.8	[3]36.5	8.0	36.5	.912	40.5	8.5	40.5	.859	50.5	11.5	50.5	.635	3,670	16	131	760	14.0
14	Point of Rocks	43.6	6.3	24.1	44.0	7.5	44.0	.840	48.5	8.0	48.5	.788	60.5	10.0	60.5	.630	3,790	9.3	99	600	16.5
15	Whites Ferry	31.2	12.4	36.5	59.0	15.0	59.0	.827	63.0	14.5	63.0	.855	77.5	17.0	77.5	.729	3,960	3.6	52	465	18.5
Injected 288 liters of 30-percent rhodamine BA dye at mile 43.6 at 1205 on May 25, 1964																					
15	Whites Ferry	31.2	12.4	12.4	12.5	12.5	12.5	0.992	14.0	14.0	14.0	0.886	15.5	15.5	15.5	0.800	4,680	28	19	3,530	3.0
16	Seneca	18.0	13.2	25.6	[3]31	18.5	31	.714	[3]34.0	20.0	34.0	.660	[3]37.0	21.5	37.0	.614	4,520	36	46	1,810	6.0
17	Little Falls Dam	1.2	16.8	42.4	[3]61	30	61	.560	[3]68	34	68	.494	[3]84	47	84	.357	4,530	-	-	-	23.0

[1] Values greater than 100 percent or increasing dye recovery in the downstream direction are indicative of incomplete mixing or inadequate definition of the discharge-weighted time-concentration curve.

[2] $C_{up} = 4,440 \frac{C_{p(obs)}}{A_{t-c(obs)}}$ in micrograms per liter per pound per cubic foot per second.

$A_{t-c(obs)}$ is the area under the observed time-concentration curve.

[3] Estimated.

Table 3. Traveltime, dispersion, and related data for dye study of September and October 1981

Site No.	Site name	Distance: Upstream from Chain Bridge (mi)	Distance: Sub-reach length (mi)	Distance: From point of injection (mi)	Leading edge (LE): Time since injection (h)	Leading edge (LE): Travel-time (h)	Leading edge (LE): Cumu-lative travel-time (h)	Leading edge (LE): Velocity (mi/h)	Peak concentration (C_p): Time since injection (h)	Peak concentration (C_p): Travel-time (h)	Peak concentration (C_p): Cumu-lative travel-time (h)	Peak concentration (C_p): Velocity (mi/h)	Trailing edge (TE) at 0.1 C_p: Time since injection (h)	Trailing edge (TE) at 0.1 C_p: Travel-time (h)	Trailing edge (TE) at 0.1 C_p: Cumu-lative travel-time (h)	Trailing edge (TE) at 0.1 C_p: Velocity (mi/h)	Discharge at sampling site, Q (ft^3/s)	Observed peak concen-tration, C_p (µg/L)	Calculated dye recovery, R_p (percent)[1]	Unit peak concen-tration, C_{up} [2]	Duration of dye cloud (h)
Injected 24.8 liters of 20-percent rhodamine WT dye at mile 190.9 at 1135 on Oct. 10, 1981																					
1	Cumberland	188.7	2.2	2.2	4.0		0		4.8		0		6.3		0		245	223	93	4,580	2.3
2	North Branch	180.0	8.7	10.9	25.0	21.0	21.0	0.414	31.5	26.7	26.7	0.326	43.0	36.7	36.7	0.237	255	20	76	516	18.0
3	Oldtown	171.3	8.7	19.6	41.0	16.0	37.0	.544	50.5	19.0	45.7	.458	67.0	24.0	60.7	.362	280	14	81	367	26.0
4	Paw Paw	160.6	10.7	30.3	63.0	22.0	59.0	.486	74.5	24.0	69.7	.446	93.5	26.5	87.2	.404	460	6.8	79	302	30.5
5	Doe Gully	140.8	19.8	50.1	104	41.0	100	.483	119	44.5	114	.445	148	54.5	142	.363	430	4.7	74	209	44.0
6	Hancock	122.7	18.1	68.2	138	34.0	134	.532	158	39.0	153	.464	195	47.0	189	.385	525	3.4	77	177	57.0
Injected 15.2 liters of 20-percent rhodamine WT dye at mile 126.8 at 1230 on Oct. 10, 1981																					
6	Hancock	122.7	4.1	4.1	7.5		0		9.0		0		12.0		0		570	36	115	2,220	4.5
7	Fort Frederick	111.2	11.5	15.6	30.0	22.5	22.5	0.511	33.5	24.5	24.5	0.469	44.5	32.5	32.5	0.354	610	8.0	91	668	14.5
8	Dam No. 5	101.5	9.7	25.3	104	74.0	96.5	.131	135	101	126	.096	218	174	206	.056	550	1.2	103	80	114
9	Williamsport	94.9	6.6	31.9	130	26.0	122	.254	166	31.0	157	.213	259	41.0	247	.161	620	0.9	102	70	129
Injected 30.3 liters of 20-percent rhodamine WT dye at mile 100.9 at 1700 on Oct. 10, 1981																					
9	Williamsport	94.9	6.0	6.0	21.5		0		24.0		0		29.5		0		690	32	108	1,300	8.0
10	Dam No. 4	79.4	15.5	21.5	120	98.5	98.5	0.157	167	143	143	0.108	[3]261	232	232	0.067	690	1.3	84	67	141
11	Shepherdstown	67.7	11.7	33.2	150	30	128	.390	203	36	179	.325	[3]304	43	275	.272	710	1.1	82	60	154
Injected 50.0 liters of 20-percent rhodamine WT dye at mile 72.2 at 1150 on Sept. 26, 1981																					
11	Shepherdstown	67.7	4.5	4.5	12.5		0		14.5		0		21.0		0		1,120	31	99	1,350	8.5
12	Dam No. 3	57.2	10.5	15.0	59.0	46.5	46.5	0.226	66.5	52.0	52.0	0.202	89.0	68.0	68.0	0.154	1,140	7.3	100	318	30.0
13	Brunswick	49.9	7.3	22.3	70.0	11.0	57.5	.664	79.0	12.5	64.5	.584	103	14.0	82.0	.521	1,440	6.0	114	287	33.0
14	Point of Rocks	43.6	6.3	28.6	79.0	9.0	66.5	.700	90.5	11.5	76.0	.548	114.5	11.5	93.5	.548	1,420	5.4	110	266	35.5
Injected 67.6 liters of 20-percent rhodamine WT dye at mile 49.0 at 1630 on Sept. 26, 1981																					
14	Point of Rocks	43.6	5.4	5.4	8.0		0		9.5		0		11.0		0		1,680	50	74	3,180	3.0
15	Whites Ferry	31.2	12.4	17.8	29.0	21.0	21.0	0.590	31.5	22.0	22.0	0.564	35.5	24.5	24.5	0.506	1,800	30	102	1,490	6.5
16	Seneca	18.0	13.2	31.0	63.0	34.0	55.0	.388	67.0	35.5	57.5	.372	76.0	40.5	65.0	.326	1,770	14	85	823	13.0
17	Little Falls Dam	1.2	16.8	47.8	130	67.0	122	.251	144	77.0	134	.218	[3]184	108	173	.156	[4]1,800	1.9	60	159	54.0

[1] Values greater than 100 percent or increasing dye recovery in the downstream direction are indicative of incomplete mixing or inadequate definition of the discharge-weighted time-concentration curve.

[2] $C_{up} = 4{,}440 \frac{C_{p(obs)}}{A_{t-c(obs)}}$, in micrograms per liter per pound per cubic foot per second.

$A_{t-c(obs)}$ is the area under the observed time-concentration curve.

[3] Estimated.

[4] Adjusted for diversions.

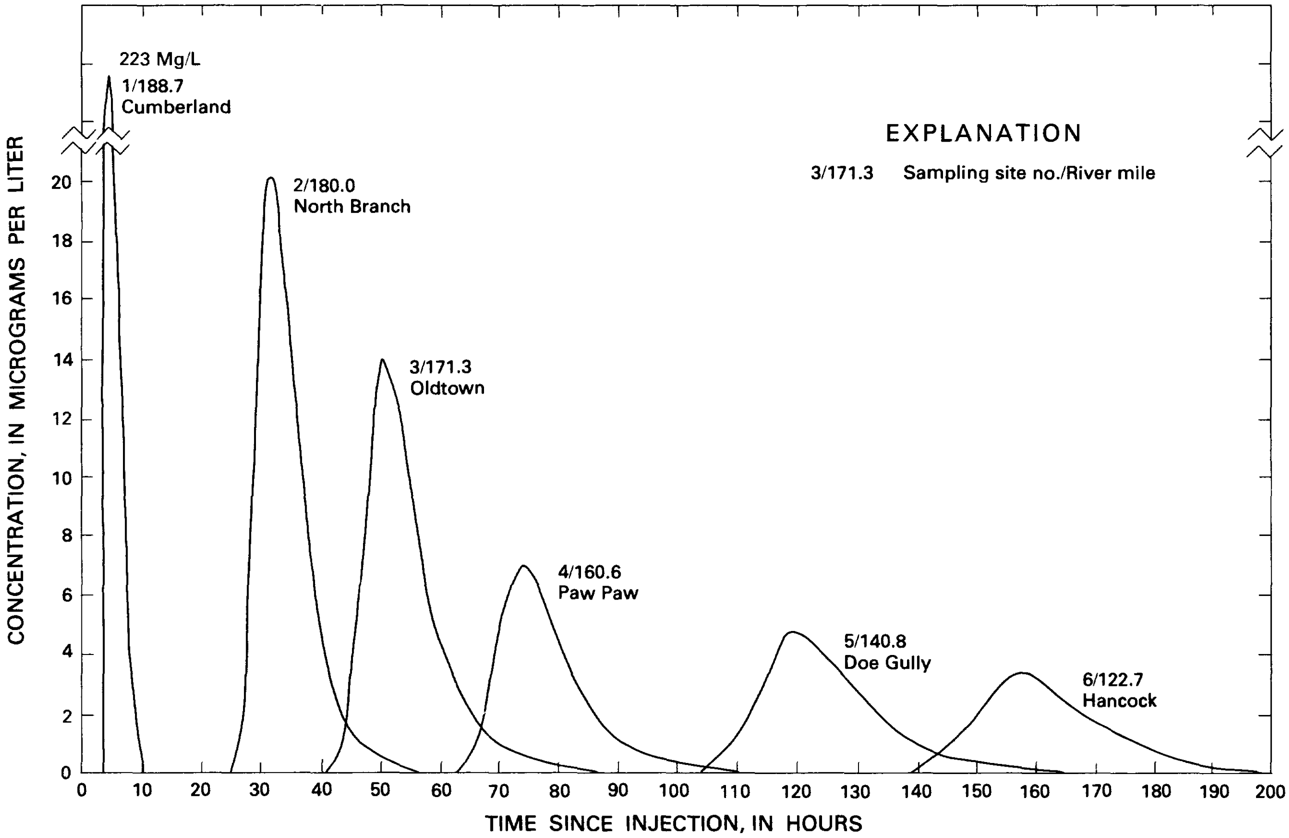

Figure 2. Observed time-concentration curves for Cumberland-to-Hancock subreach, October 1981 study.

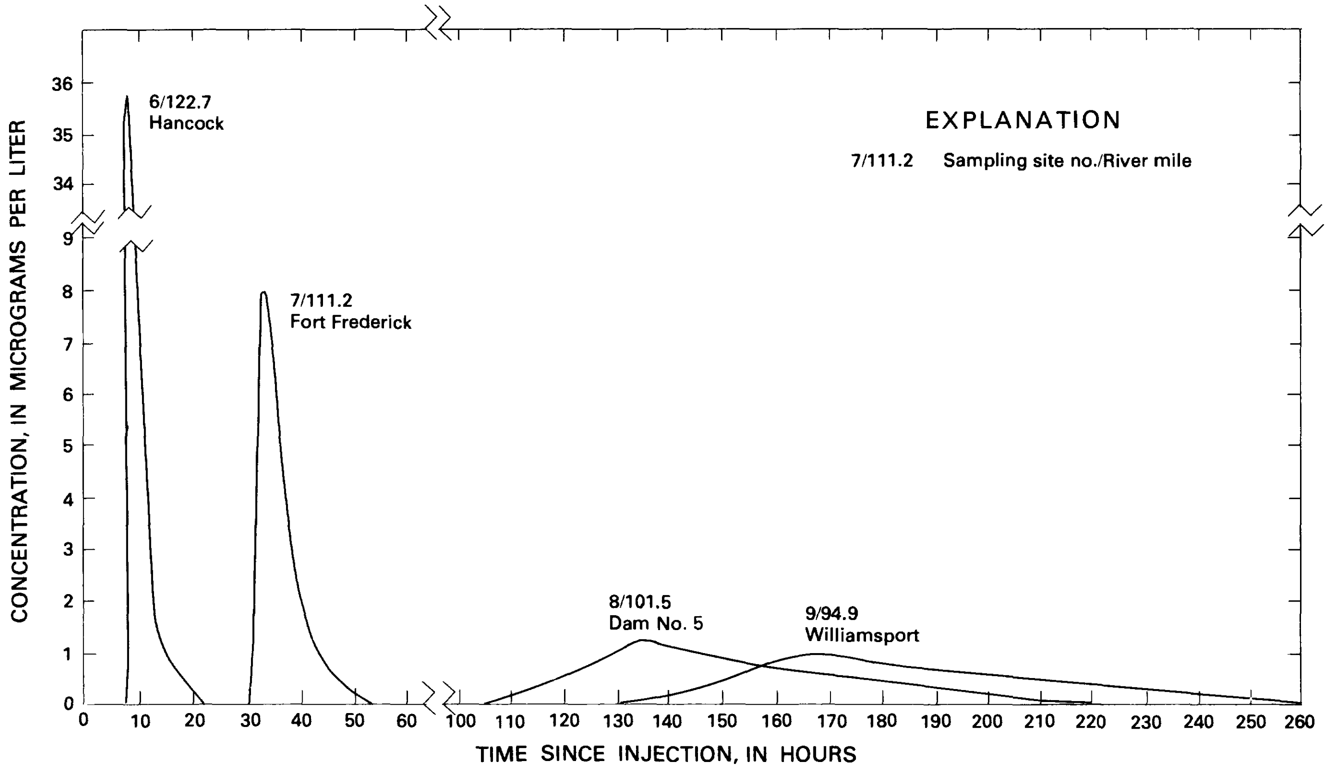

Figure 3. Observed time-concentration curves for Hancock-to-Williamsport subreach, October 1981 study.

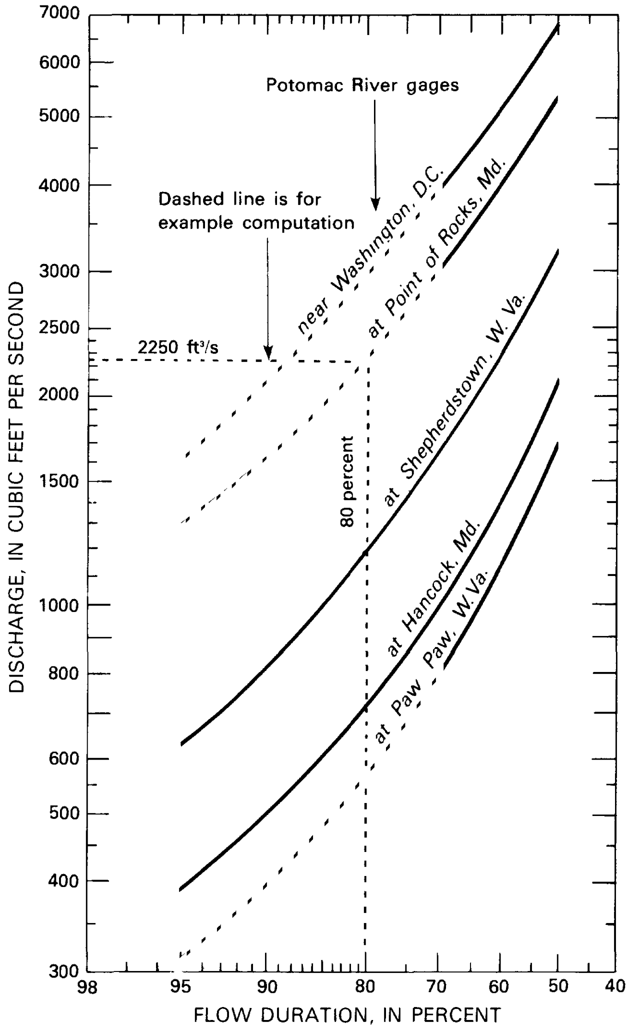

Figure 4. Relation between flow duration and mean-daily discharge at Potomac River gaging stations.

edge, peak concentration, and trailing edge. The final result of this computation was a specific velocity between two successive sampling sites for flow duration values of 50, 55, 60, 65, 70, 75, 80, 85, 90, and 95 percent. Figure 5 shows the computation for the 6.6-mi reach between sampling site 8 at Dam No. 5 and site 9 at Williamsport. Sixteen computations similar to that in figure 5 provided incremental velocities at 10 flow levels for the entire reach between Cumberland and Washington.

The distance between sampling sites was divided by its incremental velocity to provide an incremental traveltime at each of the 10 flow levels for the leading edge, peak concentration, and trailing edge. These incremental times were accumulated from Cumberland to Washington. Tables 4, 5, and 6 give the traveltimes from Cumberland for the leading edge, the peak concentration, and the trailing edge, respectively, for each flow duration. Figures 6, 7, and 8 are three-parameter graphical presentations of the data. The data in tables 4 to 6, or figures 6 to 8, can be used to estimate the time required for a soluble substance to move from any point in the study reach to any point downstream. These graphical presentations provide a straight-line interpolation between sampling sites, and therefore may be easier to use in most situations.

Because traveltime is related to discharge in the river, use of the traveltime relations requires some information about flow rates at a minimum of one of the five gaging stations used as index stations. (See fig. 4.) Each of these gaging stations is equipped with remote telemetry equipment operated for various agencies. This remote equipment allows those who are most likely to need the information to acquire real-time river discharge data.

Suppose there is a spill of a water-soluble substance in the river. To use the graphs (figs. 6–8) enter with a flow-duration value that represents the discharge in the river. The approximate flow duration can be determined from figure 4 after determining the discharge at one of the index gaging stations (preferably the station nearest the location of the spill). Locate the point of the spill relative to the distance the point is upstream from Chain Bridge near Washington (table 1 and fig. 1 are helpful). Determine the traveltime from Cumberland (site 1) for the specific flow duration to the location of the spill. Next, in the same manner, determine the traveltime from Cumberland to the point of interest downstream. Subtract one traveltime from the other to get the time required to travel the intervening distance. The subtraction process initializes the time at zero at the point of the spill.

This procedure can be used to estimate traveltime of the leading edge (fig. 6), the peak concentration (fig. 7), and the trailing edge (fig. 8). The procedure is expected to give more accurate estimates of traveltime of the peak concentration and leading edge of the dye cloud than of the trailing edge. The truncation of the trailing edge is the reason for concern about accurately predicting the traveltime of the trailing edge of the dye cloud. Therefore, calculations of traveltime of the trailing edge should be considered approximations, particularly when the spill occurred in one subreach and the point of interest is in another subreach downstream.

The difference between the arrival time of the leading edge and the arrival time of the trailing edge is an approximation of the time required for the soluble substance to pass a given point. In the remainder of the report, this interval of time is referred to as the time of passage, or duration (*D*), of the dye or contaminant cloud.

Dispersion

When a soluble dye is injected into a flowing river, it immediately starts dispersing in the vertical, lateral,

Reach	Dam No. 5 to Williamsport	Length 6.6 mi
Index gages	Paw Paw (PP), Hancock (Hanc.)	

Peak	$Vel._{1981}$ = 0.213 mi/h $Vel._{1964}$ = 0.440 mi/h	Q_{PP} = 412 ft^3/s Q_{PP} = 835 ft^3/s	$Q_{Hanc.}$ = 514 ft^3/s $Q_{Hanc.}$ = 1,080 ft^3/s	$Q = \bar{Q}_{Oct.}$ 15-20 $Q = \bar{Q}_{May}$ 27-30
Leading edge	$Vel._{1981}$ = 0.254 mi/h $Vel._{1964}$ = 0.508 mi/h	Q_{PP} = 412 ft^3/s Q_{PP} = 835 ft^3/s	$Q_{Hanc.}$ = 514 ft^3/s $Q_{Hanc.}$ = 1,080 ft^3/s	$Q = \bar{Q}_{Oct.}$ 15-20 $Q = \bar{Q}_{May}$ 27-30
Trailing edge	$Vel._{1981}$ = 0.161 mi/h $Vel._{1964}$ = 0.330 mi/h	Q_{PP} = 412 ft^3/s Q_{PP} = 835 ft^3/s	$Q_{Hanc.}$ = 514 ft^3/s $Q_{Hanc.}$ = 1,080 ft^3/s	$Q = \bar{Q}_{Oct.}$ 15-20 $Q = \bar{Q}_{May}$ 27-30

Flow duration			Velocity, in mi/h								
Per-cent	Q, in ft^3/s		Peak			Leading edge			Trailing edge		
	PP	Hanc.	PP	Hanc.	Avg.	PP	Hanc.	Avg.	PP	Hanc.	Avg.
50	1,700	2,100	0.890	0.860	0.875	1.03	1.00	1.015	0.670	0.625	0.648
55	1,390	1,730	.740	.710	.725	.840	.820	.830	.540	.520	.530
60	1,160	1,460	.610	.600	.605	.700	.700	.700	.450	.440	.445
65	960	1,200	.505	.495	.500	.585	.575	.580	.375	.360	.368
70	810	1,000	.425	.410	.418	.490	.480	.485	.315	.305	.310
75	670	840	.350	.345	.348	.410	.405	.408	.265	.257	.261
80	565	710	.295	.295	.295	.345	.345	.345	.220	.220	.220
85	470	590	.245	.245	.245	.288	.286	.287	.185	.183	.184
90	390	490	.200	.202	.201	.240	.240	.240	.152	.154	.153
95	310	390	.158	.164	.161	.192	.190	.191	.122	.124	.123

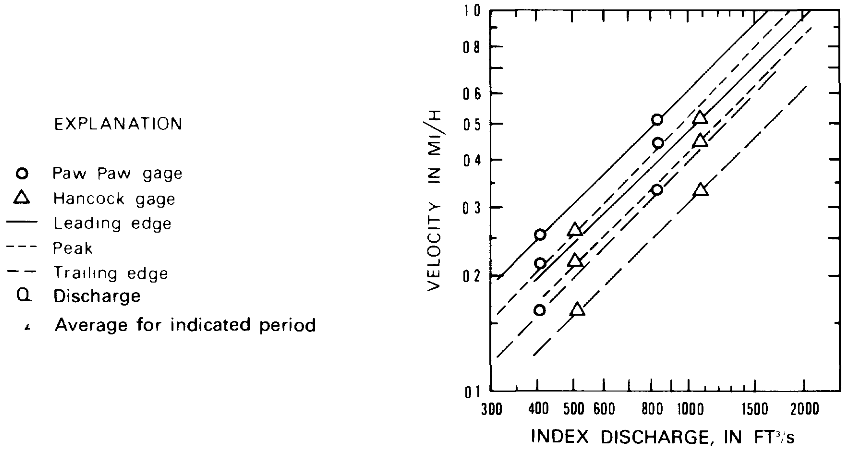

Figure 5. Typical computation of velocities for 5-percent increments of flow duration.

Table 4. Traveltimes for leading edge of dye cloud at selected flow durations

Site No.	Site name	Miles upstream from Chain Bridge	Distance between sampling sites (miles)	Traveltime of leading edge of dye cloud, in hours, for indicated flow duration, in percent									
				50	55	60	65	70	75	80	85	90	95
1	Cumberland	188.7	-	0	0	0	0	0	0	0	0	0	0
2	North Branch	180.0	8.7	12	13	14	15	16	18	19	21	23	25
3	Oldtown	171.3	8.7	21	23	25	27	29	32	34	37	40	44
4	Paw Paw	160.6	10.7	33	36	39	42	46	50	54	59	64	71
5	Doe Gully	140.8	19.8	48	53	59	65	72	79	87	97	107	122
6	Hancock	122.7	18.1	65	72	79	87	96	106	116	129	142	161
7	Fort Frederick	111.2	11.5	73	81	90	100	111	123	135	151	167	191
8	Dam No. 5	101.5	9.7	93	105	118	134	151	171	192	219	249	293
9	Williamsport	94.9	6.6	99	113	128	145	165	187	211	242	277	328
10	Dam No. 4	79.4	15.5	123	142	163	188	215	249	285	332	385	466
11	Shepherdstown	67.7	11.7	131	152	174	202	232	268	308	359	418	507
12	Dam No. 3	57.2	10.5	154	177	202	232	264	303	346	402	465	561
13	Brunswick	49.9	7.3	161	185	210	240	273	312	356	412	475	572
14	Point of Rocks	43.6	6.3	168	192	217	248	281	320	364	420	484	581
15	Whites Ferry	31.2	12.4	178	204	230	262	296	337	382	439	505	605
16	Seneca	18.0	13.2	193	221	248	282	318	360	408	469	539	644
17	Little Falls Dam	1.2	16.8	215	246	276	313	353	400	454	522	600	720

Table 5. Traveltimes for peak concentration of dye cloud at selected flow durations

Site No.	Site name	Miles upstream from Chain Bridge	Distance between sampling sites (miles)	Traveltime of peak concentration of dye cloud, in hours, for indicated flow duration, in percent									
				50	55	60	65	70	75	80	85	90	95
1	Cumberland	188.7	-	0	0	0	0	0	0	0	0	0	0
2	North Branch	180.0	8.7	15	16	18	19	21	22	24	26	29	32
3	Oldtown	171.3	8.7	26	28	31	33	36	39	42	45	49	54
4	Paw Paw	160.6	10.7	39	42	46	50	54	59	63	69	75	83
5	Doe Gully	140.8	19.8	56	62	68	76	83	92	100	111	123	139
6	Hancock	122.7	18.1	75	83	91	101	111	122	133	147	162	183
7	Fort Frederick	111.2	11.5	85	94	104	115	127	141	155	172	191	217
8	Dam No. 5	101.5	9.7	112	128	143	163	183	207	233	264	301	354
9	Williamsport	94.9	6.6	120	137	154	176	199	226	255	291	334	395
10	Dam No. 4	79.4	15.5	153	177	203	236	271	313	362	420	492	596
11	Shepherdstown	67.7	11.7	162	189	217	253	291	336	388	453	531	645
12	Dam No. 3	57.2	10.5	189	219	249	287	328	376	432	501	584	706
13	Brunswick	49.9	7.3	197	227	258	297	338	386	443	512	596	719
14	Point of Rocks	43.6	6.3	205	235	266	305	347	395	452	522	606	729
15	Whites Ferry	31.2	12.4	218	249	280	321	364	413	471	543	629	754
16	Seneca	18.0	13.2	234	267	300	342	388	438	499	574	664	796
17	Little Falls Dam	1.2	16.8	258	295	331	379	428	484	552	634	734	882

Table 6. Traveltimes for trailing edge of dye cloud at selected flow durations

Site No.	Site name	Miles upstream from Chain Bridge	Distance between sampling sites (miles)	Traveltime of trailing edge of dye cloud, in hours, for indicated flow duration, in percent									
				50	55	60	65	70	75	80	85	90	95
1	Cumberland	188.7	-	0	0	0	0	0	0	0	0	0	0
2	North Branch	180.8	8.7	20	22	24	26	28	31	34	37	40	44
3	Oldtown	171.3	8.7	34	37	40	44	47	52	56	60	66	73
4	Paw Paw	160.6	10.7	49	54	58	64	68	74	80	87	94	104
5	Doe Gully	140.8	19.8	72	80	87	96	105	116	126	139	153	173
6	Hancock	122.7	18.1	96	106	116	128	139	153	167	183	202	227
7	Fort Frederick	111.2	11.5	106	118	130	144	158	176	192	213	237	270
8	Dam No. 5	101.5	9.7	155	176	198	226	255	291	327	375	427	501
9	Williamsport	94.9	6.6	165	189	213	244	277	316	357	411	470	554
10	Dam No. 4	79.4	15.5	214	249	287	336	389	455	526	618	725	891
11	Shepherdstown	67.7	11.7	225	263	304	356	413	483	559	657	771	949
12	Dam No. 3	57.2	10.5	259	301	344	400	460	533	614	718	838	1,027
13	Brunswick	49.9	7.3	269	311	354	411	472	545	627	731	852	1,041
14	Point of Rocks	43.6	6.3	278	320	364	421	482	555	637	742	863	1,053
15	Whites Ferry	31.2	12.4	291	335	379	437	500	575	658	765	888	1,081
16	Seneca	18.0	13.2	309	355	401	461	526	603	690	800	928	1,128
17	Little Falls Dam	1.2	16.8	343	394	444	511	582	666	763	885	1,027	1,250

and longitudinal directions. Vertical and lateral mixing takes place relatively quickly and can be enhanced by injecting the dye simultaneously at several points in the cross section. "Until the dye is mixed laterally, its movement does not represent that of the total flow" (Hubbard and others, 1982, p. 17). The longitudinal mixing process is a continuing one.

The ideal situation for studying longitudinal dispersion would be one in which (1) the total reach could be studied without segmentation and (2) complete lateral mixing could be assumed to exist after the initial mixing period. Unfortunately, the ideal situation does not exist when conducting dispersion studies on long rivers, particularly those with large width-to-depth ratios. The threat of precipitation, sampling logistics, and control of maximum dye concentrations at water intakes require that the total reach be divided into shorter segments, or subreaches, as was done in this study. Additionally, tributary inflows work against complete lateral mixing. According to formulas presented by Hubbard and others (1982, eq. 1, 2, p. 17), a side injection of water from a tributary requires a mixing length four times greater than that for a single midstream injection of dye. For most dye studies, complete lateral mixing is seldom accomplished.

In spite of mixing problems, time-of-travel studies using a slug injection of a water-tracing dye can provide considerable insight into the longitudinal dispersive characteristics of a river. Figures 2 and 3 show how the peak concentration of the dye cloud is attenuated as it moves downstream and the dye mixes into increasing amounts of water. It is typical of time-concentration curves that the peak concentration is lower and the time required for a dye cloud to pass a sampling point is longer at each successive downstream location.

Often, long reaches of rivers have similar dispersive capabilities (Hubbard and others, 1982, p. 32). However, abrupt changes can occur. For example, the subreach between Cumberland (site 1) and Hancock (site 6) has fairly uniform dispersive characteristics. The uniform slope of the time-distance relation for the subreach (fig. 7) and the gradual attenuation, or reduction, of the peak concentration (fig. 2) is evidence of a fairly uniform dispersive capability. In contrast, the stream segment between Fort Frederick (site 7) and Dam No. 5 (site 8) shows an abrupt change in dispersive properties due to the storage pool created by Dam No. 5. The increased slope in the time-distance relation (fig. 7) and the large difference in peak concentrations between successive sampling points (fig. 3) indicate an abrupt change in dispersive characteristics for this stretch of the river. The effect of Dam No. 5, as might be expected, is very pronounced at the higher flow durations (lower river discharges) and less pronounced at the lower flow durations (higher river discharges), when the dam is less effective.

"The shape and magnitude of a time-concentration curve that is in response to a dye injection is determined by (1) the amount of the dye injected, (2) losses undergone by the dye, (3) the discharge that serves to dilute the

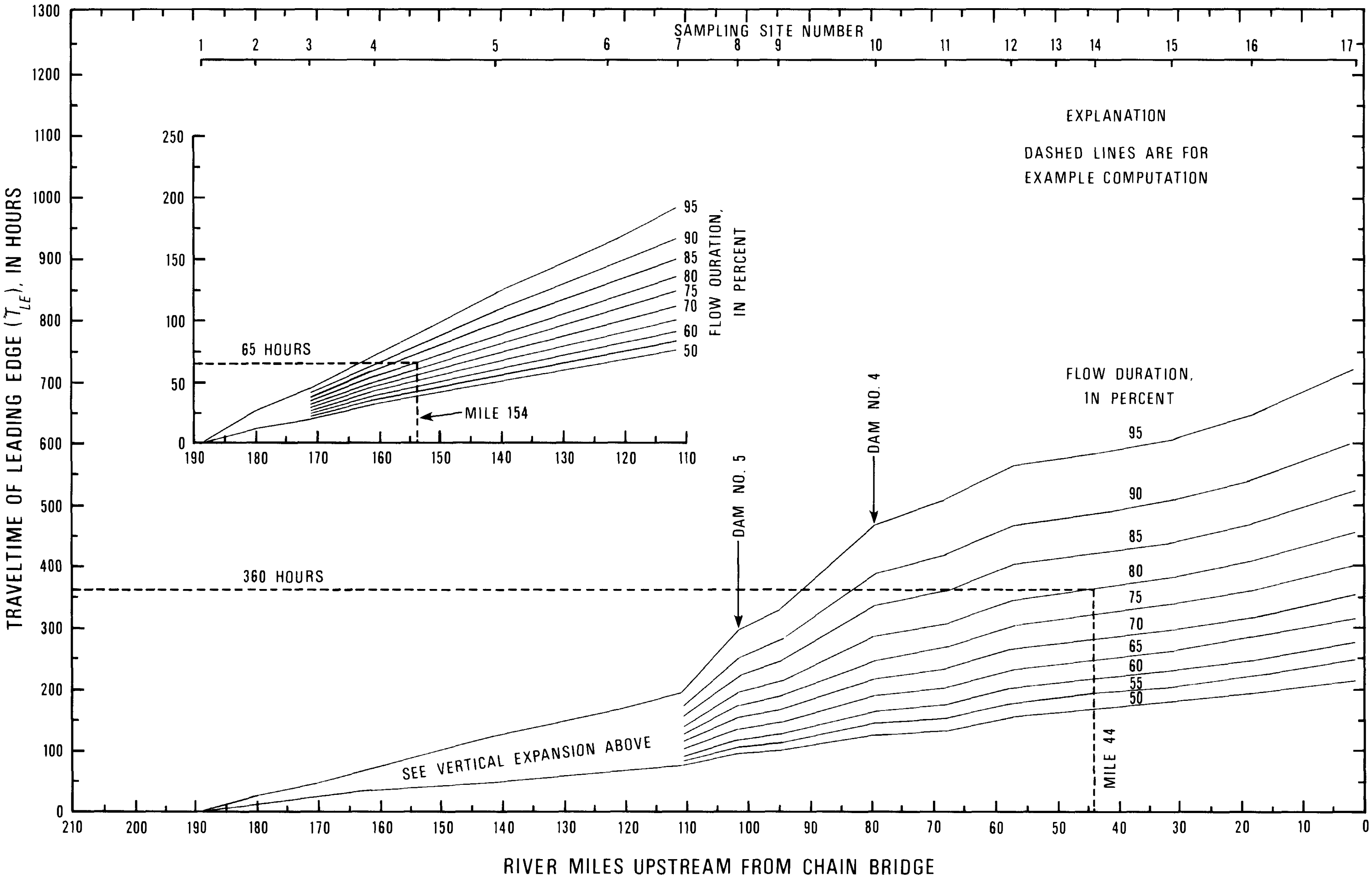

Figure 6. Traveltime-distance relation for leading edge of dye cloud at selected flow durations. See figure 1 for location of sampling sites.

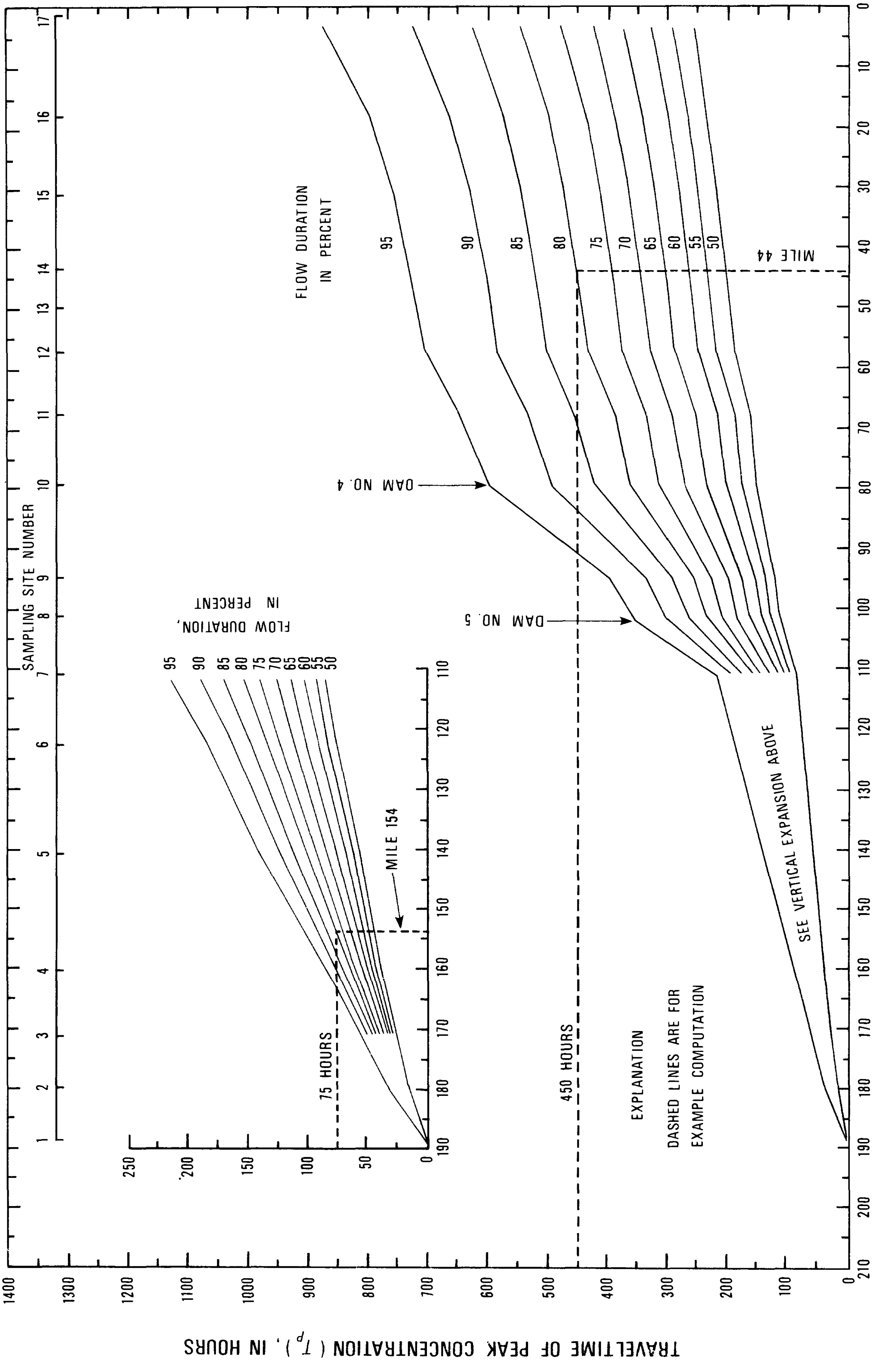

Figure 7. Traveltime-distance relation for peak concentration of dye cloud at selected flow durations. See figure 1 for location of sampling sites.

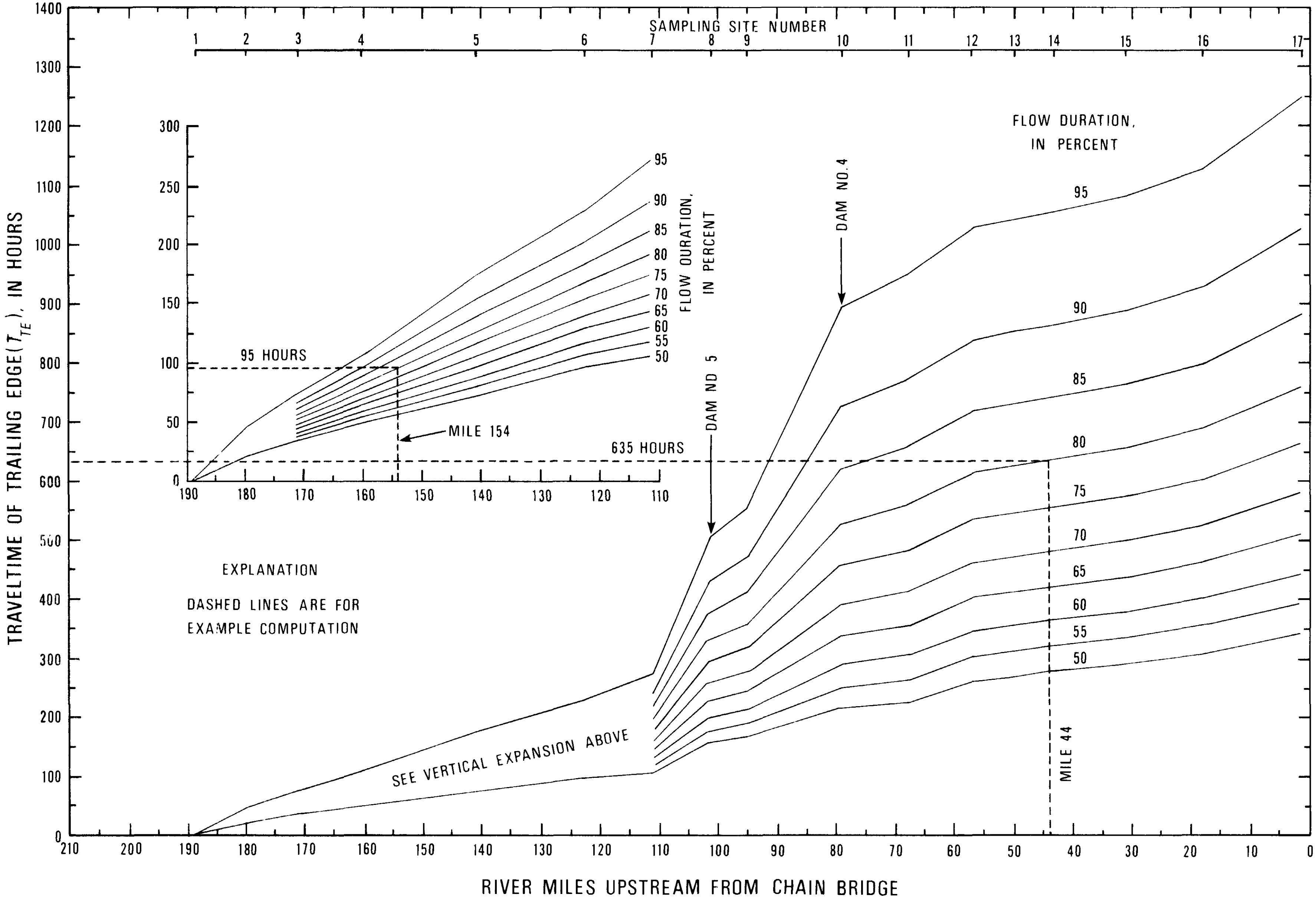

Figure 8. Traveltime-distance relation for trailing edge of dye cloud at selected flow durations. See figure 1 for location of sampling sites.

cloud in the reach, and (4) longitudinal dispersion" (Hubbard and others, 1982, p. 34). The concept of unit concentration (C_u) was formulated by Kilpatrick (Hubbard and others, 1982, p. 34) to remove all of the effects listed above, except longitudinal dispersion. Unit concentration can be defined as the concentration produced in one unit of flow rate by the injection of one unit weight of solute, provided that no losses of solute occur. Kilpatrick's formulation of unit concentration for the general case is:

$$C_u = \frac{C_{con} Q}{W_d} , \tag{1}$$

where

C_u = unit concentration,
C_{con} = conservative concentration (a concentration that would be produced if the total quantity of injected material were undiminished for any reason as it moved downstream and were uniformly mixed in the entire flow),
Q = discharge at the sampling point, and
W_d = weight of pure dye injected.

A more specific use of the unit-concentration concept is its applicability to peak concentrations only. Unit peak concentration (C_{up}) can be used to explain the attenuation of the peak concentration as the dye cloud moves downstream. The formulation for unit peak concentration is

$$C_{up} = \frac{C_{p(con)} Q}{W_d} , \tag{2}$$

where

C_{up} = unit peak concentration and
$C_{p(con)}$ = conservative peak concentration.

The ultimate use of C_{up} will be to allow computation of the conservative peak concentration ($C_{p(con)}$) resulting from a spill of a specified amount of contaminant into a specified flow. Rearrangement of equation 2 gives the following equation useful for this purpose:

$$C_{p(con)} = \frac{C_{up} W_d}{Q} , \tag{2A}$$

where, in this instance,

$C_{p(con)}$ = conservative peak concentration,
W_d = weight of spilled contaminant, and
Q = discharge at the point of interest.

Use of equations 1 and 2 requires that the amount of dye passing the sampling point be determined in order to calculate a conservative concentration. The formulas presented by Hubbard and others (1982, p. 33, 34) for calculating dye recovery and conservative concentrations are

$$R_p = \frac{KQA_{t\text{-}c(obs)}}{W_d} \tag{3}$$

and

$$C_{p(con)} = \frac{C_{p(obs)}}{R_p} \times 100, \tag{4}$$

where

R_p = percentage of dye recovered,
K = constant, depending on the system of units used,
$A_{t\text{-}c(obs)}$ = mean area of the observed discharge-weighted time-concentration curves,
W_d = weight of pure dye injected, and
$C_{p(obs)}$ = peak observed concentration.

Equation 4 is shown in the form useful for working with peak concentrations rather than with concentrations in general.

The accuracy of calculated values of C_{up}, using equations 2, 3, and 4, is directly related to the accuracy with which the mean discharge-weighted time-concentration curve is defined at each sampling site. Seldom are sufficient data available for this purpose, except for a few, pure research studies. Because of the lateral mixing problems previously discussed, accurate definition of the mean discharge-weighted time-concentration curve requires multiple-point sampling across the river and weighting of each time-concentration curve by the appropriate discharge in that subsection. The multiple time-concentration curves must then be composited in order to calculate unit peak concentration. Inaccessible sampling sites, difficulties associated with around-the-clock sampling, large personnel requirements for discharge measurements, problems associated with handling a large number of samples, and insufficient funds all combine to preclude collection of enough data to define adequately the mean discharge-weighted time-concentration curve for dye studies on major rivers.

When data from which to accurately calculate unit peak concentration by the above method are not available, another approach can be taken. By substituting equations 3 and 4, equation 2 can be expressed in the form:

$$C_{up} = 4{,}440 \frac{C_{p(obs)}}{A_{t\text{-}c(obs)}} . \tag{5}$$

This form of the equation allows calculation of unit peak concentration without going through the process of calculating dye recovery. It, in effect, takes the shape of an observed time-concentration curve and fits one unit weight of dye into that shape, assuming that one unit of flow exists during the passage of the dye cloud. Actually, the relation between $C_{p(obs)}$ and $A_{t\text{-}c(obs)}$ can be defined by use of fluorometer dial readings just as well as by use of absolute concentrations. U.S. Geological Survey policy, however, requires that, at a minimum, absolute concentration of the peaks be determined.

C_{up} formulated in this manner, and using 4,440 as the constant, must be assigned the units of micrograms per liter per pound of pure dye per cubic foot per second. When presented in this form, C_{up} can be seen to represent the changing relationship between the peak concentration and the area under the time-concentration curve. This relationship is analogous to the simpler geometric relationship between the height of a scalene triangle (three unequal sides) and the area of the triangle. This analogy will be shown to be useful later in this section.

Values of C_{up} were computed by equation 5 for each sampling site for the two studies on the Potomac River and are shown in tables 2 and 3. The percentages of dye recovery were calculated and are also shown in tables 2 and 3. The C_{up} values are plotted against the traveltime of the peak concentration in figure 9. The inconsistency of computed dye recoveries for successive downstream sampling sites (tables 2 and 3) provides strong evidence that lateral mixing was not complete in many instances. Consequently, sampling at one point in a sampling section did not provide adequate definition of the mean discharge-weighted time-concentration curve at each sampling site, and thus would not allow computation of unit peak concentration by using equation 2.

It can also be seen from the data plotted in figure 9 that dispersive characteristics vary widely in the total reach of river. The slope of the line between successive sampling sites is an index of the dispersive capability of the intervening segment of river. The steeper slopes indicate higher dispersive capabilities.

Because of the segmentation of the total reach into five or six subreaches, no values of C_{up} are available for traveltimes exceeding 200 hours. From figure 7, it can be seen that the peak concentration would require almost 900 hours to travel from Cumberland to Washington at a flow duration of 95 percent. This would indicate a potential need for peak-concentration attenuation data for much longer traveltimes than could be obtained from figure 9. (A value of C_{up} cannot be computed unless a time-concentration curve has been defined for such a time.) Others (Taylor, 1970) have overcome this handicap by extrapolating the curve where the total reach had fairly uniform dispersive characteristics; Lindskov (1974) used an envelope curve to define the extreme value or conservative curve. Because of the large amount of scatter of the data and the nonuniform dispersive characteristics, neither of these solutions seems appropriate for the Potomac River data.

To provide a technique useful in estimating the peak concentration expected at any point in the total reach from a spill of a water-soluble substance at any point upstream for a wide range of flows, it was necessary to develop a new method for computing C_{up}. The new method could not depend on the availability of time-concentration curves for long traveltimes.

The analogy between the time-concentration curve and the scalene triangle was previously mentioned. In the analogy, the peak concentration relative to the area under the time-concentration curve is similar to the height of the scalene triangle relative to the area of the triangle. The scalene triangle, being a simpler shape, was tested to see if it could serve as a simplified time-concentration curve. The graphical portrayal of the analogy is shown in figure 10.

The advantage of the scalene triangle is that the ratio of the height of the triangle to the area of the triangle (analogous to $C_{p(obs)} \div A_{t\text{-}c(obs)}$ in eq. 5) can be expressed entirely in terms of the length of the base of the triangle. If unit peak concentration could be expressed in terms of the length of the dye cloud (analogous to the base of the triangle), it would reduce the problems with incomplete lateral mixing often encountered in the field and the associated problem of defining discharge-weighted concentrations. In addition, it would allow calculation of C_{up} values for long traveltimes without the need for observed time-concentration curves for those traveltimes.

To test the analogy, the first 90 time-concentration curves given by Nordin and Sabol (1974, appendix B, p. 113–212) were used. The true areas under the time-concentration curves were computed. The areas were then calculated by using the scalene triangle approach ($\frac{1}{2}D \times C_{p(obs)}$, where D = duration of the dye cloud). Figure 11 shows the areas calculated by the triangle approach plotted versus the actual areas. The Potomac River data are shown on the graph, but were not used in the test. The equation of best fit was determined by linear regression on the log-transformed data partitioned in three ways. The parameters of the regression analyses are:

Equation in the form: $\log Y = \log a + b \log X$.

Area	Intercept (a)	Slope (b)	Coefficient of determination (r^2)	Standard error, in percent (SE)
All values	1.100	1.011	0.994	±9
All values >10	1.056	0.998	0.992	±8
All values >10 but <300	1.042	1.002	0.990	±8

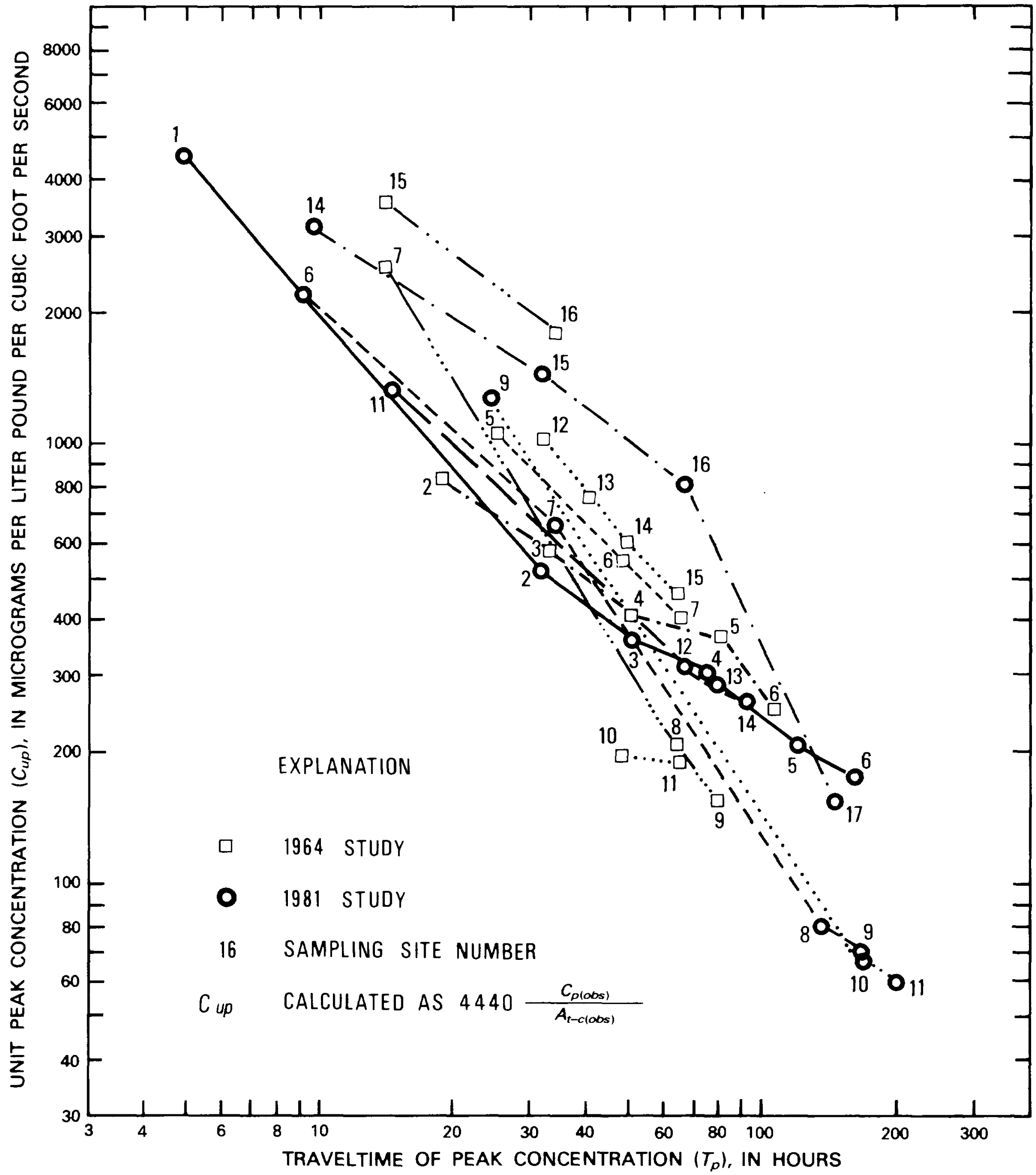

Figure 9. Relation between unit peak concentration and traveltime of peak concentration for dye studies on the Potomac River.

Owing to U.S. Geological Survey limitations on dye concentrations allowed at water intakes and at the ends of test reaches, the great majority of the areas of time-concentration curves encountered in the field will fall between values of 10 and 300 μg/L times hours. Therefore, the equation for that range of data is considered appropriate for use. By taking the antilogs, the equation may be expressed in the form $Y = a(X)^b$, which yields the following regression equation:

$$A_{t\text{-}c(\Delta)} = 1.042(A_{t\text{-}c(obs)})^{1.002},$$

where

$A_{t\text{-}c(\Delta)}$ = area under the time-concentration curve calculated as $\frac{1}{2} D \times C_{p(obs)}$.

The true value of the slope parameter (b = 1.002) is assumed to be unity and suggests that the relation is valid

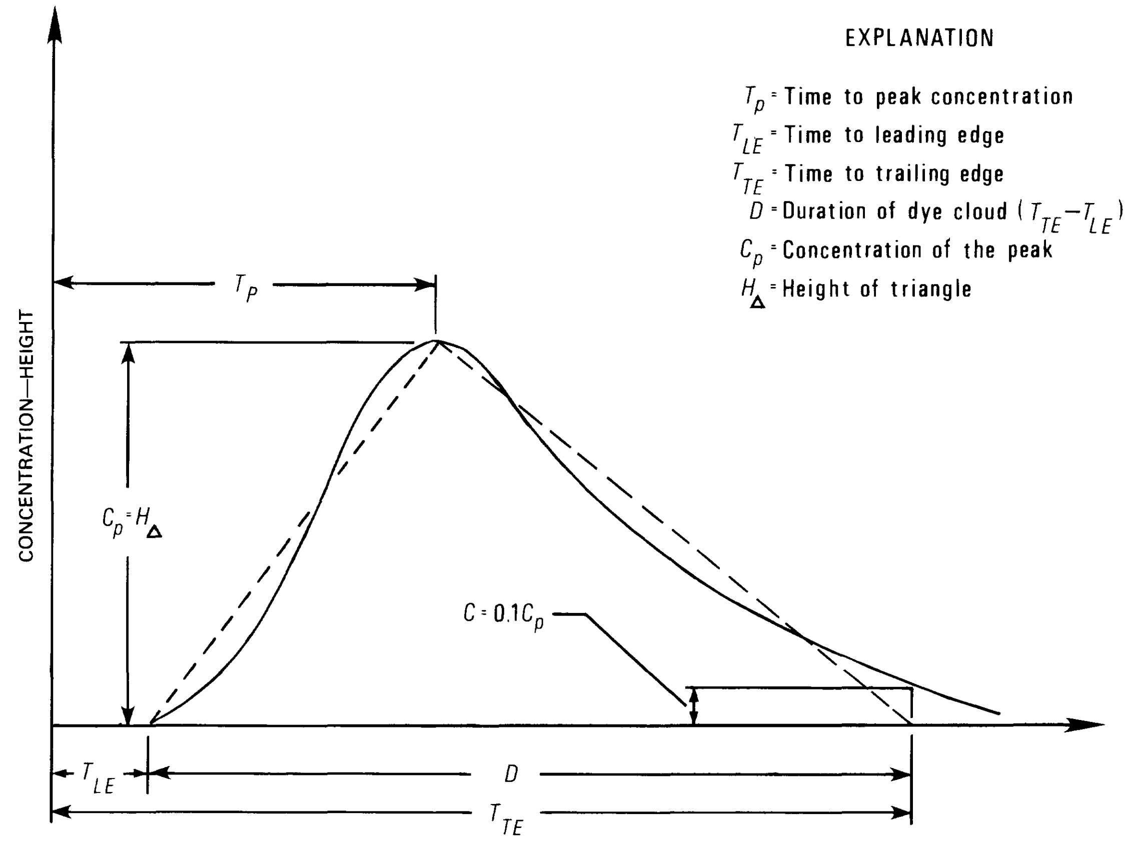

Figure 10. Relation between time-concentration curve and scalene triangle.

throughout the range of areas. The intercept value (a) of 1.042 indicates that calculated areas using the triangle method are on the average 4.2 percent higher than the true areas. The standard error of the regression is ±8 percent, which indicates that two out of three calculations of areas by the triangle approach will be within 8 percent of the true areas. The "true area" under the time-concentration curve can now be estimated from the regression equation (rearranged), as follows:

$$A_{t\text{-}c(obs)} = \frac{A_{t\text{-}c(\Delta)}}{1.042} . \qquad (6)$$

By substituting this value in equation 5 for the area under the time-concentration curve, equation 5 becomes

$$C_{up} = 4{,}440 \frac{1.042\, C_{p(obs)}}{A_{t\text{-}c(\Delta)}} . \qquad (7)$$

The area contained by the triangle now can be expressed, in the normal way, as one-half of the base times the height. By definition (fig. 10), the base of the triangle is the difference between the traveltime of the leading edge and the traveltime of the trailing edge ($T_{TE}-T_{LE}$), or, in other words, the duration (D) of the dye cloud. The height of the triangle, by definition, is equal to $C_{p(obs)}$. The area now can be expressed as

$$A_{t\text{-}c(\Delta)} = 0.5\, DC_{p(obs)} . \qquad (8)$$

Substituting equation 8 for the area of the triangle in equation 7 gives

$$C_{up} = 4{,}440 \frac{1.042\, C_{p(obs)}}{0.5\, DC_{p(obs)}}$$

or

$$C_{up} = \frac{9{,}250}{D} = 9{,}250\, D^{-1} . \qquad (9)$$

Dimensional analysis shows that unit peak concentration is an inverse function of time. The derived equation conforms to this analysis: It is an inverse function of time of passage, or duration, of the dye cloud. Furthermore, according to H. H. Barnes (written commun., 1974), plots of cloud duration versus C_{up} using large amounts of data show the following empirical relationship:

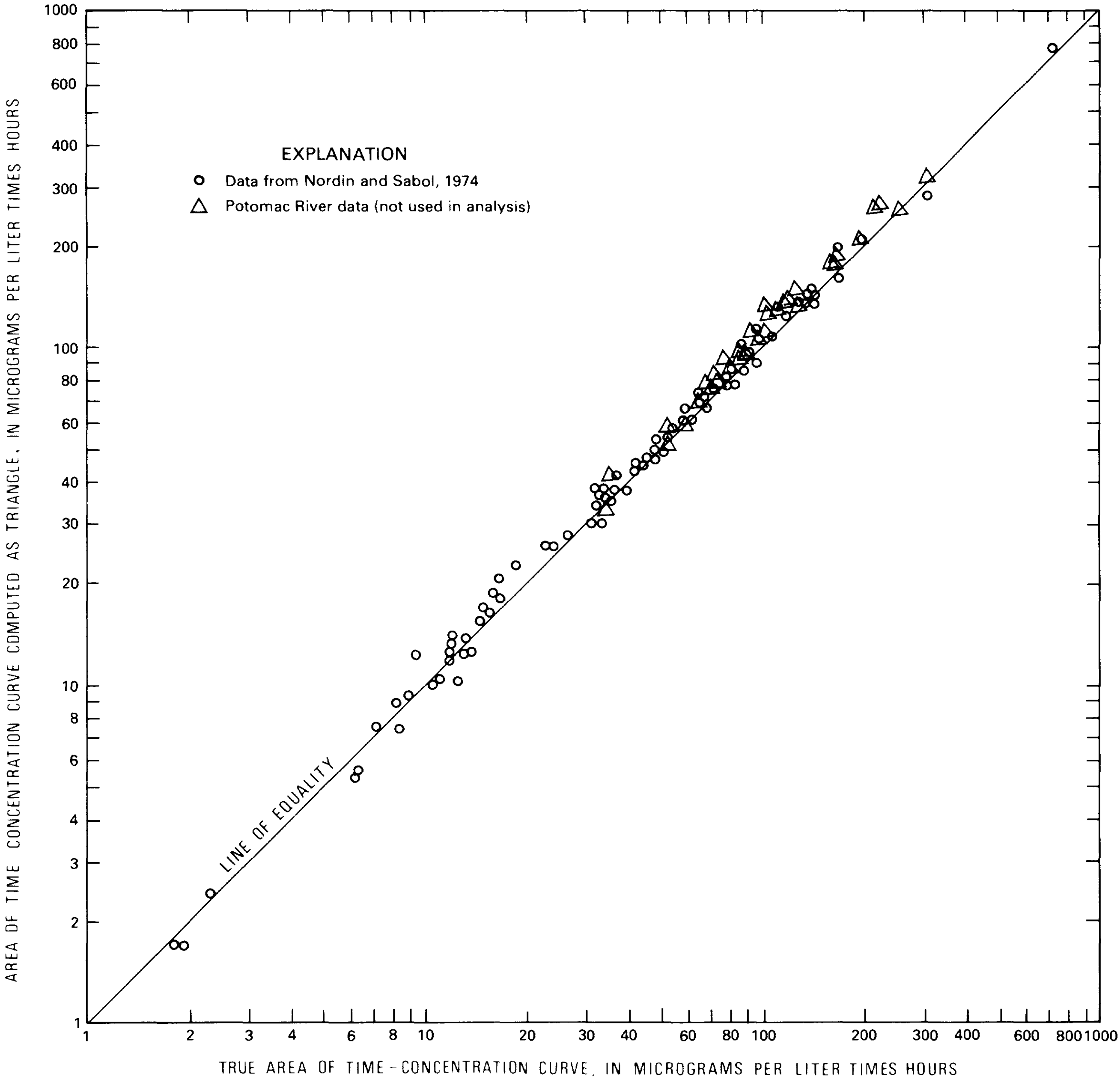

Figure 11. Relation between true area of time-concentration curve and area computed by triangle approach.

$$C_{up} \approx 9{,}000\ D^{-1}.$$

The derived relationship in equation 9 is only 2.8 percent different from the relationship observed by Barnes. The advantages of this formulation of unit peak concentration are

1. It allows computation of unit peak concentration values without calculation of dye recovery, which requires intensive field-data collection and analysis for each sampling cross section.
2. Combined with cloud-duration data, it allows computation of values of unit peak concentration, as a continuous function, for long, subdivided study reaches and can be initialized (that is, T_p, traveltime of the peak concentration, can be set equal to zero) at any point where a spill may occur.
3. Combined with cloud-duration data, it allows computation of unit peak-concentration values for several flow levels.

Using data from tables 4 and 6, dye-cloud durations (D) were calculated for each sampling point and

Table 7. Duration of dye cloud at selected flow durations

Site No.	Site name	Miles upstream from Chain Bridge	Distance between sampling sites (miles)	Duration of dye cloud, in hours, for indicated flow duration, in percent									
				50	55	60	65	70	75	80	85	90	95
1	Cumberland	188.7	-	0	0	0	0	0	0	0	0	0	0
2	North Branch	180.0	8.7	8	9	10	11	12	13	15	16	17	19
3	Oldtown	171.3	8.7	13	14	15	17	18	20	22	23	26	29
4	Paw Paw	160.6	10.7	16	18	19	22	22	24	26	28	30	33
5	Doe Gully	140.8	19.8	24	27	28	31	33	37	39	42	46	51
6	Hancock	122.7	18.1	31	34	37	41	43	47	51	54	60	66
7	Fort Frederick	111.2	11.5	33	37	40	44	47	53	57	62	70	79
8	Dam No. 5	101.5	9.7	62	71	80	92	104	120	135	156	178	208
9	Williamsport	94.9	6.6	66	76	85	99	112	129	146	169	193	226
10	Dam No. 4	79.4	15.5	91	107	124	148	174	206	241	286	340	425
11	Shepherdstown	67.7	11.7	94	111	130	154	181	215	251	298	353	442
12	Dam No. 3	57.2	10.5	105	124	142	168	196	230	268	316	373	466
13	Brunswick	49.9	7.3	108	126	144	171	199	233	271	319	377	469
14	Point of Rocks	43.6	6.3	110	128	147	173	201	235	273	322	379	472
15	Whites Ferry	31.2	12.4	113	131	149	175	204	238	276	326	383	476
16	Seneca	18.0	13.2	116	134	153	179	208	243	282	331	389	484
17	Little Falls Dam	1.2	16.8	128	138	168	198	229	266	309	363	427	530

each flow duration by subtracting the traveltimes of the leading edge of the dye clouds, from the traveltimes of the trailing edges of the dye clouds. These dye-cloud duration values are presented in table 7 and, graphically, in figure 12.

Using equation 9 and *D* values from table 7, a C_{up} value can be calculated for each of the sampling sites at the 10 flow-duration levels. When values of C_{up} are plotted against traveltimes of the peak concentration (T_p) from table 5, unit peak-concentration attenuation curves similar to those in figure 13 can be developed. The curves in figure 13 illustrate the attenuation of unit peak concentrations for a spill occurring at Cumberland (sampling site 1), when flows in the river are at the 50-, 70-, and 90-percent flow-duration levels. This procedure can be used for a spill at any point on the river by initializing the data in tables 5 and 7 or figures 7 and 12 to zero at the point of the spill. A sample problem demonstrating this procedure is presented in the following section.

USE OF DATA

The primary objective of this report is to provide a generalized procedure that will allow the user to make predictions concerning the traveltime and downstream concentrations resulting from a spill of a water-soluble substance in the river. Use of the procedure can best be demonstrated by an example computation.

Suppose there was a train derailment at Magnolia, W. Va., and a tank car spilled 20,000 pounds of water-soluble toxic material into the river. Downstream, the town of Point of Rocks, Md., needs information on (1) when the toxic material will arrive at the bridge on U.S. Highway 15, (2) when the maximum concentration will arrive, (3) what the magnitude of the maximum concentration will be, and (4) when the contaminant will be essentially past the bridge.

The following additional facts would be needed before using the procedures:

1. When did the spill occur?
   Assumption: June 3 at 10 a.m.
2. What is the flow in the river?
   This would require determining the river stage at one of the index streamflow gaging stations and then determining the discharge from a stage-discharge relation.
   Assumption: Flow at Point of Rocks gage is 2,250 ft³/s.

The following procedure can be used to make estimates concerning traveltime and concentration:

1. When will the toxic material first arrive at Point of Rocks?
   Procedure:
   A. Use figure 4. Determine the flow-duration value for a discharge of 2,250 ft³/s at the Point of Rocks index gage. From figure 4, the flow duration is 80 percent.

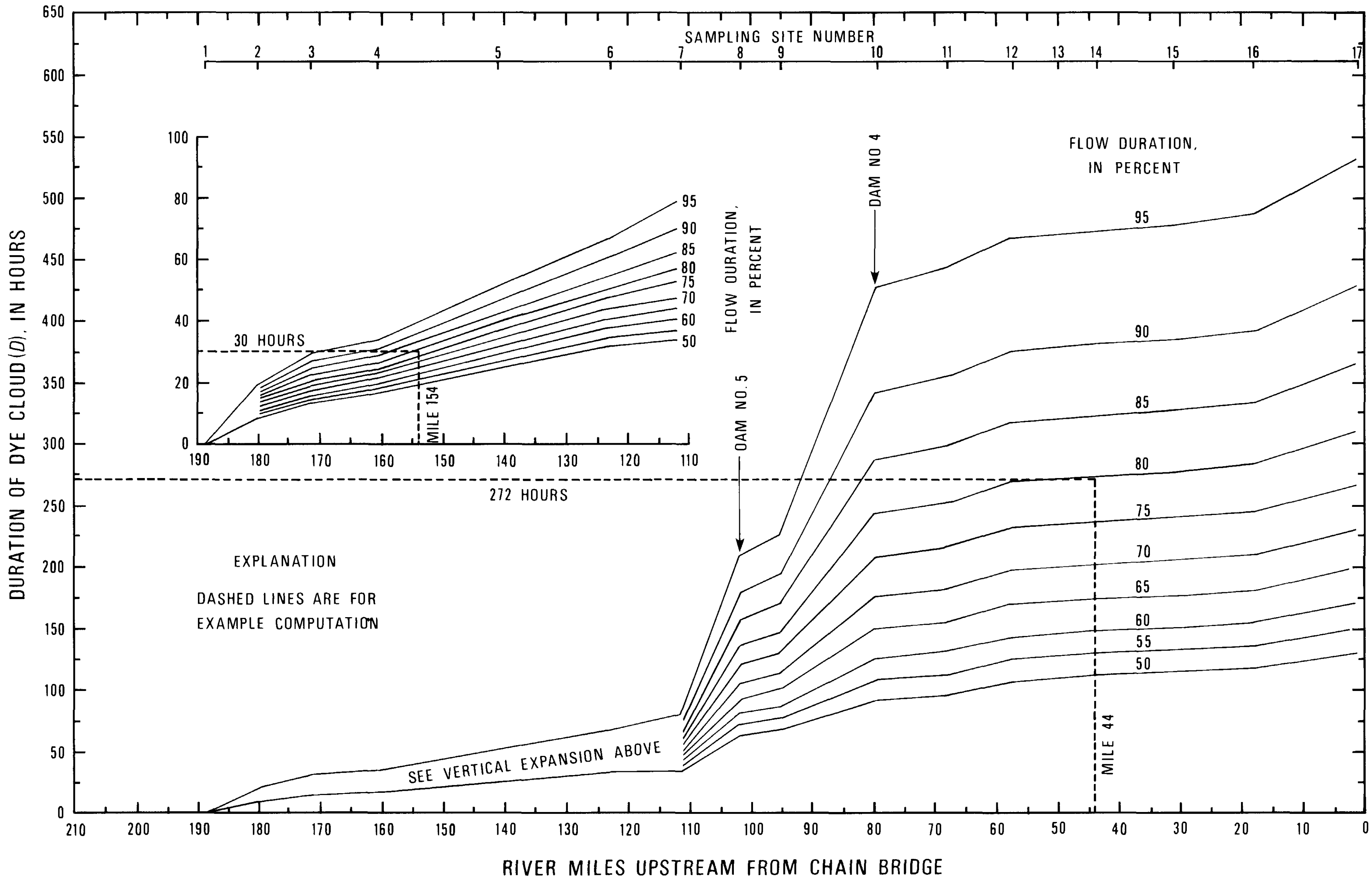

Figure 12. Relation among dye-cloud duration, flow duration, and distance for dispersion studies on the Potomac River. See figure 1 for location of sampling sites.

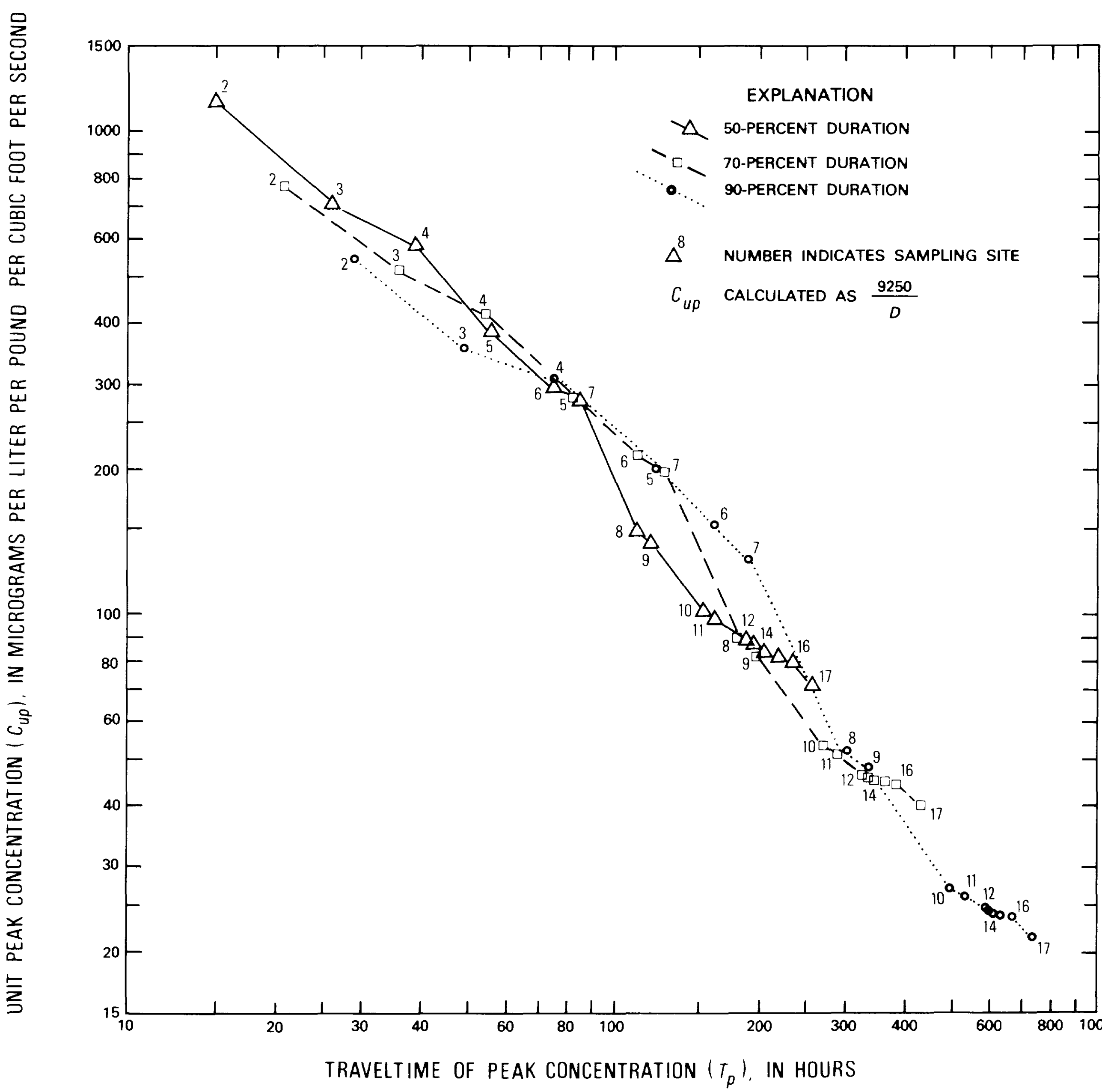

Figure 13. Relation between unit peak concentrations and traveltimes of the peak concentrations at the 50-, 70-, and 90-percent flow durations for a spill at Cumberland, Maryland. Note the greater slope between sampling sites 7–8 and 9–10 caused by Dams No. 5 and 4, respectively. Also note the similarity of slope of the line segments between the same sampling sites for the three flow levels.

B. Use figure 6. Determine the leading-edge traveltimes (T_{LE}) at Magnolia, W. Va. (mile 154), and at Point of Rocks, Md. (mile 44), for a flow duration of 80 percent. $T_{LE(\text{mile } 154)} = 65$ hours; $T_{LE(\text{mile } 44)} = 360$ hours. The approximate time for the leading edge of the contaminant to travel from Magnolia to Point of Rocks is 360 hours minus 65 hours, or 295 hours (12 days and 7 hours). Thus, the leading edge would arrive at Point of Rocks at approximately 5 p.m. on June 15.

2. When will the maximum concentration arrive?
   Procedure:
   A. Use figure 7. Use the same basic procedure as in 1B. $T_{p(\text{mile } 154)} = 75$ hours; $T_{p(\text{mile } 44)} = 450$ hours. The approximate time for the peak concentration to arrive at Point of Rocks is 450 hours minus 75 hours, or 375 hours (15 days

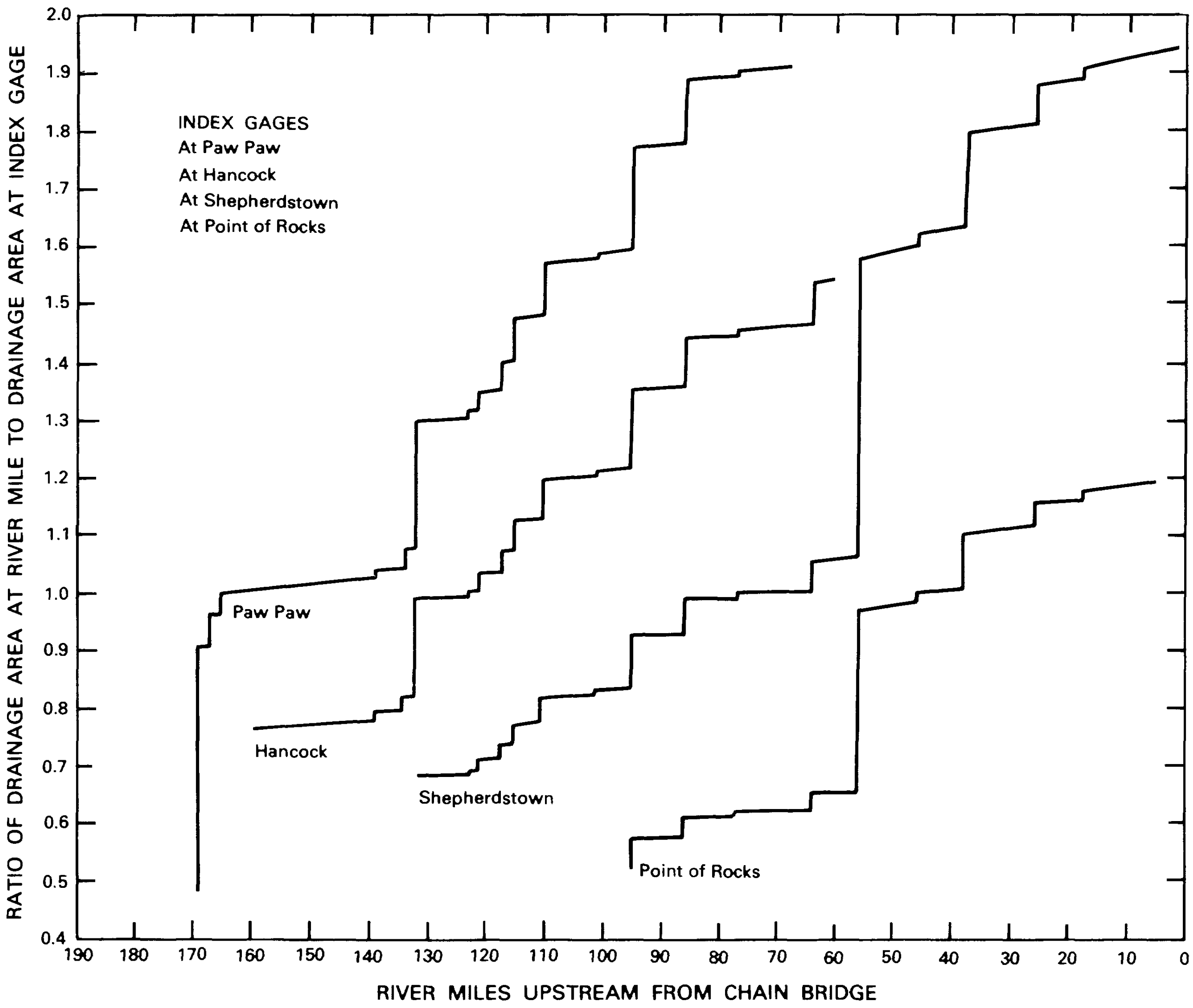

Figure 14. Relation between drainage areas at index gages and drainage areas upstream and downstream from index gages.

and 15 hours). Thus, the peak concentration would arrive at Point of Rocks on June 19 at approximately 1 a.m.

3. When will the contaminant be essentially past Point of Rocks?

Procedure:

A. Use figure 8. Use the same basic procedure as in 1B and 2A. $T_{TE(\text{mile } 154)} = 95$ hours; $T_{TE(\text{mile } 44)} = 635$ hours. The estimated time for the trailing edge of the contaminant to reach Point of Rocks is 635 hours minus 95 hours, or 540 hours (22 days and 12 hours). Therefore, the trailing edge would pass the Point of Rocks bridge at about 10 p.m. on June 25. It must be remembered that the trailing edge is defined as the time the concentration reaches a level of 10 percent of the peak concentration. Therefore, relatively small and diminishing concentrations of the contaminant would probably be passing the site of interest for many days more.

4. What will the peak concentration of the contaminant be (assuming a conservative contaminant) at Point of Rocks?

Procedure:

A. Use figure 12. Use the same procedure as in 1B, 2A, and 3A. The duration of the contaminant cloud at mile 154 is 30 hours. The duration of the contaminant cloud at mile 44 is 272 hours. The cloud duration (D) is the difference (242 hours). Note that $D = T_{TE} - T_{LE}$. The duration of the contaminant cloud could have been obtained directly from previous computations in 1B and 3A, $D = 540 - 295 = 245$ hours. The difference between the two values is caused by inability to read the graphs precisely.

B. Use equation 9 to calculate unit peak concentration:

$$C_{up} = 9{,}250\ D^{-1}$$

$$= \frac{9{,}250}{242}$$

$$= 38.2\ \frac{\mu g/L \times ft^3/s}{lb}.$$

C. Use equation 2A to calculate the peak conservative concentration at Point of Rocks:

$$C_{p(con)} = \frac{C_{up} W_d}{Q},$$

where

W_d = weight of the spilled material and
Q = discharge at Point of Rocks (assume the discharge has not changed).

$$C_{p(con)} = 38.2\ \frac{\mu g/L \times ft^3/s}{lb} \times \frac{20{,}000\ lb}{2{,}250\ ft^3/s}$$

$$= 340\ \mu g/L.$$

In summary, the available information is

1. The leading edge will arrive at approximately 5 p.m., June 15.
2. The peak concentration will arrive at approximately 1 a.m., June 19.
3. The magnitude of the peak concentration of contaminant will be approximately 340 $\mu g/L$ (assuming a conservative contaminant).
4. The concentration will be approximately 34 $\mu g/L$ ($0.1\ C_{p(con)}$) at approximately 10 p.m. on June 25.

The above information is sufficient to construct an approximation of the time-concentration curve at Point of Rocks. Computations similar to the above can be made at any intervening point between the point of the spill and the point of interest. Thus, the behavior of the contaminant cloud as it moves downstream can be predicted as it relates to time, distance, or concentration for any flow level between 50- and 95-percent flow duration.

Many other types of problems can be solved using the graphs and tables. For example, using the previous problem, suppose that it is determined that the contaminant is not harmful in concentrations of less than 1,000 $\mu g/L$. When will the maximum contaminant concentration be less than 1,000 $\mu g/L$, and where will the contaminant cloud be at that time?

The solution to the above problem requires information about discharge along the river. Figure 14 gives the ratios of drainage area (DA_a) at river miles upstream and downstream from the index gage to the drainage area (DA_g) at the index gage. Although the relation between drainage area and discharge is not absolute, the relation $Q_a = (DA_a/DA_g)Q_g$ will provide a fair approximation of the discharge at river-mile points a short distance upstream and downstream from the index gage. The index gage should be used where the ratio values are nearest to unity (1.00).

Suppose for purposes of this problem that the discharge throughout the reach is at the 80-percent flow-duration level. (In practice, the flow-duration level should be determined.) The following information is available for solving the problem:

Peak conservative contaminant concentration ($C_{p(con)}$) = 1,000 $\mu g/L$ (given),
Flow duration = 80 percent (given),
Q (Hancock) = 710 ft^3/s (fig. 4),
Q (Shepherdstown) = 1,170 ft^3/s (fig. 4),
Q (Point of Rocks) = 2,250 ft^3/s (fig. 4), and
W_d = 20,000 pounds (given).

Solution:

Use equations 9 and 2A:

$$C_{up} = 9{,}250\ D^{-1} \text{ or } D = \frac{9{,}250}{C_{up}}$$

$$C_{p(con)} = \frac{C_{up} W_d}{Q} \text{ or } Q = \frac{C_{up} W_d}{C_{p(con)}}$$

$$D \times Q = 9{,}250\ \frac{W_d}{C_{p(con)}}$$

(This product has the units of volume, but units are not pertinent to the solution of the problem and will not be shown.)

$$D \times Q = 9{,}250\ \frac{20{,}000\ lb}{1{,}000\ \mu g/L} = 185{,}000.$$

Because there are two unknowns in the equation, the answer will require a trial-and-error or a graphical solution. The trial-and-error solution will be demonstrated to show the process. The graphical solution will be explained at the end of the problem.

Trial Solution 1 (check at mile 105):

From figure 14,

$$Q_{(\text{mile } 105)} = 1.20\, Q_{(\text{Hancock})} = 1.20 \times 710 = 852 \text{ ft}^3/\text{s}$$

From figure 12, for 80-percent flow duration,

Cloud duration (mile 154) = 30 hours (spill location) and

Cloud duration (mile 105) = 110 hours.

$D_{(\text{mile } 105)}$ = 110–30 = 80 hours (cloud duration initialized to zero at mile 154)

$D \times Q = 80 \times 852 = 68{,}160$

$68{,}160 < 185{,}000$

Because D and Q are increasing in the downstream direction, try farther downstream.

Trial Solution 2 (check at mile 80):

From figure 14,

$$Q_{(\text{mile } 80)} = 0.99\, Q_{(\text{Shepherdstown})} = 0.99 \times 1{,}170 = 1{,}160 \text{ ft}^3/\text{s}$$

From figure 12,

Cloud duration$_{(\text{mile } 80)}$ = 235 hours

$D_{(\text{mile } 80)}$ = 235 − 30 = 205 hours (initialized to zero at mile 154)

$D \times Q = 1{,}160 \times 205 = 238{,}000$

$238{,}000 > 185{,}000$

Move back upstream. From figure 14, it can be seen that the discharge remains constant to mile 86. Therefore, a D value of 159 (185,000 ÷ 1,160) is needed at that point. Check to see if $D \geq 159$ at mile 86. $D = 210 - 30 = 180$ hours. The solution is farther upstream. From figure 14, the Q from mile 86 to mile 95 is constant at 0.93 $Q_{(\text{Shepherdstown})}$, or 1,088 ft³/s. A value of D equal to 170 hours (185,000 ÷ 1,088) is needed. Cloud duration = D + 30 = 170 + 30 = 200 hours. In figure 12, a cloud duration of 200 hours is found at mile 87, which satisfies the equation as follows:

$$D = 200 - 30 = 170 \text{ hours}$$
$$Q = 0.93\, Q_{(\text{Shepherdstown})} = 0.93 \times 1{,}170 = 1{,}088 \text{ ft}^3/\text{s}$$
$$D \times Q = 170 \times 1{,}088 = 185{,}000$$

Therefore, the peak concentration of a conservative contaminant will be approximately 1,000 µg/L when the peak concentration reaches mile 87. From figure 7, the peak concentration will arrive at mile 87, 245 hours (320 − 75) after the spill. The solution is, therefore, June 13 at approximately 3 p.m., at mile 87.

A graphical solution to the above problem can be accomplished as follows:

$$D \times Q = 185{,}000$$

or

$$D = \frac{185{,}000}{Q}.$$

Use figure 14 to calculate how Q varies upstream and downstream from the Shepherdstown gage. Use the calculated Q to calculate how D must vary to satisfy the equation. Plot calculated D versus miles above Chain Bridge. Use figure 12 to determine how D actually varies with distance above Chain Bridge. Remember that D equals the cloud duration at the point of calculation minus the cloud duration at the point of the spill. Plot actual D values on the same graph. The intersection of the two lines gives the solution to the problem. (Note: The cloud-duration values at the breaks in slope in figure 12 can be obtained from table 7.)

The following is a partial list of the types of problems that can be solved with the information contained in this report:

1. Time of arrival of leading edge of contaminant cloud at a point.
2. Time of arrival of maximum concentration of contaminant cloud at a point.
3. Time of arrival of trailing edge of contaminant cloud at a point.
4. Maximum concentration of contaminant cloud at a point.
5. Time of passage of contaminant cloud at a point.
6. Location of leading edge of contaminant cloud at any time.
7. Location of maximum concentration of contaminant cloud at any time.
8. Location of trailing edge of contaminant cloud at any time.
9. Length of contaminant cloud at any time.
10. Attenuation curve of peak concentration related to distance.
11. Attenuation curve of peak concentration related to time.
12. Time when peak concentration will be below a specified value.
13. Location where peak concentration will be less than a specified value.

DISCUSSION

The methods and procedures given in this report have been generalized to make them applicable to a wide range of circumstances. In developing the techniques, a number of assumptions were made and are discussed below. In using the techniques, many subjective judgments will have to be made by the user to adjust for the difference between assumed conditions and actual field conditions.

The river flow during the two dye studies was generally one of slowly decreasing flow. No precipitation occurred during the studies (which would have introduced a flood wave into the flow system). If precipitation had occurred, the studies would have been aborted. The effect of a hydraulic wave on the movement of a discrete particle of water is indeterminate by dye-tracer studies, and procedures to handle such a situation are beyond the scope of this study. Therefore, extreme caution should be exercised in using the procedures when a significant flood wave is present in the system.

Two velocities and associated river discharges were available for each river segment between sampling sites. In the interpolation and extrapolation to other discharges, a log-linear relationship was assumed to exist between the velocity of the peak concentration and the average discharge at the index gage during the period the peak concentration was moving between successive sampling points. A similar assumption was made for the velocity of the leading edge and the trailing edge of the dye cloud. This assumption is known to be more credible with the peak concentration and the leading edge than with the trailing edge because of the truncation of the trailing edge at 10 percent of peak concentration.

In the example computation, steady flow rates were assumed to exist for a long period of time. Actually, steady flow never exists in a natural flow system. If precipitation is occurring or has recently occurred, the discharge is always increasing. In the case of no precipitation, the discharge is always decreasing. The data for this study were collected under conditions of no precipitation. The procedures are most useful under similar conditions. Even under ideal flow conditions, the solution to a problem will be an iterative one because of the long traveltimes involved and the likelihood that flow rates will change significantly during the period of interest, particularly during low-flow periods. Calculations using the procedures, when a hydraulic wave is present in the reach, are subject to potentially large and unquantifiable errors.

Complete lateral mixing was forced to exist in the development of the concentration attenuation procedures. However, under natural conditions, complete mixing never occurs because of the side injection of water from tributaries. In the sample problem, a peak conservative concentration of contaminant of 340 μg/L was calculated for Point of Rocks. The 340 μg/L is an average peak concentration. In an actual situation, the concentration would be higher on the Maryland side of the river and lower on the Virginia side owing to the large side injection of water from the Shenandoah River. A gross calculation of mixing length for this side injection indicates that complete mixing would not occur within the remainder of the study reach. Considerable personal judgment must be exercised by the user in deciding how the calculated average concentration is distributed across the river.

All calculations and procedures relative to concentration assume conservation of mass. In other words, it is assumed that the dye or contaminant is conservative and is not lost for any reason as it moves downstream. In an actual situation, there are processes other than dilution by mixing that would cause a decreasing concentration. These processes could be physical, chemical, or biological in nature, depending on the substance. As a result of the assumed conservation of mass, the user's calculation of average concentrations will be higher than observed average concentrations. However, lateral mixing may not be complete; hence, a localized peak concentration in the cross section may be higher than the average peak concentration determined from the relation. These two factors are compensating and the relations should provide a safe answer. Adjustments based on the user's knowledge of the characteristics of the spilled substance may be warranted in some instances.

The dye used in the studies performs as would a soluble substance when mixed in the river. The behavior of immiscible or floating substances cannot be determined by using the techniques presented in this report.

The studies measured the results of a direct slug injection of dye at several points across the river. The probability of an actual contaminant spill occurring in this manner is extremely small. It is much more likely that a spill would enter the river as a side injection either from the streambank or from a tributary stream. In such a situation, time must be allowed for lateral mixing before applying the relations to determine average peak concentration. The distance required for lateral mixing of a side injection of contaminant would be substantial for the Potomac River because of the river's high width-to-depth ratio. According to F. A. Kilpatrick (written commun., 1983), the mixing distance for a center or side injection can be approximated from the following equations:

$$L_m \text{ [center spill]} = 0.0885 \frac{vW^2}{d^{3/2}S^{1/2}} \quad (10)$$

and

$$L_m \text{ [side spill]} = 0.354 \frac{vW^2}{d^{3/2}S^{1/2}} \quad (11)$$

where

L_m = distance required for mixing, in feet,
v = mean river velocity, in feet per second,
W = mean river width, in feet,
d = mean depth of the river, in feet, and
S = water-surface slope, in foot per foot (see table on p. 3).

The methods presented in this report are intended to be used as a guide in monitoring the movement of a soluble material in the Potomac River. It would be inconceivable that those responsible for managing and regulating water resources would not continually monitor a situation such as that described in the sample problem. Extensive technical and personnel resources to collect and analyze samples, to monitor and measure the discharge in the river, and to track the actual movement of the contaminant cloud would be necessary. The procedures in this report will allow a rapid assessment of the magnitude of the problem and will assist in scheduling the necessary monitoring activities. A very important use of the report should be to enhance the understanding (in advance of a serious problem) of how the river system works to transport, disperse, and dilute a soluble material spilled in the river.

SUMMARY

Dye studies on the Potomac River between Cumberland, Md., and Washington, D.C., were made in 1964 and 1981. Data from the studies were used to develop a generalized method for predicting traveltimes and concentration attenuation resulting from a spill of a soluble substance into the river.

The procedures are most useful during periods of nearly steady or slowly decreasing rates of flow. The procedures will allow the user to estimate parameters to construct the approximate time-concentration curve, at any point along the river, resulting from a spill of any amount of water-soluble material at any point upstream, under a wide range of flow conditions.

An example computation using the graphs and tables shows that with flow conditions at the 80-percent duration level, a spill of 20,000 pounds of water-soluble contaminant at Magnolia, W. Va., would have the following effect on the river at Point of Rocks, Md.: (1) The leading edge of the contaminant cloud would reach Point of Rocks approximately 12½ days after the spill; (2) the peak concentration of contaminant would occur about 15½ days after the spill; (3) the magnitude of the peak concentration would be about 340 μg/L, if the contaminant were conservative; and (4) the concentration of contaminant would be about 34 μg/L 22½ days after the spill.

The methods and procedures are intended primarily as a reconnaissance tool for use by water managers and regulatory authorities. The tool will allow the user to rapidly assess the seriousness of a spill and more efficiently plan and execute a program to mitigate its effects. An even more important use of the report will be to provide the opportunity to understand, in advance of a serious spill, how the river transports, disperses, and dilutes a water-soluble substance.

The conditions under which the field data were collected and the assumptions under which the data were interpreted have been described. The user is cautioned not to depend on the procedures under conditions that depart radically from those described. The user is also advised that many subjective decisions will be required to adjust the results to reflect the field situation existing at the time a problem occurs.

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Conversion of Measurement Units

The following factors may be used by readers who wish to convert inch-pound units to the International System of Units (SI).

Multiply inch-pound units	by	To obtain SI units
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Mass	
pound (lb)	453.6	gram (g)
	Volume	
gallon (gal)	3.785	liter (L)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow	
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)

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