TRAVELTIME AND DISPERSION IN THE SHENANDOAH RIVER AND ITS TRIBUTARIES, WAYNESBORO, VIRGINIA, TO HARPERS FERRY, WEST VIRGINIA

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

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DONALD PAUL HODEL, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
208 Carroll Building
8600 La Salle Road
Towson, Maryland 21204

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CONVERSION FACTORS AND ABBREVIATIONS

For the convenience of readers who may prefer to use metric (International System) units rather than the inch-pound units used in this report, values may be converted by using the following factors:

Multiply inch-pound unit	By	To obtain metric unit
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
pound (lb)	453.6	gram (g)
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)
mile per hour (mi/h)	1.609	kilometer per hour (km/h)

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ABSTRACT

Two traveltime and dispersion measurements using rhodamine dye were conducted on a 178-mile reach of the Shenandoah River between Waynesboro, Virginia, and Harpers Ferry, West Virginia. The flows during the two measurements were at approximately the 85- and 45-percent flow durations.

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 reach studied. The procedure can be used to calculate traveltime and concentration data for almost any spillage that occurs during relatively steady flow between 40- to 95-percent flow duration.

Based on an analogy between the general shape of a time-concentration curve and a scalene triangle, the procedures can be used on long river reaches to approximate the conservative time-concentration curve for instantaneous spills of contaminants. The triangular-approximation technique can be combined with a superposition technique to predict the approximate, conservative time-concentration curve for constant-rate and variable-rate injections of contaminants.

The procedure is applied to a hypothetical situation in which 5,000 pounds of contaminant is spilled instantaneously at Island Ford, Virginia. The times required for the leading edge, the peak concentration, and the trailing edge of the contaminant cloud to reach the water intake at Front Royal, Virginia (85 miles downstream), are 234, 280, and 340 hours, respectively, for a flow at the 80-percent flow duration. The conservative peak concentration would be approximately 940 micrograms per liter at Front Royal.

The procedures developed in this study cannot be depended upon when a significant hydraulic wave or other unsteady flow condition exists in the flow system or when the spilled material floats or is immiscible in water.

INTRODUCTION

Background

Public and private water-supply managers and State and local health agencies need traveltime and dispersion information on rivers used for water supply in case a toxic substance is spilled into the river upstream from water intakes. A river is a dynamic system, and, without a generalized procedure to integrate the effect of different flows, different amounts of spill, and different channel characteristics on the transport, dispersion, and dilution of a toxic substance, the responsible authorities cannot respond effectively to a contaminant spill.

In the Potomac River basin, the traveltime and dispersive characteristics of the main stem and all the major tributaries, except the Shenandoah River, have been studied by dye-tracing methods (Taylor, 1970; Taylor and Solley, 1971; Taylor and others, 1985; and Jack, 1986). In the fall of 1983, at the request of the Interstate Commission on the Potomac River Basin (ICPRB), this study was initiated to define the traveltime and dispersive characteristics of the Shenandoah River, a major tributary of the Potomac River (fig. 1). The study was done by the U.S. Geological Survey in cooperation with the ICPRB and the Virginia State Water Control Board.

Purpose and Scope

The purposes of this report are twofold: (1) To describe the movement of a soluble substance in the Shenandoah River under a wide range of flow conditions, and (2) to present techniques for predicting traveltimes and concentrations at any downstream location resulting from the spillage of any amount of soluble contaminant at any point within the study reach.

Acknowledgments

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

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DESCRIPTION OF THE STUDY REACH

The study reach (fig. 1) is approximately 178 mi (miles) long and consists of the South River downstream from Waynesboro, Va., the South Fork Shenandoah River, and the Shenandoah River. In this reach, the river flows generally northeastward from Waynesboro until it joins the Potomac River at Harpers Ferry, W. Va. The two principal tributaries to this reach are the North River, which has a drainage area of 823 mi^2 (square miles) at its confluence with the South River, and the North Fork Shenandoah River, which has a drainage area of 1,033 mi^2 at the confluence with the South Fork Shenandoah River. The other tributary inflows come from small streams that drain the flanks of the narrow Shenandoah Valley. The total drainage area for the Shenandoah River basin is 3,054 mi^2.

The South River in the study reach has a fairly uniform slope of about 9 ft/mi (feet per mile). The slope on the South Fork Shenandoah River is fairly uniform at about 6 ft/mi. The Shenandoah River falls at the rate of slightly more than 3 ft/mi, except for the last 7-mi section, which steepens sharply to a rate of 11 to 12 ft/mi where the river flows through an almost continuous series of rapids.

River mileages used in this report were measured on U.S. Geological Survey 7½-minute (1:24,000) topographic maps, beginning at the mouth of the river. Therefore, any reference to mile numbers denotes miles upstream from the mouth of the Shenandoah River. Table 1 gives a selected list of landmarks and the associated river-mile locations. All of these landmarks can be found on U.S. Geological Survey 7½-minute topographic maps, but not all are shown in figure 1.

The total reach was divided into 15 stream segments for study. The 16 sampling sites that define the segments are shown in figure 1 and are numbered to increase in the downstream direction. Table 2 gives the sampling site name, river mile, segment lengths between sampling sites, and a drainage-area ratio described in the next section of this report.

Many low-head dams are located in the study reach. These dams, in most cases, do not store sufficient water to significantly impede its movement. Generally, the dams are run-of-the-river type and are not used to regulate flow. The power dams at mile 101.4 near Luray, Va., mile 51.0 near Front Royal, Va., and at mile 5.7 near Millville, W. Va., do retard the flow noticeably, particularly during low-flow periods.

Table 1.--River-mile location of selected tributaries, bridge crossings, and other identifiable landmarks on the Shenandoah River

[Landmarks are shown on U.S. Geological Survey 7 1/2-minute (1:24,000) topographic maps]

River mile	Landmark	River mile	Landmark
[1]179.9	State Highway 650, Waynesboro, Va.	[2]99.2	State Highway 675, Bixler Bridge
[2]178.5	State Highway 664, Waynesboro, Va. (SWCB gage)	79.9	Burners Ford
175.5	U.S. Highway 340, Waynesboro, Va.	[2]73.1	State Highway 613, Bentonville, Va.
[2]173.2	Hopeman Parkway, Waynesboro, Va. (SWCB gage)	[2,3]57.7	Pumping Station, Front Royal, Va. (USGS gage)
170.6	State Highway 611, Dooms, Va.	55.2	U.S. Highway 340, Front Royal, Va.
[2]165.8	State Highway 612, Crimora, Va.	54.6	Confluence North Fork
[2,3]159.4	State Highway 778, Harriston, Va. (SWCB gage)	52.9	Power plant
155.3	State Highway 256, Grottoes, Va.	[1]51.0	Power-plant dam
152.0	Confluence North River, Port Republic, Va.	[2]47.5	State Highway 624, Morgan Ford, Va.
[3]148.6	Gaging Station, Lynnwood, Va. (SWCB gage)	[2]36.6	U.S. Highway 17 and 50
[2]142.6	State Highway 649, Island Ford, Va.	[2]22.1	State Highway 7, Castlemans Ferry, Va.
136.1	U.S. Highway 33, Elkton, Va.	19.5	Virginia-West Virginia state line
[1,2]129.1	State Highway 602, Shenandoah, Va.	[2]8.4	State Highway 9, Bloomen, W.Va.
[2]121.2	U.S. Highway 340, Grove Hill, Va.	5.7	Power-plant dam
115.8	Power-plant dam, Newport, Va.	4.8	Gaging station, Millville, W.Va. (USGS gage)
[2]106.2	U.S. Highway 211 (SWCB gage)	[2]0.8	U.S. Highway 340, Harpers Ferry, W.Va.
101.4	Power-plant dam, Luray, Va.	0	Mouth

[1] Dye-injection site
[2] Dye-sampling site
[3] Index gaging station

Table 2. -- Location, segment length, and drainage-area ratios for sampling sites used in study

[Drainage-area ratio: Approximate ratio of drainage area at sampling site to drainage area at indicated index gage. Index gages: H = Harriston, L = Lynnwood, F = Front Royal, C = Composite (Sum of drainage areas at South Fork Shenandoah River at Front Royal and North Fork Shenandoah River near Strasburg)]

Sampling site no. [1]	River mile	Segment length (mi)	Sampling site name	Drainage-area ratio and index gage
1	178.5		Waynesboro	
		5.3		
2	173.2		Hopeman Parkway	0.70(H)
		7.4		
3	165.8		Crimora	0.87(H)
		6.4		
4	159.4		Harriston (Index Gage)	1.00(H)
		16.8		
5	142.6		Island Ford	1.06(L)
		13.5		
6	129.1		Shenandoah	1.18(L)
		7.9		
7	121.2		Grove Hill	1.19(L)
		15.0		
8	106.2		U.S. Highway 211	1.27(L)
		7.0		
9	99.2		Bixler Bridge	1.29(L)
		26.1		
10	73.1		Bentonville	0.96(F)
		15.4		
11	57.7		Front Royal (Index Gage)	1.00(F)
		10.2		
12	47.5		Morgan Ford	1.15(C)
		10.9		
13	36.6		U.S. Highway 17 and 50	1.16(C)
		14.5		
14	22.1		State Highway 7	1.22(C)
		13.7		
15	8.4		State Highway 9	1.25(C)
		7.6		
16	0.8		Harpers Ferry	1.27(C)

[1] See figure 1.

RIVER DISCHARGE

River discharge is directly related, although not in an absolute sense, to the velocity of water. Therefore, a knowledge of the discharge of the river is required, both in the development of the methods and procedures in this report and, subsequently, in the use of the methods and procedures to solve a problem. Seven gaging stations are located directly in the study reach and one important station is located near the mouth of the North Fork Shenandoah River; these stations are used to monitor river discharges. The gaging stations are operated by the Virginia State Water Control Board or the Geological Survey. The stations are shown in the following table.

Station no.	Station name	Miles above mouth	Average slope in reach (ft/ft)	Drainage area (mi^2)
(Operated by Virginia State Water Control Board)				
01626000	South River near Waynesboro, Va.	178.5		127
			0.0018	
01626850	South River near Dooms, Va.	173.2		149
			0.0016	
01627500	South River at Harriston, Va.	159.4		212
			0.0020	
01628500	South Fork Shenandoah River near Lynnwood, Va.	148.6		1,084
			0.0013	
01629500	South Fork Shenandoah River near Luray, Va.	106.2		1,377
(Operated by U.S. Geological Survey)				
			0.0010	
01631000	South Fork Shenandoah River at Front Royal, Va.	57.7		1,642
			0.0006	
01636500	Shenandoah River at Millville, W. Va.	4.8		3,040
01634000[1]	North Fork Shenandoah River near Strasburg, Va.			768

[1] Station not located in study reach.

The daily mean discharges at the above gaging stations for the two periods of field data collection for this study are given in table 3. As can be seen from these discharge data, the flow during the study periods was fairly stable. During the September 1983 study, the average of the daily discharges was at about the 85-percent flow-duration level. The flow-duration level for the average of the daily discharges during the June 1984 study period was about 45 percent. Flow duration, expressed in percent, is defined as the percentage of time that the historic daily discharges have equaled or exceeded a specified discharge at a gaging station.

Time of travel varies inversely with river discharge. In order to develop a method to predict traveltimes that can be used over a range of discharges, it is necessary to relate time of travel in some way to river discharge. Over a long reach of river, discharge generally increases in the downstream direction as the drainage area increases. These increases, however, do not occur uniformly with distance along the river. Where tributaries enter the river, discharge increases abruptly. Depending in part on the drainage area of the tributary, these increases in discharge can be substantial. Usually, however, the river channel adjusts 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 characteristic for the relation 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 river discharge for use in developing a relation between discharge and time of travel. The relation between discharge and flow duration is shown in figure 2 for four gaging stations chosen as index gages for this study. Note that one of these index stations is a composite of the most downstream stations on the North Fork and the South Fork of the Shenandoah River. This composite station gives a better representation of flow, particularly during low-flow periods, on most of the length of the main stem of the Shenandoah River than does the station at Millville, where flow is regulated by the power-generating plant just upstream.

Flows at locations other than at the gaging stations are required when using some of the procedures in this report. Figure 3 gives the relation between river-mile location and the ratio of the drainage areas (DA_x) upstream and downstream

Table 3.--Daily mean discharge, in cubic feet per second, at indicated gaging stations during dye studies, September 1983 and June 1984

[Discharge for composite gaging station is the sum of the discharges of the South Fork Shenandoah River at the Front Royal gaging station and the North Fork Shenandoah River near Strasburg gaging station.]

Basin	South River			South Fork Shenandoah River			Shenandoah River	
Gaging station location	near Waynesboro	near Dooms	at Harriston	near Lynnwood	near Luray	at Front Royal	Composite	at Millville
Drainage area (square miles)	127	149	212	1,084	1,377	1,642	2,410	3,040
Date \ River mile	178.5	173.2	159.4	148.6	106.2	57.7	-	4.8
9-06-83	36	65	79	298	398	440	644	652
9-07-83	36	65	77	289	398	428	579	617
9-08-83	36	62	77	285	379	423	554	631
9-09-83	36	60	76	280	379	421	561	584
9-10-83	35	60	75	271	373	399	561	533
9-11-83	34	58	74	271	367	401	537	552
9-12-83	35	58	73	271	373	398	523	558
9-13-83	35	67	77	289	430	439	577	564
9-14-83	35	60	81	325	430	471	615	604
9-15-83	34	58	75	298	430	491	619	645
9-16-83	34	58	73	285	411	460	588	631
9-17-83	34	58	73	276	398	452	597	624
9-18-83	33	58	71	271	385	420	560	610
9-19-83	32	60	73	271	379	398	528	597
9-20-83	32	60	73	267	367	385	506	578
9-21-83	33	65	76	267	392	397	534	578
9-22-83	34	60	81	285	385	420	559	597
6-04-84	109	134	190	724	940	1,120	1,480	1,910
6-05-84	103	128	183	689	900	1,060	1,410	1,850
6-06-84	99	125	175	669	998	1,040	1,360	1,830
6-07-84	94	119	168	639	844	1,110	1,520	1,730
6-08-84	91	116	162	618	828	909	1,310	1,800
6-09-84	88	112	157	599	780	988	1,330	1,670

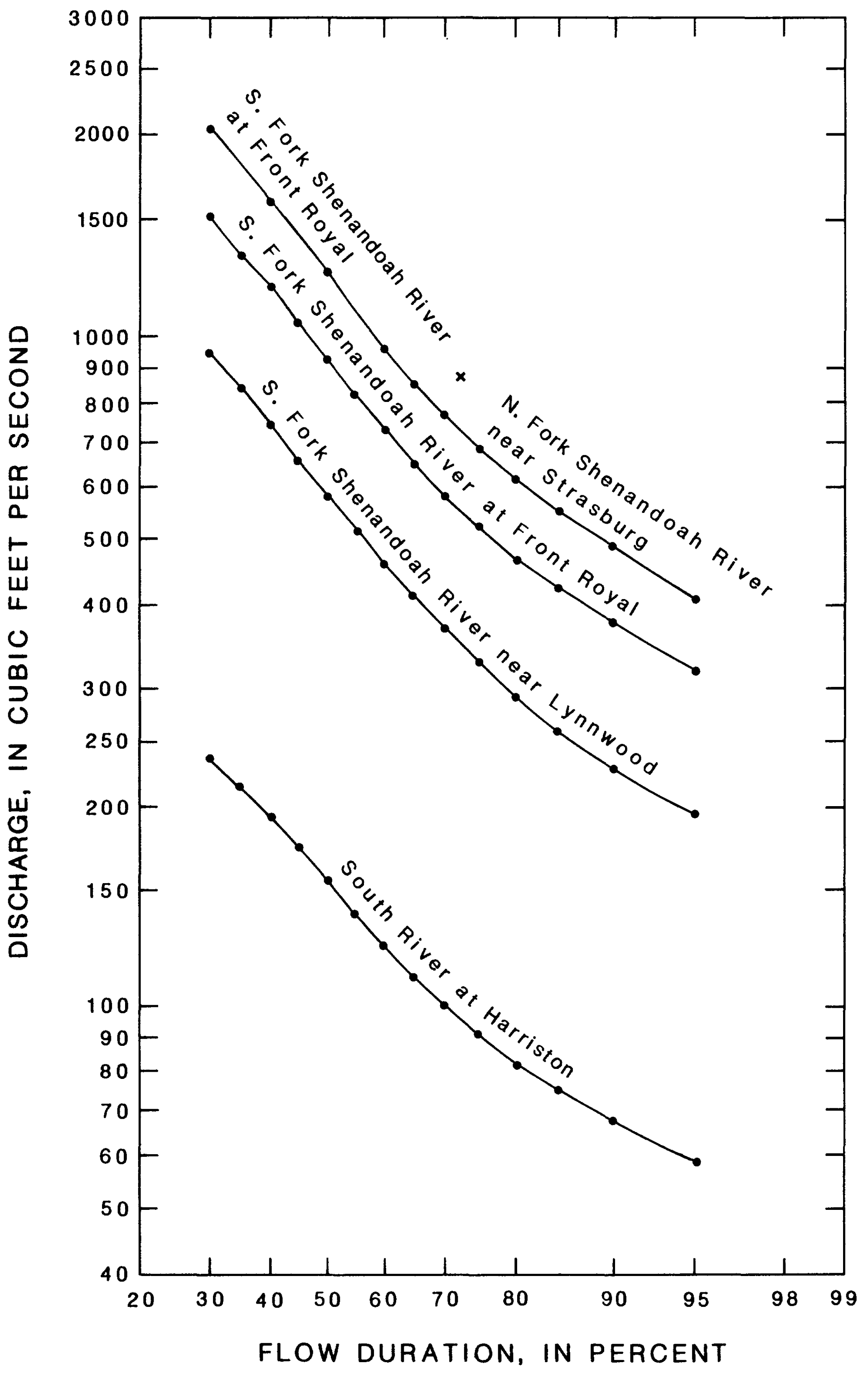


Figure 2.-- Relation between flow duration and discharge at index gaging stations.

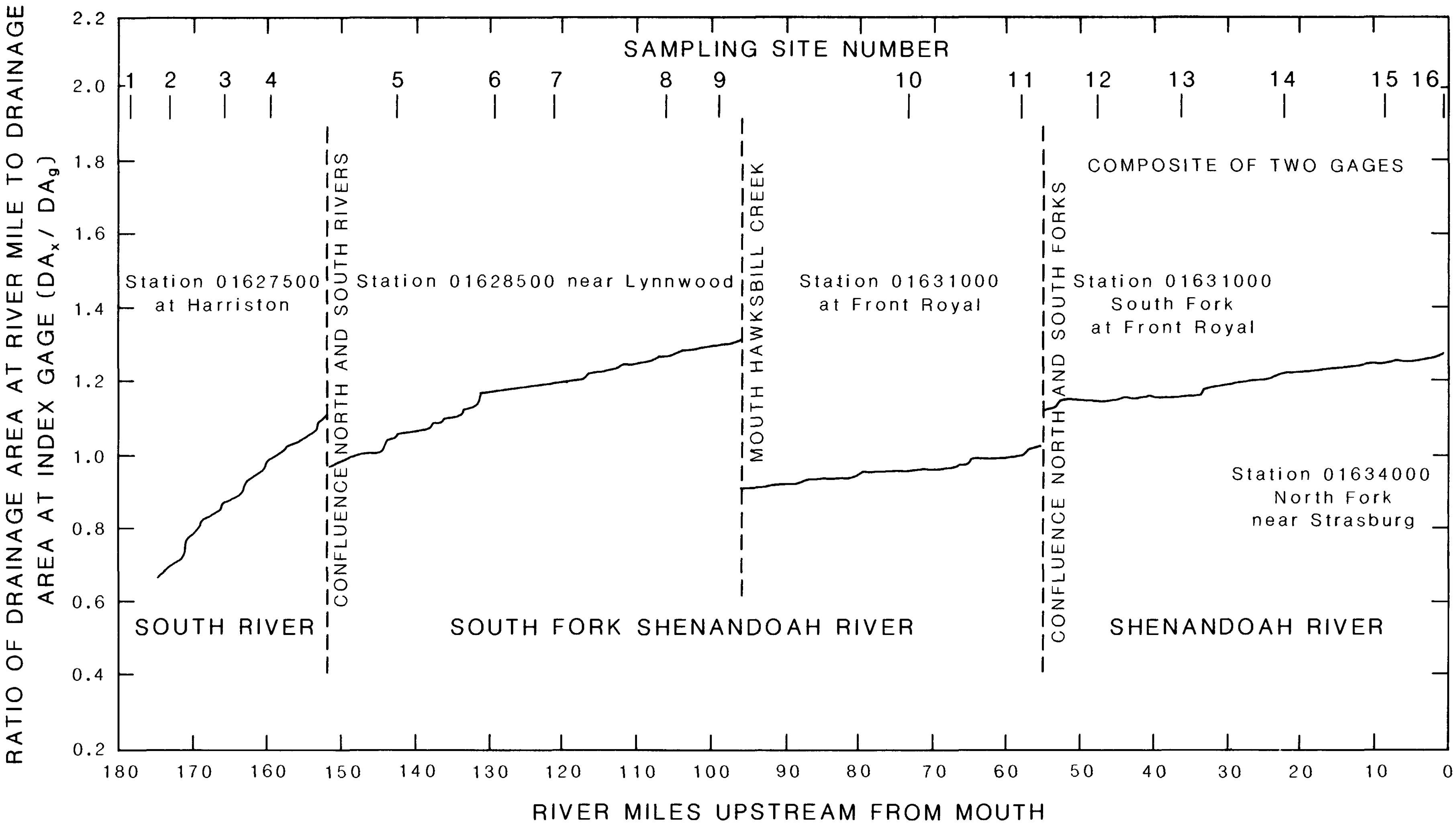


Figure 3.-- Relation between drainage areas at index gages and drainage areas upstream and downstream from index gages.

from the index gages to the drainage areas (DA_g) at the index gages. Although the relation between drainage area and discharge is not absolute, these ratios can be used with the discharge from the index gage to make a reasonable estimate of the discharge at any location by the formula $Q_x = Q_g(DA_x/DA_g)$. The term (DA_x/DA_g) is the ratio given in figure 3. This ratio at any river-mile location multiplied by the discharge (Q_g) at the indicated index gaging station should give a reasonable estimate of the flow at that location. Table 2 gives a list of the drainage-area ratios for the sampling sites used in this study. The discharge (Q_g) at the composite index gage, for the main stem of the Shenandoah River, is obtained by adding the flows from the South Fork Shenandoah River at Front Royal and the North Fork Shenandoah River at Strasburg.

Each of the gaging stations used as an index gage, except South River at Harriston, is equipped with remote telemetry equipment operated for various agencies. This remote equipment allows those who are most likely to need it to acquire real-time discharge data by telephone.

FIELD PROCEDURES

Fluorometric procedures (Wilson and others, 1984) and field procedures (Hubbard and others, 1982) for conducting traveltime and dispersion studies on streams using dye tracers are well documented. In general, the described procedures were followed closely in conducting this study.

The 178-mile study reach was divided into three subreaches for the September 1983 study. Each of these subreaches was injected with rhodamine WT, 20-percent dye on September 6, 1983, when the flow was at about the 85-percent flow duration. The dye for the upstream subreach was injected at mile 179.9 and was sampled at seven sites. The dye for the middle subreach was injected at mile 129.1 and was sampled at six sites, and the dye for the downstream subreach was injected at mile 52.4 and was sampled at five sites. The resulting time-concentration curves are shown in figure 4.

For each subreach, the dye was injected at multiple points in the cross section sufficiently far upstream to provide time for lateral and vertical mixing prior to arriving at the first sampling site. The first sampling site for the two downstream subreaches are the same as the last sampling sites for the two upstream

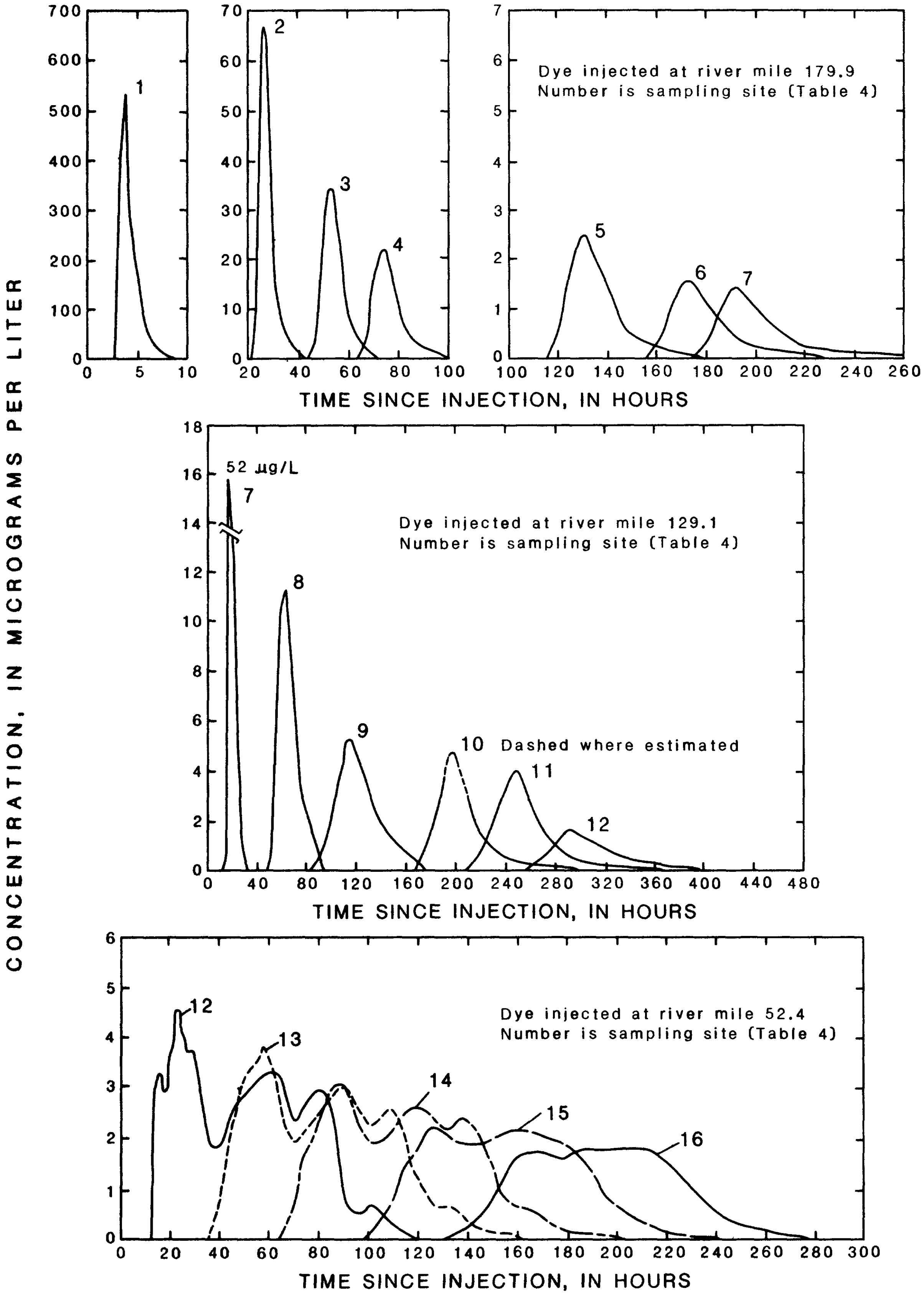


Figure 4.-- Observed time-concentration curves for the September 1983 study.

subreaches. This explains the 18 time-concentration curves when there are only 16 sampling locations.

The unusual shape of the time-concentration curves for the downstream subreach (fig. 4) can be explained. The dye was injected at multiple points across the pool of a small dam. The outlet structure for the dam (1.4 mi downstream from the injection site) is a rectangular notch in the center of the dam. The differential in downstream velocities through the pool caused the dye to be fed through the notch in the dam for a period exceeding 80 hours. Although this was not an expected result, it will be used later in the report as an example to demonstrate the solution to a variable-rate injection problem.

At each of the 16 sampling sites, hand samples were collected at one point in the cross section that was selected visually to represent the main mass of flow. The fluorescence of each sample was measured in the field on a fluorometer and converted to concentration based on a previously defined calibration curve. The frequency of sampling at each site was varied, based on the time since injection of the dye and the appearance of the time-concentration curve at the 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. At concentrations less than about 10 percent, the tail of the dye cloud becomes almost asymptotic to the zero-concentration line, particularly at the most downstream sampling sites for each dye injection. A current-meter discharge measurement was made at most sampling sites sometime during the passage of the dye cloud.

The same procedures, as previously described, were used during the study in June 1984 that was made when river flow was at the 45-percent flow-duration level. However, for this study, the total reach was divided into four subreaches. This was done to shorten the total study time and thus reduce the risk of a rainstorm washing out the study. An earlier attempt to obtain the high-flow data was aborted after the study was washed out by a storm in February 1984. The time-concentration curves and injection locations for the four subreaches are shown in figure 5. Figure 6 is a graphic portrayal of the accumulated traveltimes for the September 1983 and June 1984 studies. Tables 4 and 5 summarize the traveltime and dispersion data for the two studies.

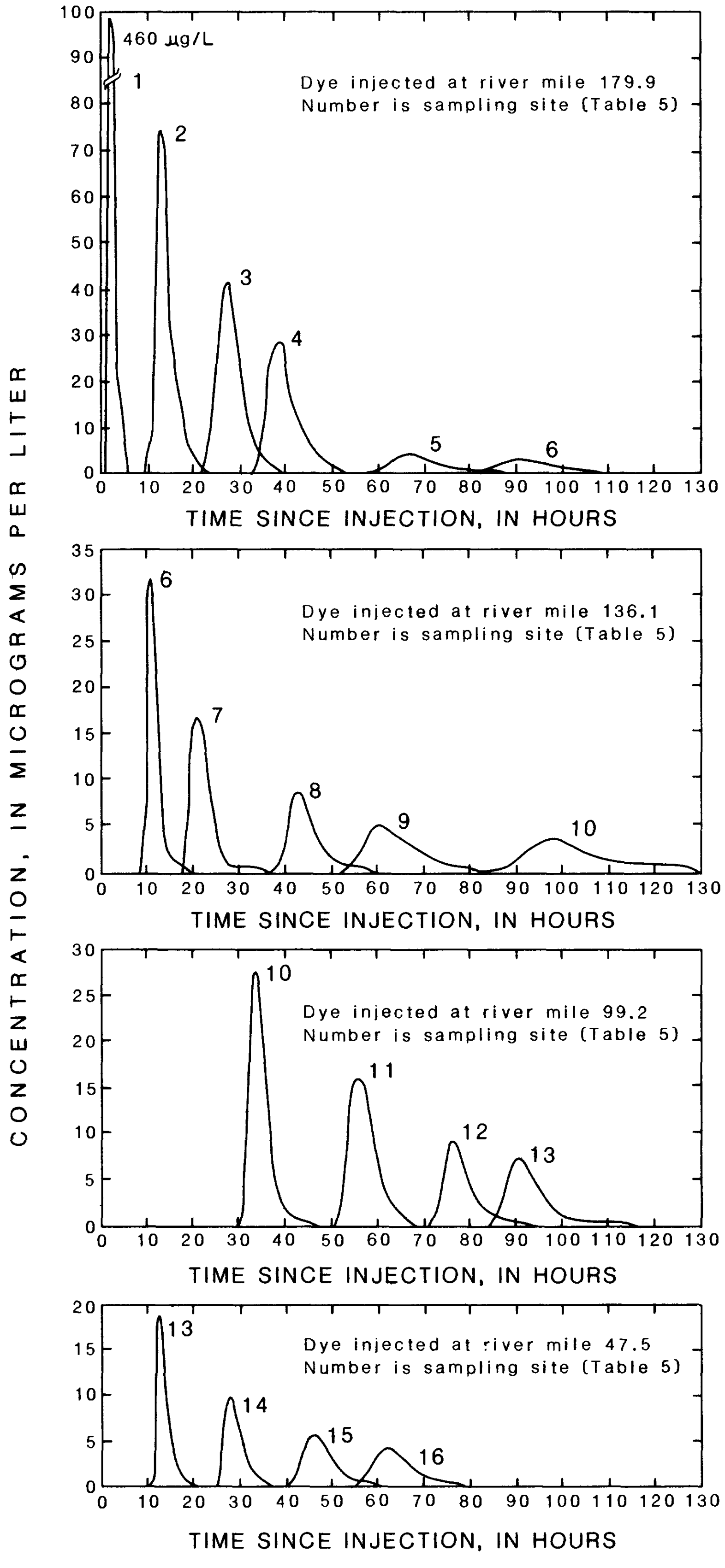


Figure 5.-- Observed time-concentration curves for the June 1984 study.

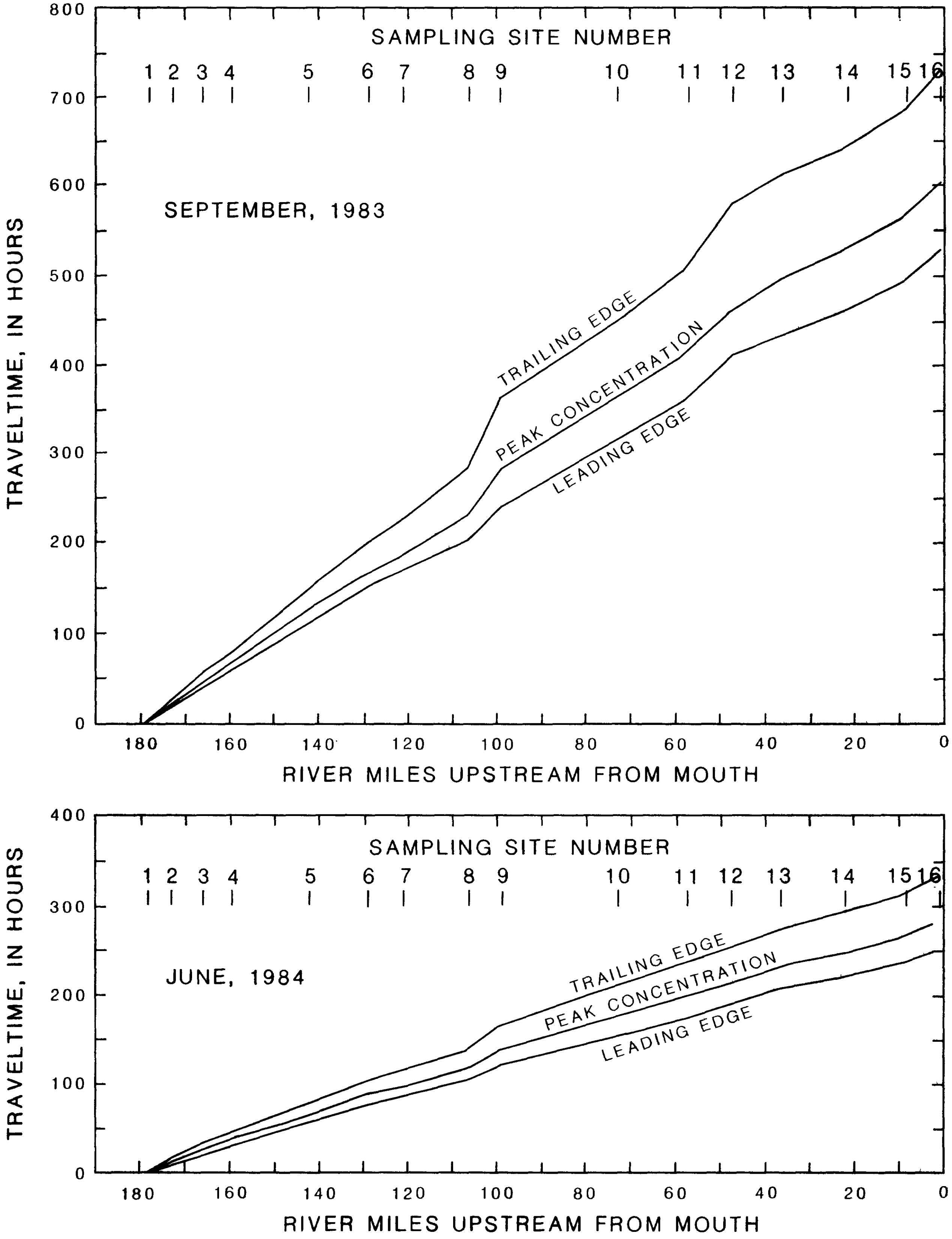


Figure 6.-- Cumulated traveltime data for dye studies on the Shenandoah River.

Table 4.—Traveltime, dispersion, and related data for dye study of September 1983 on the Shenandoah River

Site no.	Site name	Distance: Upstream from mouth (mi)	Distance: Subreach 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 (P): Time since injection (h)	Peak concentration (P): Travel-time (h)	Peak concentration (P): Cumulative travel-time (h)	Peak concentration (P): Velocity (mi/h)	Trailing edge (TE): Time since injection (h) 3/	Trailing edge (TE): Travel-time (h)	Trailing edge (TE): Cumulative travel-time (h)	Trailing edge (TE): Velocity (mi/h)	Observed peak concentration (C_p) (µg/L)	Unit peak concentration (C_{up}) 1/	Discharge at sampling site (Q) (ft³/s)	Dye-recovery ratio (RR) 2/	Duration of dye cloud (D) (h)	Area of time-concentration curve (A_{t-c}) [(µg/L)h]
	Injected 12 liters of 20-percent rhodamine WT dye at 1700 hours on September 6, 1983, at Mile 179.9																					
1	Waynesboro	178.5		1.4	3		0		4		0		6		0		535	2,870	36	1.07	3	829
2	Hopeman Parkway	173.2	5.3	6.7	21	18	18	0.294	26	22	22	0.241	34	28	28	0.189	67	729	56	.82	13	409
3	Crimora	165.8	7.4	14.1	44	23	41	.322	52	26	48	.285	66	32	60	.231	34.5	448	62	.76	22	343
4	Harriston	159.4	6.4	20.5	64	20	61	.320	75	23	71	.278	91	25	85	.256	21.5	347	68	.67	27	276
5	Island Ford	142.6	16.8	37.3	116	52	113	.323	131	56	127	.300	158	67	152	.251	2.5	214	272	.50	42	51.9
6	Shenandoah	129.1	13.5	50.8	156	40	153	.338	173	42	169	.321	210	52	204	.260	1.5	170	327	.46	54	39.2
7	Grove Hill	121.2	7.9	58.7	174	18	171	.439	193	20	189	.395	236	26	230	.304	1.4	162	376	.52	62	38.4
	Injected 35 liters of 20-percent rhodamine WT dye at 1455 hours on September 6, 1983, at Mile 129.1																					
7	Grove Hill	121.2		7.9	14		-		17		-		24		-		52	848	334	1.12	10	273
8	U.S. Highway 211	106.2	15.0	22.9	50	36	207	.417	63	46	235	.326	87	63	293	.238	11.4	259	379	.91	37	196
9	Bixler Bridge	99.2	7.0	29.9	84	34	241	.206	115	52	287	.135	163	76	369	.092	5.3	120	396	.95	79	197
10	Bentonville	73.1	26.1	56.0	162	78	319	.335	196	81	368	.322	248	85	454	.307	4.8	120	452	.98	86	178
11	Front Royal	57.7	15.4	71.4	208	46	365	.335	246	50	418	.308	305	57	511	.270	4.0	98.3	460	1.02	97	181
12	Morgan Ford	47.5	10.2	81.6	256	48	413	.212	292	46	464	.222	378	73	584	.140	1.6	77.8	640	.72	122	91.5
	Injected 150 pounds of 20-percent rhodamine WT dye at 1100 hours on September 6, 1983, at Mile 52.4																					
12	Morgan Ford	47.5		4.9	13		-		*23		-		111		-		*4.8	93.3	590	1.01	98	229
13	U.S. Highway 17 & 50	36.6	10.9	15.8	36	23	436	.474	*58	35	499	.311	143	32	616	.341	*3.8	77.9	545	.89	107	217
14	State Highway 7	22.1	14.5	30.3	64	28	464	.518	*89	31	530	.468	176	33	649	.439	*3.1	70.0	563	.83	112	197
15	State Highway 9	8.4	13.7	44.0	99	35	499	.391	*127	38	568	.360	219	43	692	.319	*2.2	55.9	597	.78	120	175
16	Harpers Ferry	0.8	7.6	51.6	131	32	531	.238	*165	38	606	.200	262	43	735	.177	*1.7	51.1	570	.63	131	148

* Used the first of the multiple peaks.

1/ $C_{up} = 4450 \frac{C_p}{A_{t-c}}$ in micrograms per liter per pound per cubic foot per second.

2/ Values greater than 1.00 or increasing dye recovery in the downstream direction are indicative of incomplete mixing or inadequate definition of the discharge-weighted time-concentration curve.

3/ Determined at 10 percent of peak concentration.

Table 5.—Traveltime, dispersion, and related data for dye study of June 1984 on the Shenandoah River

Site no.	Site name	Distance: Upstream from mouth (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 (P): Time since injection (h)	Peak concentration (P): Travel-time (h)	Peak concentration (P): Cumu-lative travel-time (h)	Peak concentration (P): Velocity (mi/h)	Trailing edge (TE): Time since injection (h)3/	Trailing edge (TE): Travel-time (h)	Trailing edge (TE): Cumu-lative travel-time (h)	Trailing edge (TE): Velocity (mi/h)	Observed peak concen-tration (C_p) (ug/L)1	Unit peak concen-tration (C_{up}) 1/	Discharge at sampling site (Q) (ft^3/s)	Dye-recovery ratio (RR) 2/	Duration of dye cloud (D) (h)	Area of time-concen-tration curve (A_{t-c}) [(ug/L)h]
Injected 50 pounds of 20-percent rhodamine WT dye at 1345 hours on June 4, 1984, at Mile 179.9																						
1	Waynesboro	178.5		1.4	1.3		0		1.8		0		3.1		0		455	5,070	110	0.99	1.8	399
			5.3			8.7		0.609		11.2		0.473		15.4		0.344						
2	Hopeman Parkway	173.2		6.7	10.0		8.7		13.0		11.2		18.5		15.4		74	1,090	130	.88	8.5	302
			7.4			12.2		.607		14.3		.517		15.7		.471						
3	Crimora	165.8		14.1	22.2		20.9		27.3		25.5		34.2		31.1		42	757	160	.89	12.0	247
			6.4			10.3		.621		11.5		.557		13.3		.481						
4	Harriston	159.4		20.5	32.5		31.2		38.8		37.0		47.5		44.4		29	597	170	.83	15.0	216
			16.8			25.5		.659		27.5		.611		33.0		.509						
5	Island Ford	142.6		37.3	58.0		56.7		66.3		64.5		80.5		77.4		3.9	391	680	.68	22.5	44.4
			13.5			21.5		.628		24.0		.562		25.5		.529						
6	Shenandoah	129.1		50.8	79.5		78.2		90.3		88.5		106.0		103		2.8	347	730	.59	26.5	35.9
Injected 75 pounds of 20-percent rhodamine WT dye at 1145 hours on June 4, 1984, at Mile 136.1																						
6	Shenandoah	129.1		7.0	8.8		-		10.8		-		14.0		-		31.9	1,670	850	1.08	5.2	84.9
			7.9			8.7		.908		10.2		.775		12.0		.658						
7	Grove Hill	121.2		14.9	17.5		86.9		21.0		98.7		26.0		115		16.8	1,010	820	.91	8.5	73.8
			15.0			19.5		.769		21.5		.698		25.2		.595						
8	U.S. Highway 211	106.2		29.9	37.0		106		42.5		120		51.2		140		8.4	640	850	.74	14.2	58.4
			7.0			16.0		.438		17.5		.400		25.3		.277						
9	Bixler Bridge	99.2		36.9	53.0		122		60.0		138		76.5		165		4.7	335	820	.77	23.5	62.5
			26.1			32.0		.816		38.5		.678		47.0		.555						
10	Bentonville	73.1		63.0	85.0		154		98.5		176		123.5		212		3.0	232	870	.75	38.5	57.6
Injected 150 pounds of 20-percent rhodamine WT dye at 1030 hours on June 4, 1984, at Mile 99.2																						
10	Bentonville	73.1		26.1	30.0		-		33.5		-		39.0		-		28.2	1,000	1,020	.96	9.0	125
			15.4			21.0		.733		22.5		.684		25.0		.616						
11	Front Royal	57.7		41.5	51.0		175		56.0		199		64.0		237		15.8	676	1,040	.76	13.0	104
			10.2			20.5		.498		20.5		.498		22.0		.464						
12	Morgan Ford	47.5		51.7	71.5		196		76.5		219		86.0		259		9.1	599	1,520	.77	14.5	67.6
			10.9			12.5		.872		14.0		.779		16.0		.681						
13	U.S. Highway 17 & 50	36.6		62.6	84.0		208		90.5		233		102.0		275		7.1	467	1,520	.77	18.0	67.6
Injected 100 pounds of 20-percent rhodamine WT dye at 0905 hours on June 4, 1984, at Mile 47.5																						
13	U.S. Highway 17 & 50	36.6		10.9	11.2		-		12.7		-		16.5		-		18.7	1,710	1,720	.94	5.3	48.7
			14.5			14.1		1.028		15.0		.967		17.8		.815						
14	State Highway 7	22.1		25.4	25.3		222		27.7		248		34.3		293		9.9	924	1,720	.92	9.0	47.7
			13.7			15.4		.890		19.8		.692		22.0		.623						
15	State Highway 9	8.4		39.1	40.7		238		47.5		268		56.3		315		5.6	539	1,700	.88	15.6	46.2
			7.6			14.0		.543		14.5		.524		18.2		.418						
16	Harpers Ferry	0.8		46.7	54.7		252		62.0		282		74.5		333		4.1	424	1,730	.84	19.8	43.0

1/ $C_{up} = 4450 \frac{C_p}{A_{t-c}}$, in micrograms per liter per pound per cubic foot per second.

2/ Values greater than 1.00 or increasing dye recovery in the downstream direction are indicative of incomplete mixing or inadequate definition of the discharge-weighted time-concentration curve.

3/ Determined at 10 percent of peak concentration.

TRAVELTIME

All samples collected in the field were analyzed with a fluorometer in the office laboratory under controlled-temperature conditions. The fluorometer was calibrated using standard solutions prepared from the same dye lot used in the studies.

The dye concentrations for each sampling site were plotted as a function of the time since injection of the dye. The traveltimes of the leading edge, the peak concentration, and the trailing edge of the dye cloud were determined from the time-concentration curve (figs. 4 and 5) for each sampling site. The traveltime of the trailing edge of the dye cloud is defined in this report as the time between injection of the dye and the time the concentration decreases to a level of 10 percent of the peak concentration observed at a sampling site.

The velocities of the leading edge, the peak concentration, and the trailing edge of the dye cloud between successive sampling sites were calculated by dividing the segment length by the traveltimes. These velocities for the two studies were plotted on log-log paper as a function of 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. For those sites on the main stem of the Shenandoah River, however, the velocities were plotted against the discharge at the composite index gage only. The relations described above were entered with discharges corresponding to flow-duration values of 40, 50, 60, 65, 70, 75, 80, 85, 90, and 95 percent for each of the index gaging stations used. The resulting velocities for each increment of flow duration were averaged for the leading edge, the peak concentration, and the trailing edge where two index gaging stations were used. Figure 7 shows the computation for the 15.0-mi segment between sampling sites 7 and 8. Fifteen computations similar to that in figure 7 provided incremental velocities at 10 flow levels for the entire reach between Waynesboro and the mouth at Harpers Ferry.

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

Reach Grove Hill to U.S. 211 Length 15.0 mi

Index gages Lynnwood (L), Front Royal (F)

Peak	$Vel._{83}$ = 0.326 mi/h $Vel._{84}$ = 0.698 mi/h	Q_1 = 285 ft^3/s Q_1 = 679 ft^3/s	Q_2 = 424 ft^3/s Q_2 = 1,050 ft^3/s	Q = $\bar{Q}_{Sept.}$ 7-9 Q = Q_{June} 5,6
Leading edge	$Vel._{83}$ = 0.417 mi/h $Vel._{84}$ = 0.769 mi/h	Q_1 = 287 ft^3/s Q_1 = 689 ft^3/s	Q_2 = 426 ft^3/s Q_2 = 1,060 ft^3/s	Q = $\bar{Q}_{Sept.}$ 7,8 Q = Q_{June} 5
Trailing edge	$Vel._{83}$ = 0.238 mi/h $Vel._{84}$ = 0.595 mi/h	Q_1 = 281 ft^3/s Q_1 = 679 ft^3/s	Q_2 = 418 ft^3/s Q_2 = 1,050 ft^3/s	Q = $\bar{Q}_{Sept.}$ 7-10 Q = Q_{June} 5,6

Flow duration			Velocity, mi/h								
Percent	Q, in ft^3/s		Peak			Leading edge			Trailing edge		
	L	F	L	F	Avg.	L	F	Avg.	L	F	Avg.
40	743	1,190	0.750	0.770	0.760	0.820	0.830	0.825	0.660	0.670	0.665
50	585	930	.600	.620	.610	.690	.700	.695	.510	.520	.515
60	463	728	.495	.505	.500	.585	.595	.590	.395	.405	.400
65	413	647	.445	.460	.452	.540	.550	.545	.350	.365	.358
70	369	579	.405	.420	.412	.500	.510	.505	.310	.330	.320
75	328	521	.360	.385	.372	.455	.470	.462	.275	.295	.285
80	291	468	.325	.350	.338	.410	.440	.425	.240	.265	.252
85	259	421	.295	.315	.305	.385	.410	.398	.215	.235	.225
90	229	377	.265	.295	.280	.350	.380	.365	.187	.213	.200
95	195	318	.230	.255	.242	.315	.335	.325	.160	.178	.169

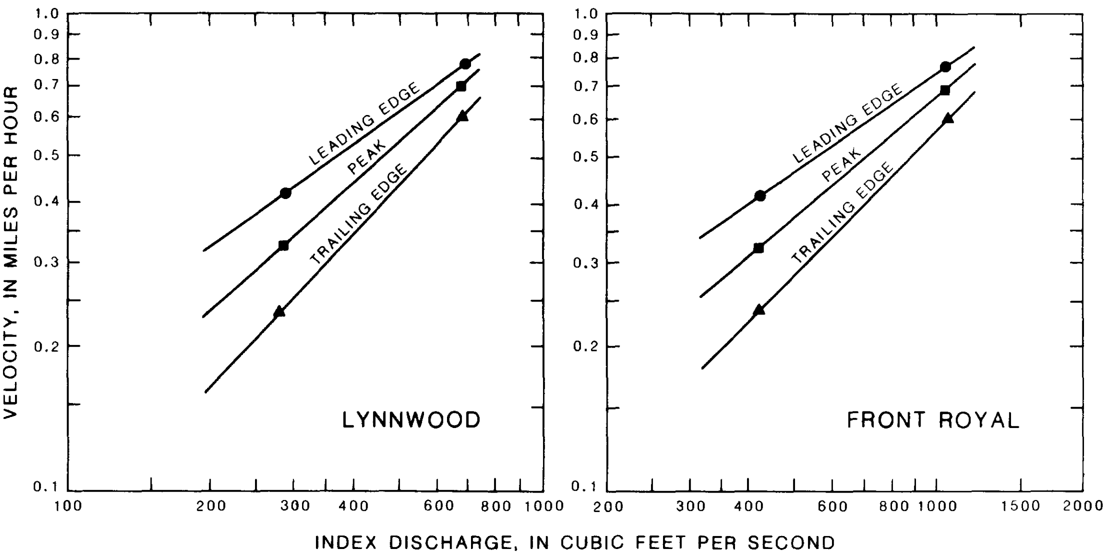


Figure 7.-- Example of typical computations of velocities for 10 increments of flow duration.

edge, peak concentration, and the trailing edge. These incremental times were accumulated from Waynesboro to Harpers Ferry. The traveltimes from Waynesboro to Harpers Ferry for the leading edge (T_{LE}), the peak concentration (T_p), and trailing edge (T_{TE}) are given in tables 6, 7, and 8, respectively. Figures 8, 9, and 10 are graphical presentations of the data. The data in tables 6, 7, and 8, or figures 8, 9, and 10, 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. The graphical presentations allow a straight-line interpolation between sampling sites and may be easier to use than the tabular data in situations where the points of interest are not at the sampling sites used in the study.

The time for the dye cloud to pass a point on the river commonly is referred to as the time of passage or duration (D) of the dye cloud. The duration of the dye cloud can be calculated by subtracting the leading-edge traveltimes (fig. 8 or table 6) from the trailing-edge traveltimes (fig. 10 or table 8). This calculation was made for all the sampling sites at the 10 flow levels, and the dye-cloud duration data are given in table 9. Figure 11 is a graphical presentation of these data.

The information in figures 8-11 and tables 6-9 show that, for a hypothetical spill at Waynesboro (site 1), the traveltime for the leading edge to reach Harpers Ferry (site 16) ranges from 233 hours at a flow duration of 40 percent to 682 hours at a flow duration of 95 percent. At the same flow-duration levels, the traveltime for the peak concentration ranges from 263 to 794 hours and, for the trailing edge, from 302 to 972 hours. The duration of the dye cloud ranges from 69 hours at the 40-percent flow-duration level to 290 hours at the 95-percent flow-duration level. In other words, the first trace of a contaminant spilled at Waynesboro at a flow duration of 95 percent would arrive at Harpers Ferry 28 days after the spill, and the contaminant would persist for another 12 days.

The use of the traveltime and dye-cloud duration data requires that discharge be obtained for the index gaging stations. These discharge data can be used with figure 2 to determine the flow-duration level prevailing in the river at the time of interest. The user would then (1) locate the point of the spill and the point of interest relative to their distances upstream from the mouth of the river (fig. 1 and table 1 may be helpful), (2) determine the traveltime from Waynesboro (site 1) to the location of the spill for the specific flow duration, (3) determine the travel-

Table 6.--Traveltimes for leading edge (T_{LE}) of dye cloud on the Shenandoah River at selected flow durations

Site no.	Site name	Miles upstream from mouth	Distance between sampling sites (miles)	Traveltime of leading edge of dye cloud, in hours, for indicated flow duration, in percent									
				40	50	60	65	70	75	80	85	90	95
1	Waynesboro	178.5		0	0	0	0	0	0	0	0	0	0
			5.3										
2	Hopeman Parkway	173.2		9	11	13	14	15	16	17	19	20	22
			7.4										
3	Crimora	165.8		21	24	29	32	34	37	39	42	45	49
			6.4										
4	Harriston (Index gage)	159.4		31	36	43	47	51	54	58	62	66	74
			16.8										
5	Island Ford	142.6		54	64	77	85	92	99	107	116	125	140
			13.5										
6	Shenandoah	129.1		74	88	104	114	123	133	144	155	167	188
			7.9										
7	Grove Hill	121.2		82	98	116	127	138	150	161	175	189	213
			15.0										
8	U.S. Highway 211	106.2		101	119	142	155	168	182	196	212	230	259
			7.0										
9	Bixler Bridge	99.2		115	137	164	179	194	211	228	248	269	304
			26.1										
10	Bentonville	73.1		145	173	208	228	248	271	294	320	349	396
			15.4										
11	Front Royal (Index gage)	57.7		164	197	239	262	286	313	341	373	408	465
			10.2										
12	Morgan Ford	47.5		182	220	269	295	323	354	387	424	465	532
			10.9										
13	U.S. Highway 17 and 50	36.6		194	235	285	314	343	375	409	448	491	561
			14.5										
14	State Highway 7	22.1		207	250	304	334	365	399	435	476	522	596
			13.7										
15	State Highway 9	8.4		221	268	325	358	392	428	467	511	561	641
			7.6										
16	Harpers Ferry	.8		233	283	344	379	415	454	495	542	595	682

Table 7.--Traveltimes for peak concentration (T_P) of dye cloud on the Shenandoah River at selected flow durations

Site no.	Site name	Miles upstream from mouth	Distance between sampling sites (miles)	Traveltime of peak concentration of dye cloud, in hours, for indicated flow duration, in percent									
				40	50	60	65	70	75	80	85	90	95
1	Waynesboro	178.5		0	0	0	0	0	0	0	0	0	0
			5.3										
2	Hopeman Parkway	173.2		12	14	16	17	19	20	21	22	24	26
			7.4										
3	Crimora	165.8		26	30	35	38	41	43	46	49	52	57
			6.4										
4	Harriston (Index gage)	159.4		37	43	51	56	60	64	68	72	77	85
			16.8										
5	Island Ford	142.6		63	74	87	96	104	112	120	130	140	157
			13.5										
6	Shenandoah	129.1		84	99	116	128	138	149	160	173	186	209
			7.9										
7	Grove Hill	121.2		94	111	131	144	155	168	181	196	211	237
			15.0										
8	U.S. Highway 211	106.2		114	136	161	177	192	208	225	245	265	299
			7.0										
9	Bixler Bridge	99.2		132	159	190	210	229	250	272	298	325	370
			26.1										
10	Bentonville	73.1		165	200	242	267	292	319	349	383	418	479
			15.4										
11	Front Royal (Index gage)	57.7		186	227	274	304	333	365	400	441	482	554
			10.2										
12	Morgan Ford	47.5		206	252	306	339	373	410	449	495	542	625
			10.9										
13	U.S. Highway 17 and 50	36.6		219	267	324	359	394	433	474	522	571	658
			14.5										
14	State Highway 7	22.1		233	284	344	381	418	460	503	554	605	697
			13.7										
15	State Highway 9	8.4		249	303	368	408	448	492	539	593	648	748
			7.6										
16	Harpers Ferry	.8		263	321	390	432	475	522	571	629	688	794

Table 8.--Traveltimes for trailing edge (T_{TE}) of dye cloud on the Shenandoah River at selected flow durations

Site no.	Site name	Miles upstream from mouth	Distance between sampling sites (miles)	Traveltime of trailing edge of dye cloud, in hours, for indicated flow duration, in percent									
				40	50	60	65	70	75	80	85	90	95
1	Waynesboro	178.5		0	0	0	0	0	0	0	0	0	0
			5.3										
2	Hopeman Parkway	173.2		14	17	20	22	23	24	26	28	29	33
			7.4										
3	Crimora	165.8		31	36	42	46	49	52	55	59	62	69
			6.4										
4	Harriston (Index gage)	159.4		43	51	60	65	69	74	79	84	89	99
			16.8										
5	Island Ford	142.6		73	87	104	113	122	131	142	153	165	185
			13.5										
6	Shenandoah	129.1		98	116	138	150	162	175	188	204	219	246
			7.9										
7	Grove Hill	121.2		110	130	155	169	182	197	212	230	249	280
			15.0										
8	U.S. Highway 211	106.2		132	159	192	211	229	250	272	297	324	369
			7.0										
9	Bixler Bridge	99.2		154	189	231	256	281	308	339	374	411	476
			26.1										
10	Bentonville	73.1		193	237	291	321	353	387	427	471	519	600
			15.4										
11	Front Royal (Index gage)	57.7		216	265	326	361	397	437	482	533	588	682
			10.2										
12	Morgan Ford	47.5		237	292	361	401	442	488	538	596	658	767
			10.9										
13	U.S. Highway 17 and 50	36.6		251	309	382	423	466	514	566	627	692	806
			14.5										
14	State Highway 7	22.1		266	328	404	448	493	543	598	662	730	849
			13.7										
15	State Highway 9	8.4		285	351	434	480	529	583	641	710	782	910
			7.6										
16	Harpers Ferry	.8		302	372	461	510	563	621	683	756	834	972

Table 9.--Duration (D) of dye cloud on the Shenandoah River at selected flow durations

Site no.	Site name	Miles upstream from mouth	Distance between sampling sites (miles)	Duration of dye cloud, in hours, for indicated flow duration, in percent									
				40	50	60	65	70	75	80	85	90	95
1	Waynesboro	178.5		0	0	0	0	0	0	0	0	0	0
			5.3										
2	Hopeman Parkway	173.2		5	6	7	8	8	8	9	9	9	11
			7.4										
3	Crimora	165.8		10	12	13	14	15	15	16	17	18	20
			6.4										
4	Harriston (Index gage)	159.4		12	15	17	18	19	20	21	22	23	25
			16.8										
5	Island Ford	142.6		19	23	27	28	30	32	35	37	40	45
			13.5										
6	Shenandoah	129.1		24	28	34	36	39	42	44	49	52	58
			7.9										
7	Grove Hill	121.2		28	32	39	42	44	47	51	55	60	67
			15.0										
8	U.S. Highway 211	106.2		31	40	50	56	61	68	76	85	94	110
			7.0										
9	Bixler Bridge	99.2		39	52	67	77	87	97	111	126	142	172
			26.1										
10	Bentonville	73.1		48	64	83	93	105	116	133	151	170	204
			15.4										
11	Front Royal (Index gage)	57.7		52	68	87	99	111	124	141	160	180	217
			10.2										
12	Morgan Ford	47.5		55	72	92	106	119	134	151	172	193	235
			10.9										
13	U.S. Highway 17 and 50	36.6		57	74	97	109	123	139	157	179	201	245
			14.5										
14	State Highway 7	22.1		59	78	100	114	128	144	163	186	208	253
			13.7										
15	State Highway 9	8.4		64	83	109	122	137	155	174	199	221	269
			7.6										
16	Harpers Ferry	.8		69	89	117	131	148	167	188	214	239	290

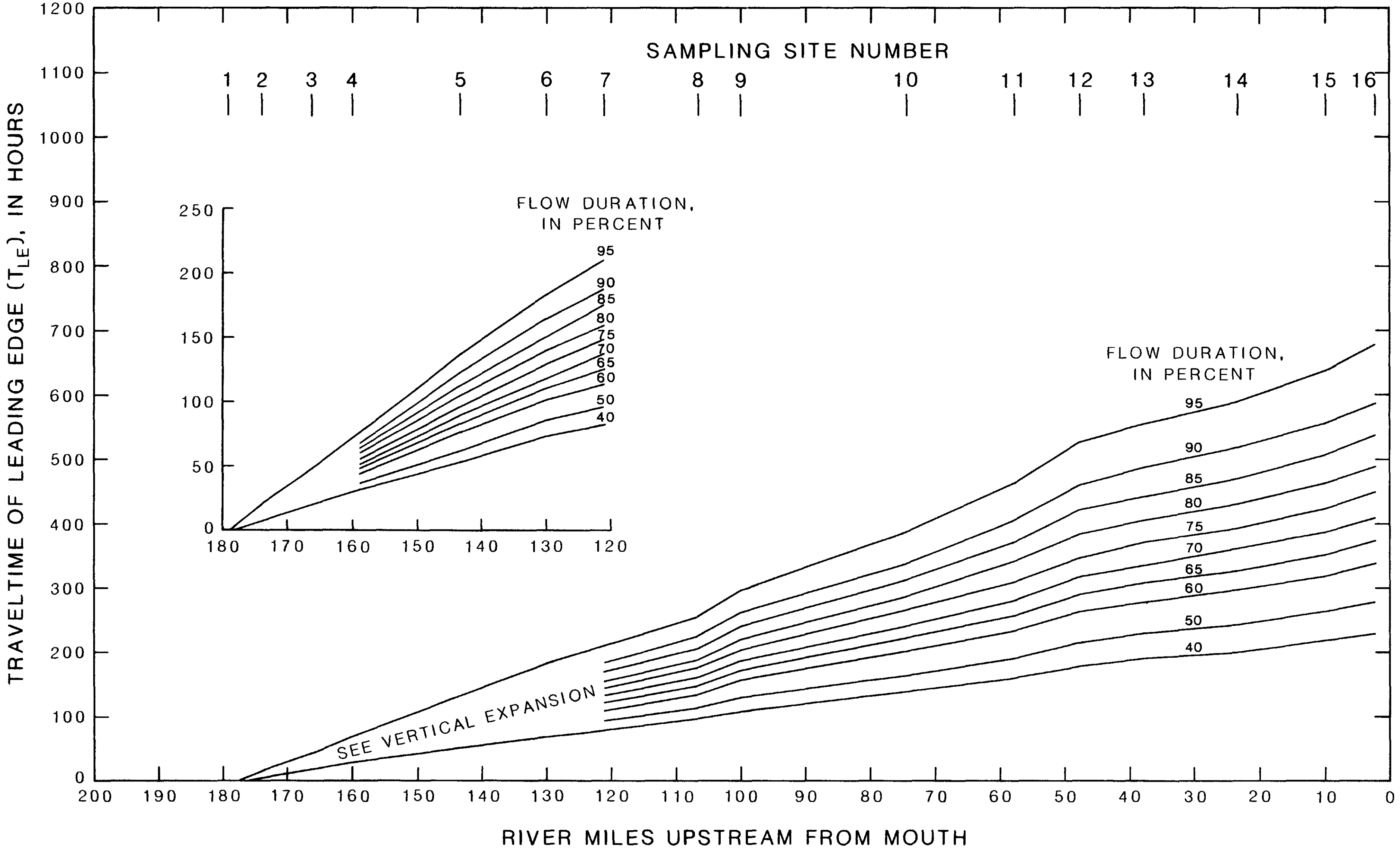


Figure 8.-- Traveltime-distance relation for leading edge (T_{LE}) of dye cloud at selected flow durations.

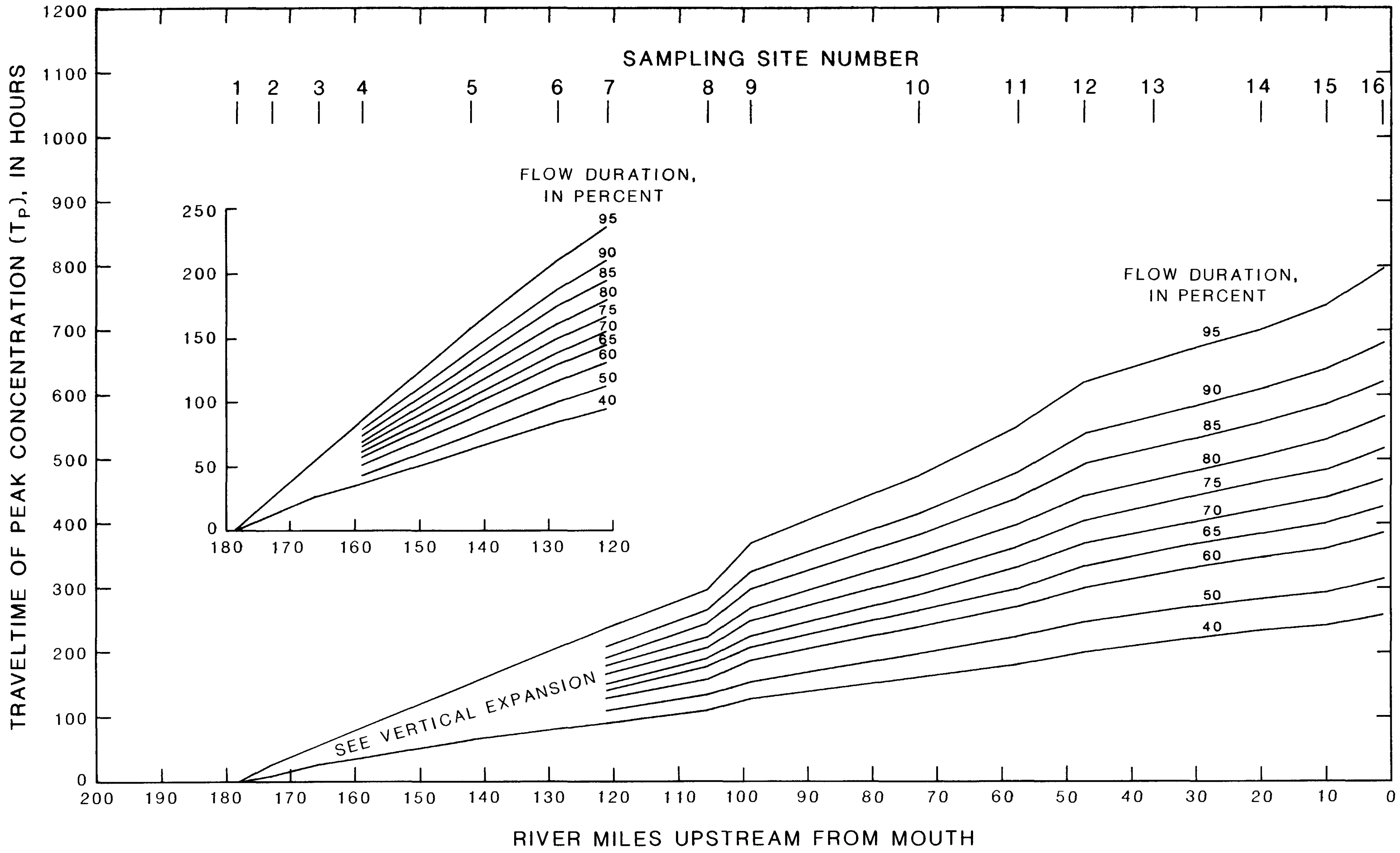


Figure 9.-- Traveltime-distance relation for peak concentration (T_P) of dye cloud at selected flow durations.

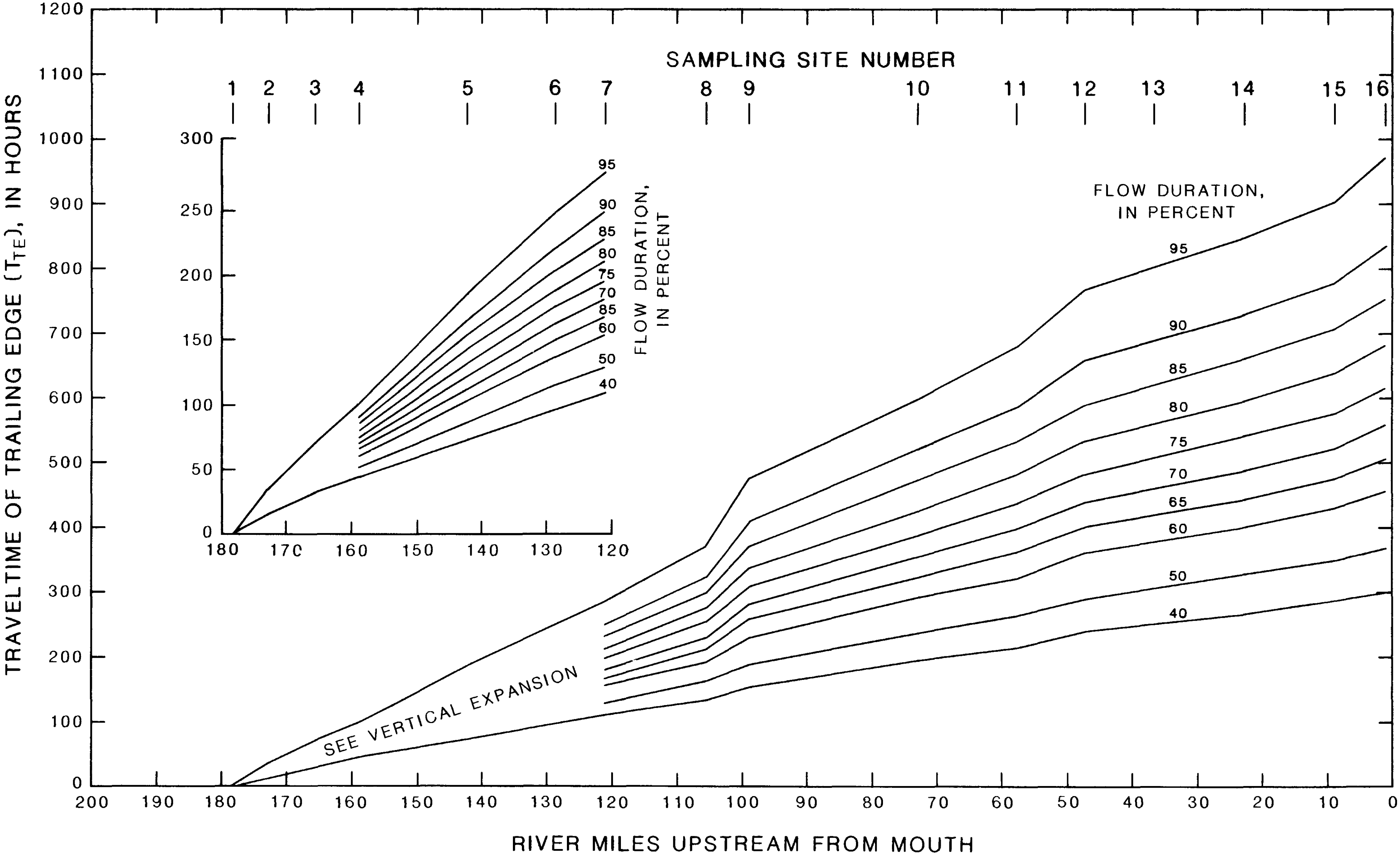


Figure 10.-- Traveltime-distance relation for trailing edge (T_{TE}) of dye cloud at selected flow durations.

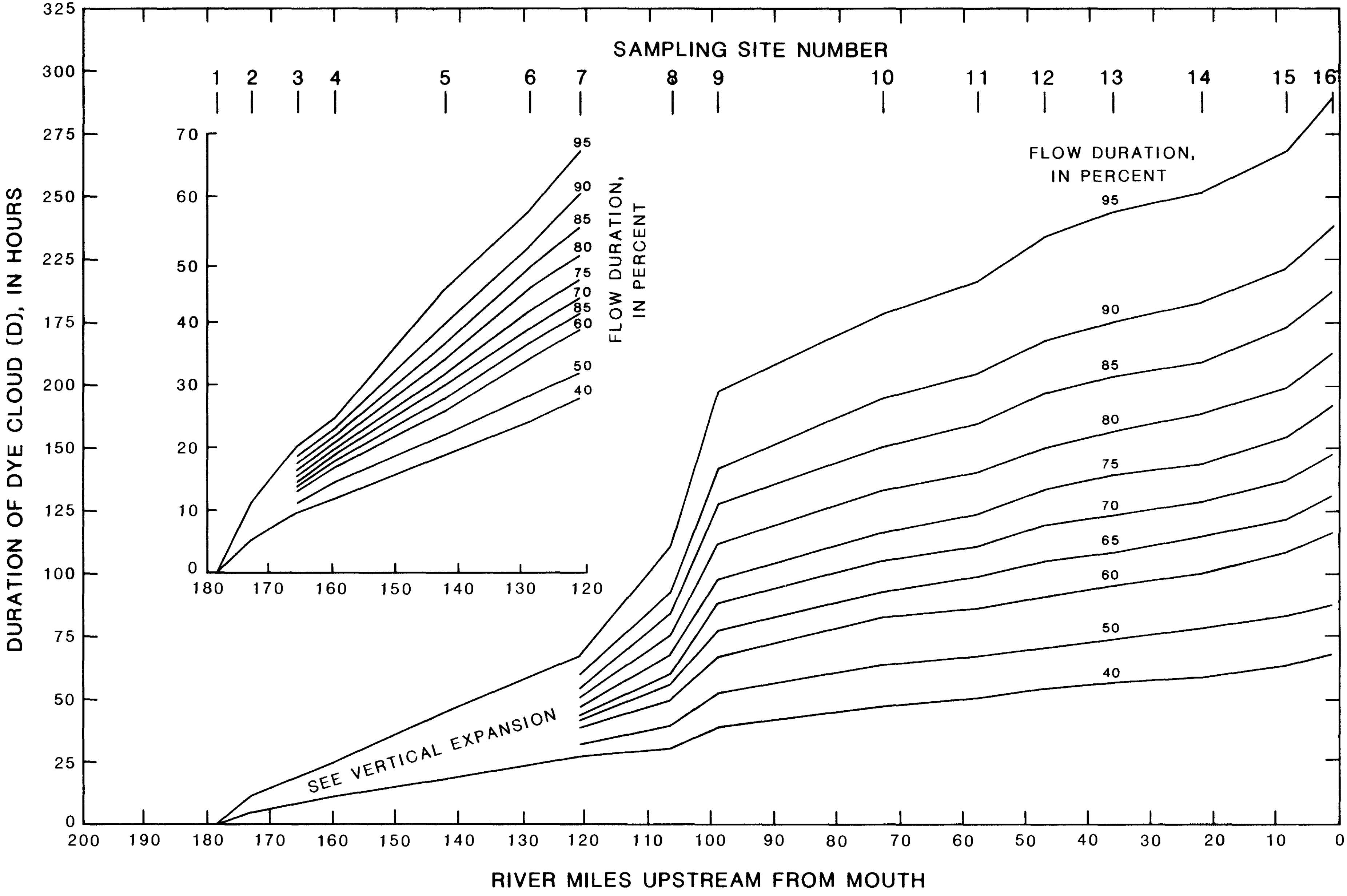


Figure 11.-- Relation between dye-cloud duration (D) and distance at selected flow durations.

time from Waynesboro in the same manner to the point of interest downstream, and (4) subtract the first traveltime from the second 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 traveltimes of the leading edge (fig. 8), peak concentration (fig. 9), trailing edge (fig. 10), or the dye-cloud duration (fig. 11).

In cases where the flow duration is determined to be between two selected values given in figures 8-11 or tables 6-9, an arithmetic interpolation between the given values will provide an adequate solution. However, it may be easier to solve the problem for the two flow-duration values that bracket the existing flow duration and then interpolate between the two final solutions. For example, if the flow in the river is at the 55-percent flow-duration level, solve the problem for the 50-percent and 60-percent flow-duration levels and then interpolate between the two answers.

In many cases where the distance between the spill and the point of interest is great, the user may want to establish what is happening at each intervening sampling site rather than just at the point of interest. The tabulated data (tables 6-9) facilitate this type of solution, and the insight into what is happening as the contaminant moves downstream is greatly enhanced.

DISPERSION

When a soluble dye is injected into a flowing river, the dye immediately starts dispersing in the vertical, lateral, and longitudinal directions. Vertical and lateral mixing occurs relatively quickly. Lateral mixing can be enhanced by injecting the dye simultaneously at multiple 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 ever-increasing time required for the dye cloud to pass a sampling point (figs. 4 and 5) as the dye moves downstream is a measure of longitudinal mixing.

The ideal situation for studying longitudinal dispersion would be one in which (1) the total reach could be studied without subdividing into subreaches, and (2) complete lateral mixing could be assumed to persist after the initial mixing period. Unfortunately, the ideal situation does not exist when conducting dispersion studies on long rivers, particularly those with a large width-to-depth ratio. The threat of precipitation, sampling logistics, and control of maximum dye concentrations at water intakes require that the total reach be divided into subreaches, as was done in this study. Even if complete lateral mixing is achieved, tributary inflows work against maintaining this condition. The processes controlling the mixing of tributary inflow are similar to those controlling the mixing of a side injection of dye. In some cases, where the tributary inflow is relatively large compared to the flow of the main channel, the tributary flow may be described more accurately as resembling a line injection on a side of the stream. A line injection on a side of the stream would require somewhat less mixing distance than a point injection on the side of the stream. According to Kilpatrick and Cobb (1985, p. 7, 34, and 35), the mixing distance for a center or side injection can be approximated from the following equations:

$$L_o \text{ [center spill]} = 0.088 \frac{v B^2}{d^{3/2} s^{1/2}}$$

$$L_o \text{ [side spill]} = 0.35 \frac{v B^2}{d^{3/2} s^{1/2}}$$

where

L_o = distance required for optimum mixing, in feet;
v = mean stream velocity, in feet per second;
B = average stream width, in feet;
d = mean depth of the stream, in feet; and
s = water-surface slope, in feet per foot.

As evidenced by the proportionality constants of these equations, a side injection of water from a tributary requires a mixing length four times greater than that for a single midstream injection of dye. Therefore, for most dye studies, particularly those on large eastern rivers, complete lateral mixing seldom is fully maintained because of tributary inflows.

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 4 and 5 show how the peak concentration of the dye cloud is attenuated as it moves downstream and the dye mixes into an increasing volume of water. The correspondent effect is that the time required for the dye cloud to pass a sampling point is longer at each successive downstream location.

Unit Concentration

"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 cloud in the reach; and (4) longitudinal dispersion." (Hubbard and others, 1982, p. 34). F. A. Kilpatrick developed the concept of unit concentration (C_u) as a method to adjust for all of the effects listed above, except longitudinal dispersion (Hubbard and others, 1982, p. 34). 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. In other words, unit concentration is the observed concentration normalized with respect to the discharge in the river and the amount of dye injected. A basic assumption in longitudinal-dispersion studies is that under similar flow conditions, the observed shape of the time-concentration curve is constant relative to time. The magnitude of the concentration, however, is directly proportional to the amount of solute injected, providing no loss of solute occurs. Kilpatrick's formulation of unit concentration for the general case (Hubbard and others, 1982, p. 35) is:

$$C_u = \frac{C_{con} \times Q}{W_d} \qquad (1)$$

where

C_u = unit concentration;

C_{con} = conservative concentration (a concentration that would be produced if the total quantity of injected material is undiminished for any reason as it moves downstream and is 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 describe the attenuation of the peak concentration as the dye cloud moves downstream. The formula for unit peak concentration is:

$$C_{up} = \frac{C_{p(con)} \times Q}{W_d} \qquad (2)$$

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:

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

where, in this instance

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

In using equation 2 to calculate unit peak concentration, a complicating factor is the determination of the conservative peak concentration. The formulation of unit peak concentration can be simplified as follows:

The weight of dye recovered (W_r) at the sampling site can be stated as the discharge times the area under the time-concentration curve denoted as:

$$W_r = Q \int_{T_{LE}}^{T_{TE}} Cdt \tag{3}$$

The dye-recovery ratio (RR) is the weight of dye recovered (W_r) divided by the weight of dye injected (W_d) and can be denoted as:

$$RR = \frac{W_r}{W_d} = \frac{Q \int_{T_{LE}}^{T_{TE}} Cdt}{W_d} \tag{4}$$

The conservative peak concentration $C_{p(con)}$ then can be calculated as:

$$C_{p(con)} = \frac{C_{p(obs)}}{RR} = \frac{C_{p(obs)} \times W_d}{Q \times \int_{T_{LE}}^{T_{TE}} Cdt} \tag{5}$$

Then from equation 2

$$C_{up} = \frac{C_{p(con)} \times Q}{W_d} = \frac{C_{p(obs)} \times W_d \times Q}{W_d \times Q \times \int_{T_{LE}}^{T_{TE}} Cdt} = \frac{C_{p(obs)}}{\int_{T_{LE}}^{T_{TE}} Cdt} \qquad (6)$$

The integral in the denominator of equation 6 is the area under the observed time-concentration curve ($A_{t\text{-}c(obs)}$), which can be determined by planimetering or by summing trapezoidal increments of area. Therefore, unit peak concentration can be calculated as:

$$C_{up} = 4{,}450 \frac{C_{p(obs)}}{A_{t\text{-}c(obs)}} \qquad (7)$$

The proportionality constant (4,450) in equation 7 gives unit peak concentration values in micrograms per liter per pound per cubic foot per second, if $C_{p(obs)}$ is in micrograms per liter and $A_{t\text{-}c(obs)}$ is in micrograms per liter hours.

Equation 7 greatly simplifies the calculation of unit peak concentration. It has limited use, however, as it can only be used where a time-concentration curve has been developed. When a long reach of a river is divided into subreaches for study, as was done with the Shenandoah River, a unit peak concentration that corresponds to the long accumulated traveltimes (table 7 and fig. 9) cannot be calculated by equation 7.

Scalene-Triangle Analogy

The examination of the time-concentration curves in figures 4 and 5 reveals a striking similarity between the characteristics of a time-concentration curve and a scalene triangle (a triangle with three unequal sides). The time-concentration curve has the following characteristics: C varies from C=0 at T_{LE}, to $C=C_{p(obs)}$ at T_P, to $C \gtrapprox 0$ (0.1 $C_{P(obs)}$) at T_{TE}. The only significant difference between the scalene triangle and the time-concentration curve is that the time-concentration curve varies curvilinearly from T_{LE} to T_P and from T_P to T_{TE} while the scalene triangle varies linearly. Figure 12 graphically portrays the analogy of the scalene triangle to the time concentration curve.

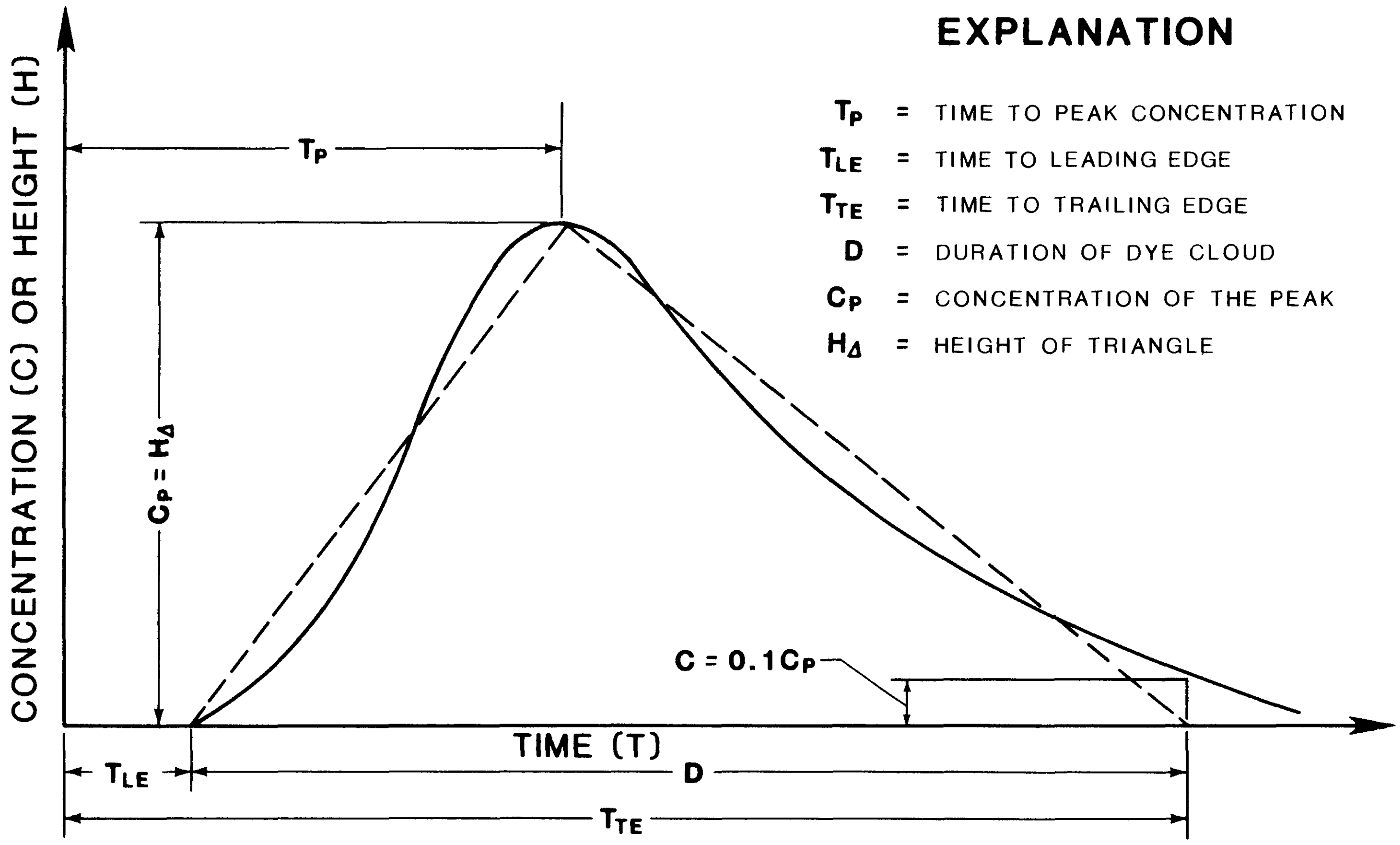


Figure 12.-- Relation between scalene triangle (dashed line) and time-concentration curve (solid line).

The advantage of the scalene triangle is that the area of the time-concentration curve can be expressed as:

$$\int_{T_{LE}}^{T_{TE}} C\,dt \approx C_{p(obs)} \times \frac{T_{TE} - T_{LE}}{2} \qquad (8)$$

Taylor and others (1985) have demonstrated the validity of the above approximation for instantaneous dye injections. If the scalene-triangle area is substituted for the integral in equation 6, unit peak concentration can be formulated as follows:

$$C_{up} = \frac{C_{p(obs)}}{C_{p(obs)} \times \frac{T_{TE} - T_{LE}}{2}} = \frac{K}{T_{TE} - T_{LE}} \qquad (9)$$

where K is a constant previously determined to be 9,270.

The term $(T_{LE} - T_{LE})$ was previously defined as the time of passage or duration (D) of the dye cloud. Unit peak concentration can then be formulated as:

$$C_{up} = 9{,}270\ D^{-1} \qquad (10)$$

The proportionality constant (9,270) used in equation 10 has been calculated to give unit peak-concentration (C_{up}) values in units of micrograms per liter per pound per cubic foot per second $\left(\frac{\mu g/L \times ft^3/s}{lb}\right)$, when dye-cloud duration (D) is in hours. Values for dye-cloud duration (D) for the entire reach of river at 10 flow levels are given in table 9 and figure 11. Using equation 10 and dye-cloud duration (D) data from table 9, the unit peak concentrations (C_{up}) were calculated for each sampling site for all 10 flow-duration levels for a hypothetical spill at Waynesboro. These C_{up} values were plotted as a function of the corresponding traveltimes (T_p) of the peak concentrations from table 7 and are shown in figure 13.

The data in figure 13 show that the unit peak-concentration approach is successful in adjusting for the dilution effects of different flow levels. The data for 10 flow levels plot essentially on one curve for peak-concentration traveltimes of less than 150 hours. The apparent scatter for peak-concentration traveltimes greater than 150 hours is the combination effect of (1) a change in slope of the curve due to the increased dispersive capabilities of two reaches with dams, and (2) a timing offset caused by the slower rate of movement of the peak concentration at lower flow levels.

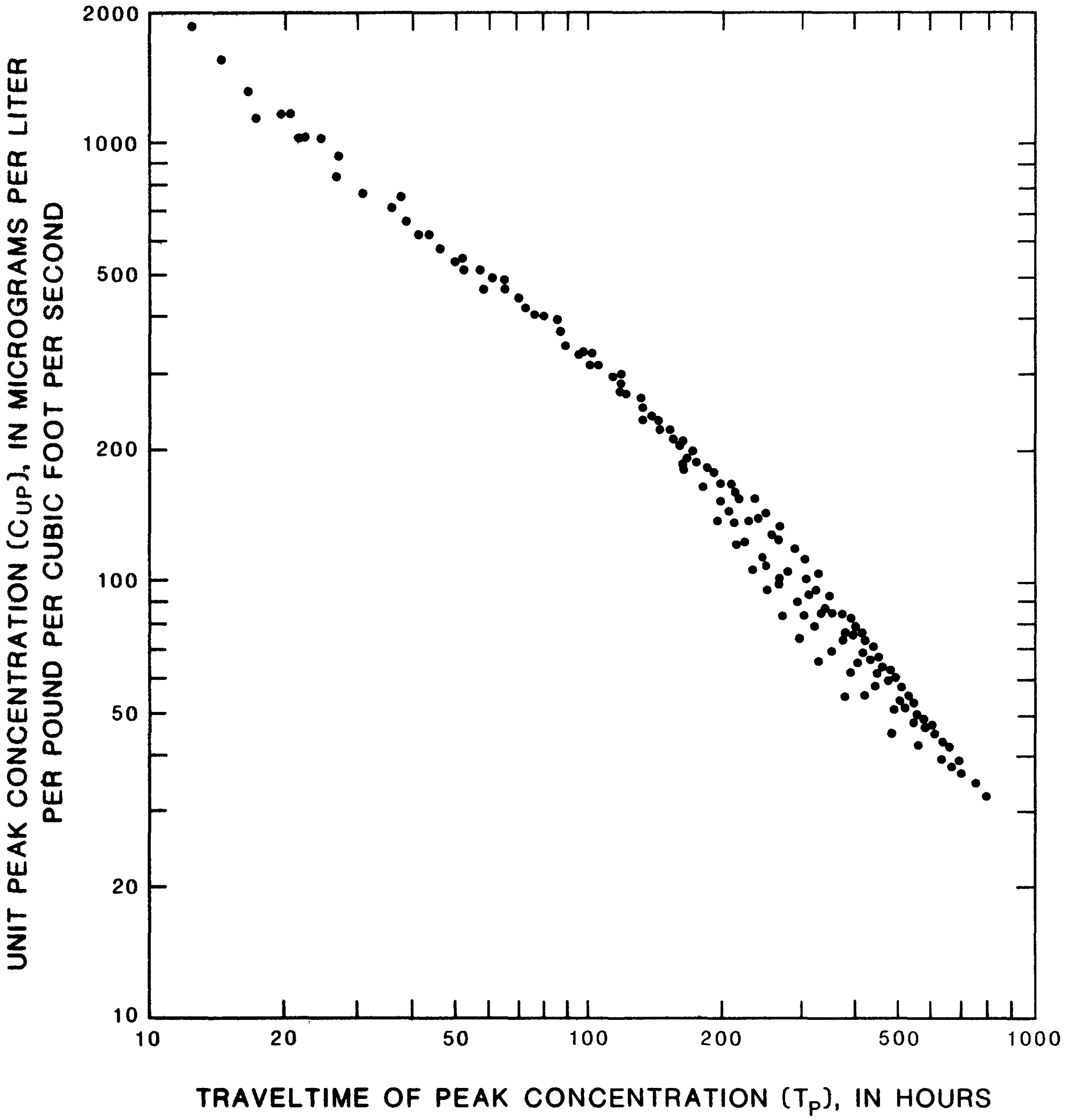


Figure 13.-- Relation between unit peak concentrations and traveltimes of peak concentrations at 10 flow levels for a hypothetical spill at Waynesboro, Virginia.

The changes in slope and timing offsets described above are clarified in figure 14, which shows only the data for the 60-, 80-, and 95-percent flow-duration levels. The slope of the line connecting two consecutive sampling sites is a measure of the longitudinal dispersive capability of the stream segment between the sampling sites. Note the similarity of slope for a specific stream segment for all three flow levels. The increased negative slopes of the lines between sampling sites 7 and 8 and between sites 8 and 9 reflect the increased longitudinal dispersive capabilities of these two stream segments due to dams located at mile 115.8 and mile 101.4.

The calculation of a conservative peak concentration at any point along the river for this hypothetical spill at Waynesboro would involve the use of equation 2A as follows:

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

where

$C_{p(con)}$ = conservative peak concentration, in µg/L;

C_{up} = unit peak concentration, in $\frac{\mu g/L \times ft^3/s}{lb}$;

W_d = weight of soluble contaminant, in pounds; and

Q = discharge in river, in ft^3/s.

The calculation of conservative peak concentrations for a spill at any other location would require the user to initialize the cloud duration (D) (fig. 11 or table 9) to zero at the location of the spill. This can be done by the same subtractive process as demonstrated in the previous section with traveltime. The user can calculate a conservative peak concentration at the point of interest or at any intervening point between the spill and the point of interest.

With the information provided thus far, the user can determine the following: (1) The traveltime of the leading edge (T_{LE}) of the contaminant cloud ($C_{(con)}$ = 0 at T_{LE}); (2) the traveltime of the trailing edge (T_{TE}) of the contaminant cloud ($C_{(con)}$ = 0 at T_{TE}); and (3) the traveltime of the peak concentration (T_p) of the contaminant cloud ($C_{p(con)} = \frac{C_{up} \times W_d}{Q}$ at T_p). With these three pairs of data points, the user can plot the triangular approximation of the conservative time-concentration curve.

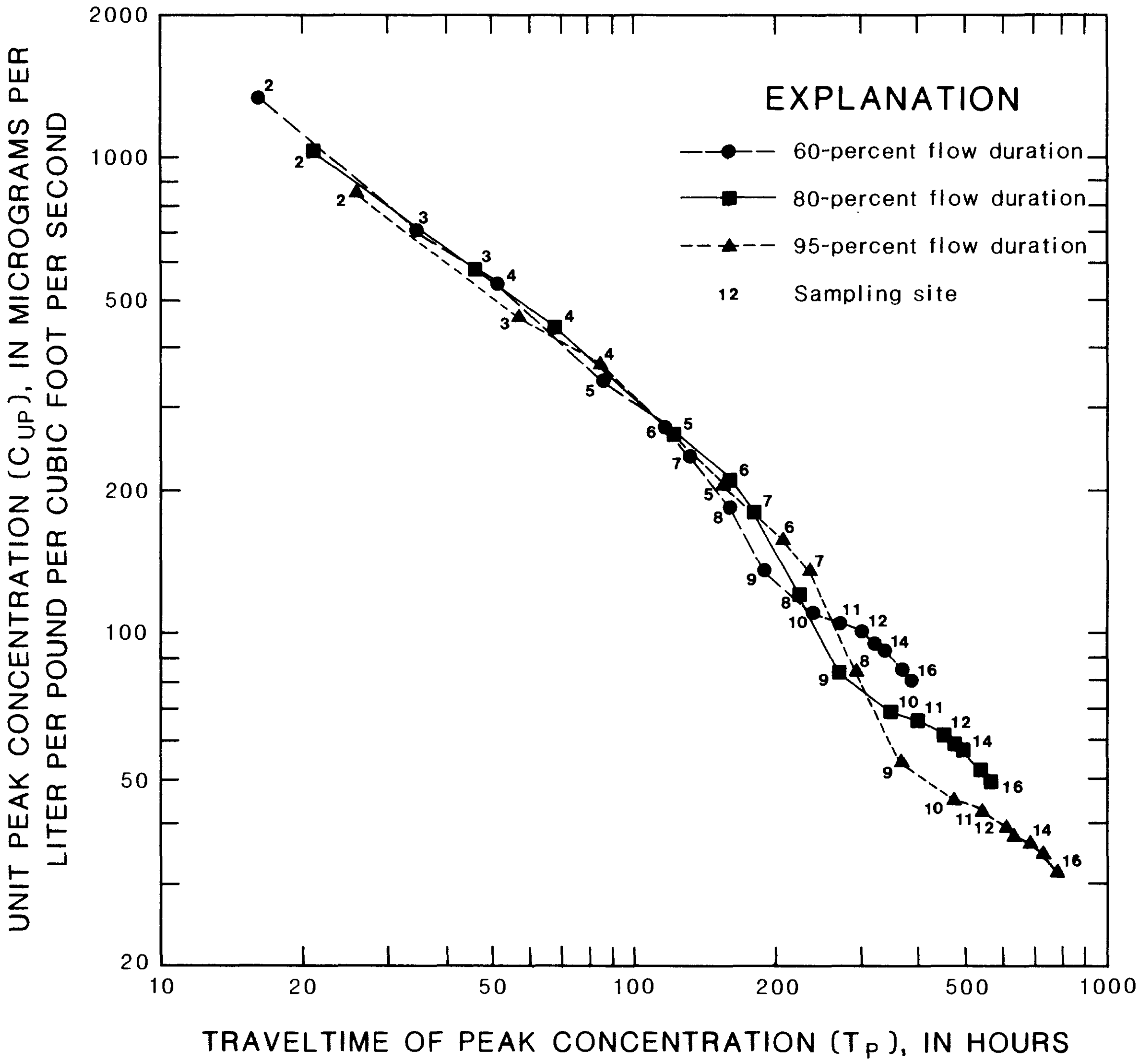


Figure 14.-- Relation between unit peak concentrations and traveltimes of the peak concentrations at the 60-, 80-, and 95-percent flow durations for a hypothetical spill at Waynesboro, Virginia.

Superposition

The dispersion measurements in the two dye studies were for a slug or instantaneous injection of dye. The methods developed from these measurements, however, can be used with minor adjustments to calculate the conservative time-concentration curve resulting from a constant-rate or variable-rate spill of contaminant. The process is known as superposition. In this process, selected time increments of the spill are routed downstream as triangular approximations of the conservative time-concentration curve. The resulting total conservative concentration at any time is the sum of the contributions of all the triangular approximations at that time.

The unusual time-concentration curves resulting from the most downstream dye injection during the September 1983 study (fig. 4) provide a good example for demonstrating the superposition method. As stated previously, the dye injection was made upstream from a dam that has a center-notch outlet. The nonuniform velocities through the pool caused the dye to be released from the pool over a period of about 4 days.

The observed time-concentration curve (fig. 4) at the site downstream from the dam (site 12) is used to simulate a variable rate injection. The weights of dye in 5-hour increments (fig. 15A) of the time-concentration curve were calculated and then routed as triangular approximations (fig. 15B) to site 15. The composite curve is then determined by summing the contributions from the 21 triangular approximations. This composite curve (fig. 15C) then is compared with the observed curve (restored to 100-percent recovery) at site 15. The same procedure can be used to calculate the response from a constant-rate injection. If equal time increments of the injection are chosen, the routed triangular approximations will be identical in shape and offset by a constant time increment, assuming the flow in the river is constant.

APPLICATION OF TECHNIQUE

A principal objective of this report is to provide a generalized procedure that can be used to predict the traveltime and downstream concentrations resulting from a spill of water-soluble substance in the river during periods of relatively stable flow. The procedures are applicable under the following conditions:

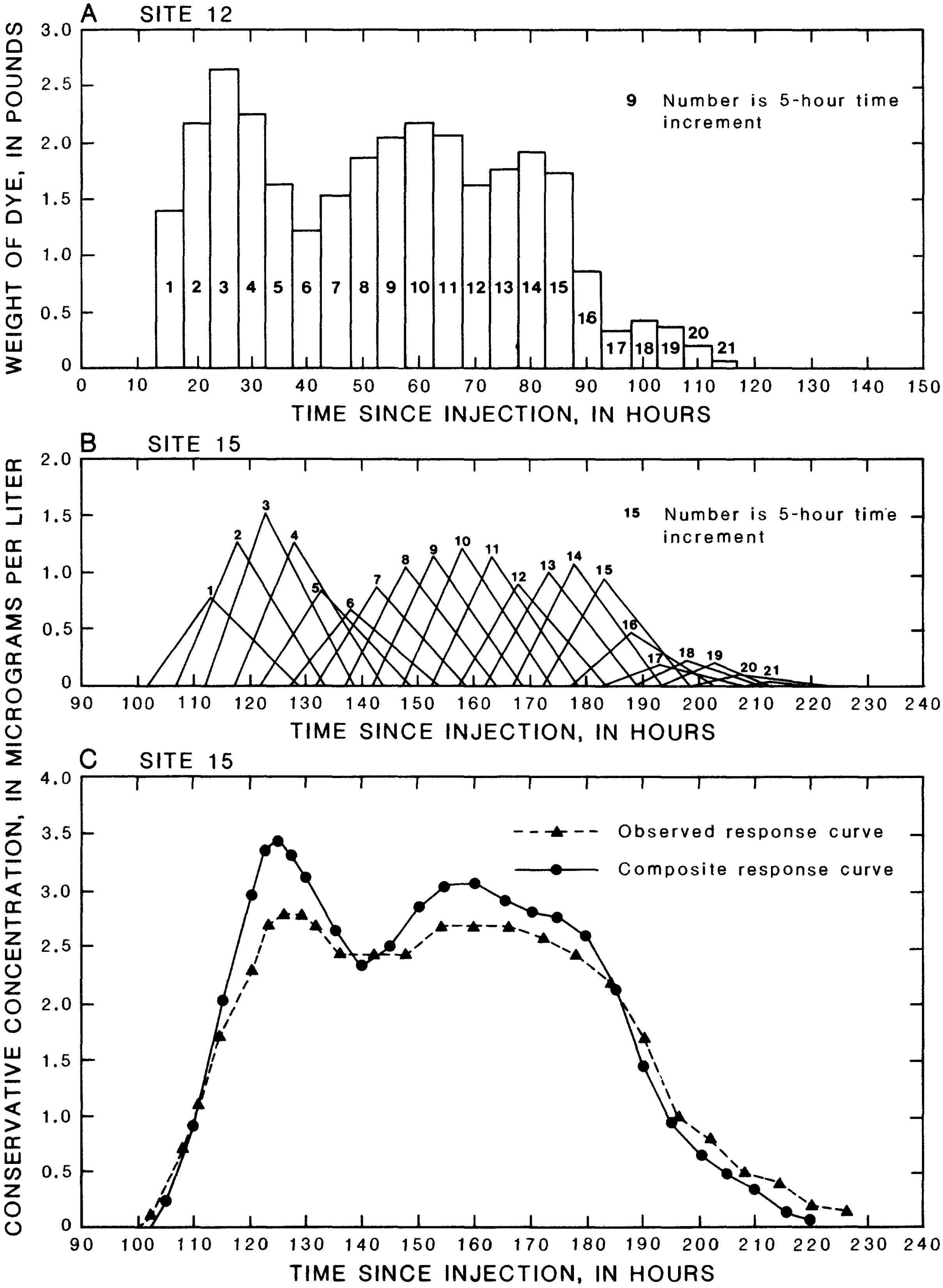


Figure 15.-- Technique for solution of variable-rate injection problem using superposition method. (A) Variable-rate injection increments; (B) Triangular responses to injection increments; and (C) Composite and observed response curves.

1. Flow conditions: 40- to 95-percent flow duration

2. Type of spill:
   (a) Instantaneous slug
   (b) Constant rate
   (c) Variable rate

3. Amount of spill: No constraint

4. Location of spill - Any point along:
   (a) South River (downstream from Waynesboro, Va.)
   (b) South Fork Shenandoah River
   (c) Shenandoah River

5. Response prediction - any point downstream from a spill on:
   (a) South River
   (b) South Fork Shenandoah River
   (c) Shenandoah River

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 less than a specified value.
(13) Location where peak concentration will be less than a specified value.

Use of the procedure can be demonstrated best by solving an example problem. Suppose, for example, that a tanker truck overturned on State Highway 649 near Island Ford, Va. (sampling site 5, at river mile 142.6), and rapidly spilled its 5,000-pound contents into the river. The spill is assumed to have occurred at 9 a.m., on July 2, and the contents are assumed to be highly toxic and soluble in water. It is further assumed that, upon being notified of the situation, health authorities telephoned the telemarks at two or more of the index stream gages and received stage data for the gages. After referring to a previously developed stage-discharge relation, the authorities could determine the discharge at the gaging stations. With these discharges, they would determine the flow duration from figure 2. For this example, assume that the flow duration is at about the 80-percent level.

The health authorities are concerned about the impact of the spill on the water supply for Front Royal (sampling site 11, at river mile 57.7). Specifically, their concerns are:

(1) When will the first traces of the contaminant arrive at the intakes?
(2) When will the highest concentration arrive?
(3) What will the maximum concentration be?
(4) When will the contaminant be essentially past the water intakes?

The following procedure can be used to predict the traveltimes and concentrations. Although the user can go directly to a solution at the point of interest (Front Royal intakes), it may be helpful and enlightening to examine what is happening at intervening points between the spill and the point of interest. The locations used as sampling sites in the studies are convenient intervening points to examine. For example:

1. When will the first trace of contaminant arrive?

Procedure:

Use figure 8 or table 6. For a flow duration of 80 percent, determine the leading-edge traveltime (T_{LE}) from Waynesboro (site 1, mile 178.5) to the location of the spill (site 5, mile 142.6). $T_{LE(142.6)}$ = 107 hours. Then tabulate the leading-edge traveltime for site 5 and each intervening sampling site to site 11 (Front Royal). Subract 107 hours from the leading-edge traveltimes determined for each of the sampling sites. The subtraction process initializes the traveltime to zero at the point of the spill. The bookkeeping procedure is shown in the following table.

	Site no.	River mile	$T_{LE(mile\ x)}$ - $T_{LE(mile\ 142.6)}$ (hours)	T_{LE} (hours)	Date	Time
Spill	5	142.6	107 - 107	0	7/2	9 a.m.
	6	129.1	144 - 107	37	7/3	10 p.m.
	7	121.2	161 - 107	54	7/4	3 p.m.
	8	106.2	196 - 107	89	7/6	2 a.m.
	9	99.2	228 - 107	121	7/7	10 a.m.
	10	73.1	294 - 107	187	7/10	4 a.m.
Front Royal	11	57.7	341 - 107	234	7/12	3 a.m.

Therefore, the first trace of contaminant will arrive at Front Royal intakes approximately 234 hours after the spill or at 3 a.m., on July 12. Also available are the times that the first trace of contaminant will arrive at each intervening site. The tabular data (table 6) is most useful when working with the sampling sites. The graphical data may be easier to use if working with sites located between the sampling sites used in the study.

2. When will the peak concentration arrive?

Procedure:

Use figure 9 or table 7 to determine traveltimes (T_p) of the peak concentration. First, the data must be initialized to zero at the point of the spill. $T_{p(142.6)}$ = 120 hours for a flow duration of 80 percent.

	Site no.	River mile	$T_{LE(mile\ x)}$ - $T_{LE(mile\ 142.6)}$ (hours)	T_{LE} (hours)	Date	Time
Spill	5	142.6	120 - 120	0	7/2	9 a.m.
	6	129.1	160 - 120	40	7/4	1 a.m.
	7	121.2	181 - 120	61	7/4	10 p.m.
	8	106.2	225 - 120	105	7/6	6 p.m.
	9	99.2	272 - 120	152	7/8	5 p.m.
	10	73.1	394 - 120	229	7/11	10 p.m.
Front Royal	11	57.7	400 - 120	280	7/14	1 a.m.

The peak concentration of contaminant will arrive at the Front Royal intakes 280 hours after the spill or at about 1 a.m., on July 14.

3. When will the contaminant be essentially past the Front Royal intakes?

Procedure:

Use figure 10 or table 8. Determine the traveltimes (T_{TE}) of the trailing edge of the contaminant cloud in the same manner as for the leading edge and peak concentration. Remember, however, that the trailing edge was defined as the time when the concentration diminished to 10 percent of the peak concentration.

	Site no.	River mile	$T_{LE(mile\ x)}$ - $T_{LE(mile\ 142.6)}$ (hours)	T_{LE} (hours)	Date	Time
Spill	5	142.6	142 - 142	0	7/2	9 a.m.
	6	129.1	188 - 142	46	7/4	7 a.m.
	7	121.2	212 - 142	70	7/5	7 a.m.
	8	106.2	272 - 142	130	7/7	7 p.m.
	9	99.2	339 - 142	197	7/10	2 p.m.
	10	73.1	427 - 142	285	7/14	6 a.m.
Front Royal	11	57.7	482 - 142	340	7/16	1 p.m.

The concentration of the contaminant at Front Royal would be down to 10 percent of the peak concentration, and diminishing, 340 hours after the spill or at about 1 p.m., on July 16.

4. What will the conservative peak concentration be at Front Royal?

A conservative concentration is the concentration that would exist if all the spilled substance is transported to Front Royal. For most substances, losses will occur during transport through physical, chemical, or biological processes. These losses will be variable depending on the characteristics of the spilled substance.

Procedure:

Use figure 11 or table 9. Determine the dye-cloud duration (D) in the same manner as the traveltimes were determined. Use 80-perent flow duration.

	Site no.	River mile	$D_{(\text{mile } x)} - D_{(\text{mile } 142.6)}$ (hours)	D (hours)
Spill	5	142.6	35 - 35	0
	6	129.1	44 - 35	9
	7	121.2	51 - 35	16
	8	106.2	76 - 35	41
	9	99.2	111 - 35	76
	10	73.1	133 - 35	98
Front Royal	11	57.7	141 - 35	106

Note that dye-cloud duration (D) also can be determined by $D = T_{TE} - T_{LE}$. In working with concentrations, river-discharge information is required. The discharges at 80-percent flow duration for the index gages at Lynnwood (L) and Front Royal (F) on the South Fork Shenandoah are: $Q_{L80} = 290$ ft^3/s and $Q_{F80} = 465$ ft^3/s (fig. 2). The discharges at the sampling sites can be estimated from the drainage-area ratios given in table 2. To obtain discharges for sites other than sampling sites, the drainage-area ratios determined from figure 3 can be used to adjust the appropriate index-gage discharge.

The unit peak concentration (C_{up}) can be calculated at each sampling point by equation 10: $C_{up} = 9{,}270\ D^{-1}$. The conservative peak concentration ($C_{p(con)}$) then can be calculated by equation 2A: $C_{p(con)} = \frac{C_{up} \times W_d}{Q}$

W_d = 5,000 pounds (given)

Q_{L80} = 290 ft^3/s

Q_{F80} = 465 ft^3/s

	Site no.	River mile	Dye-cloud duration (D) (hours)	Unit peak concentration (C_{up}*)	Drainage-area ratio	Discharge (Q) (ft^3/s)	Conservative peak concentration ($C_{p(con)}$) (µg/L)
Spill	5	142.6	0	-	1.06 L	307	-
	6	129.1	9	1,030	1.18 L	342	15,000
	7	121.2	16	579	1.19 L	345	8,390
	8	106.2	41	226	1.27 L	368	3,070
	9	99.2	76	122	1.29 L	374	1,630
	10	73.1	98	94.6	.96 F	446	1,060
Front Royal	11	57.7	106	87.5	1.00 F	465	940

* In $\frac{\mu g/L \times ft^3/s}{lb}$

The peak conservative concentration ($C_{p(con)}$), therefore, will be 940 µg/L at the Front Royal intakes. With the information available, the triangular approximations of the conservative time-concentration curves for Front Royal, as well as the intervening points, can be plotted (fig. 16). In addition, the data can be displayed in several other ways (fig. 17) which are related to time, distance, and concentration. The solution to any of the 13 types of problems posed at the beginning of this section can be determined from the five graphical presentations shown in figure 17.

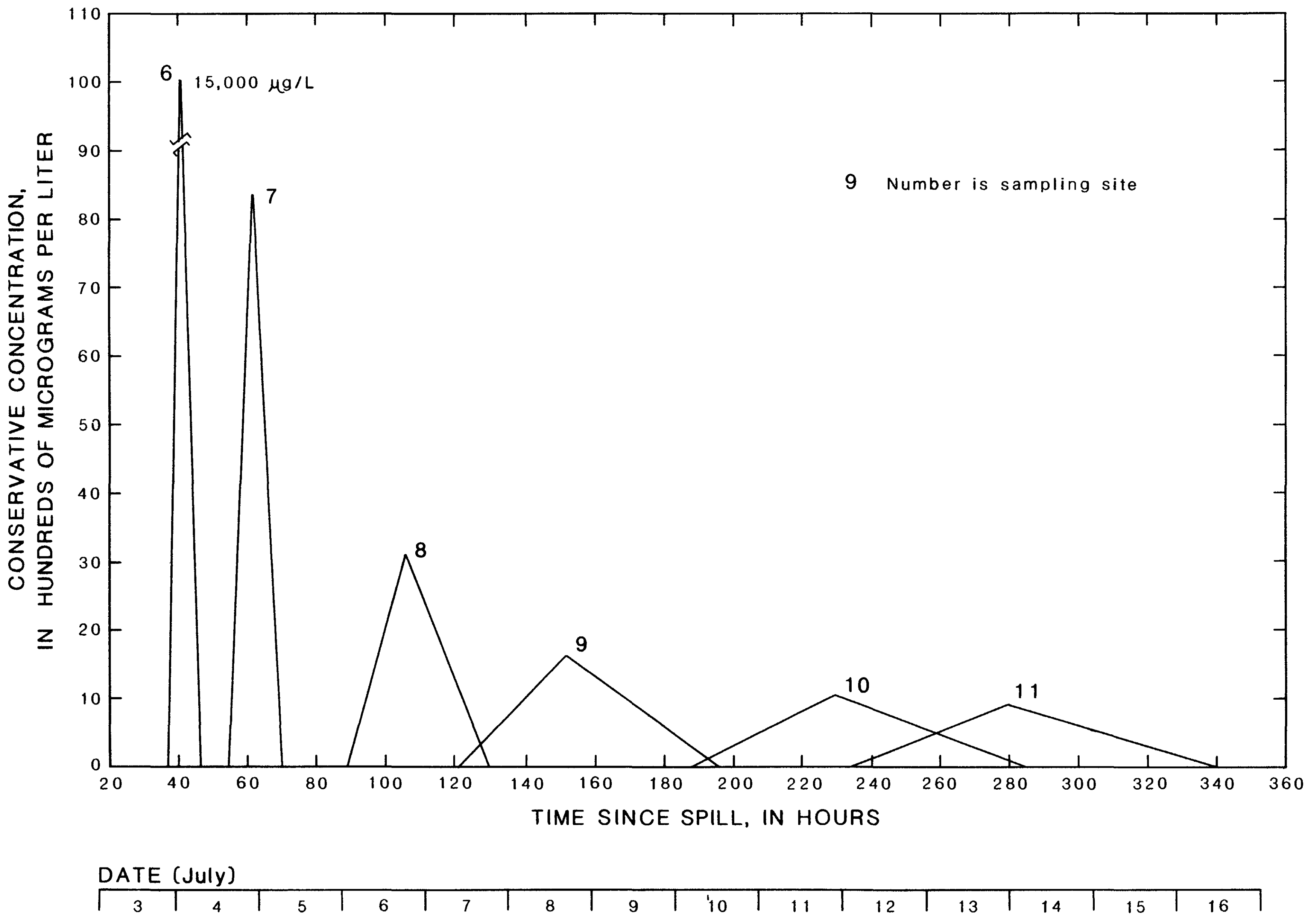
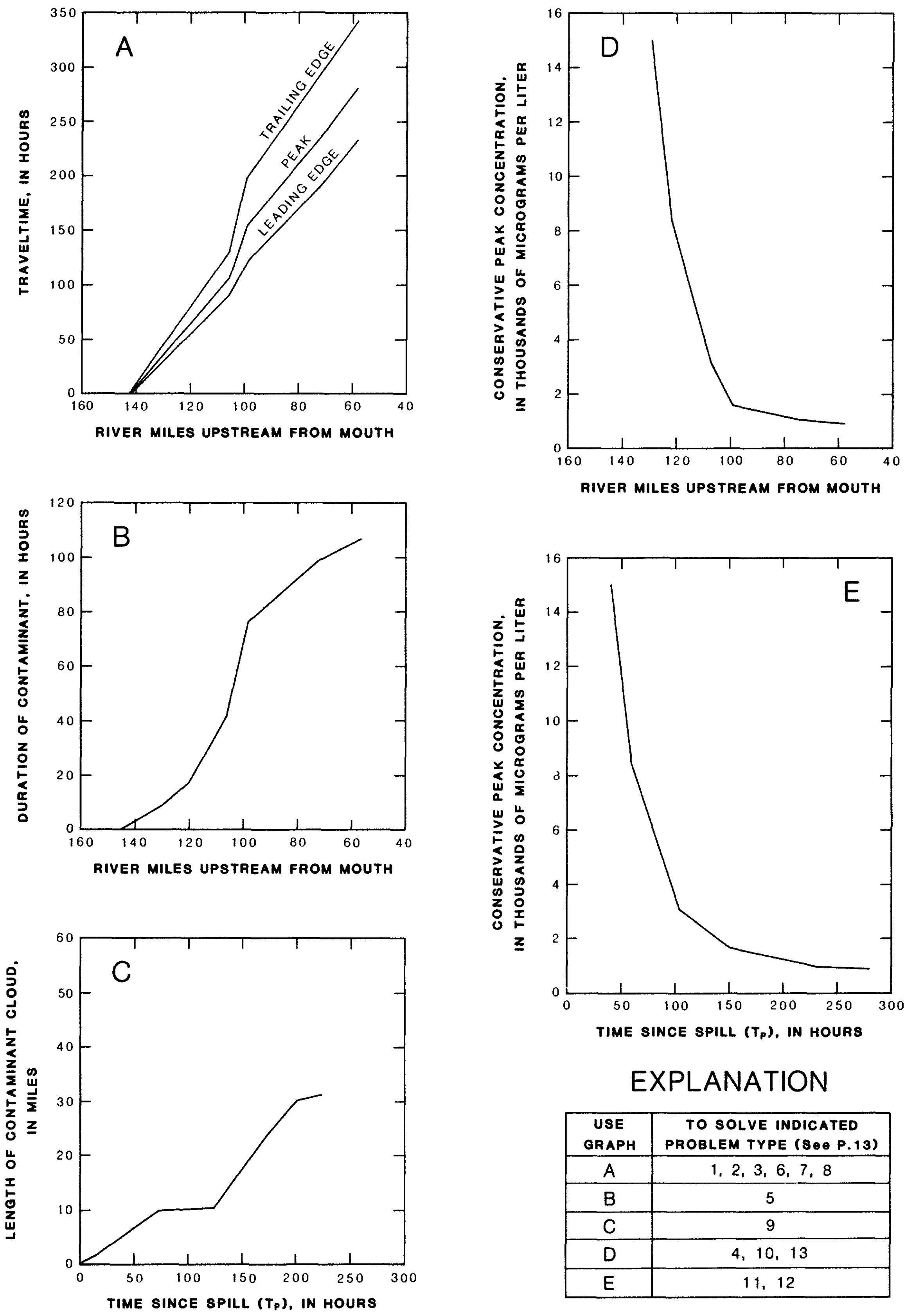


Figure 16.-- Triangular approximations of conservative time-concentration curves for hypothetical spill at Island Ford on July 2.



EXPLANATION

USE GRAPH	TO SOLVE INDICATED PROBLEM TYPE (See P.13)
A	1, 2, 3, 6, 7, 8
B	5
C	9
D	4, 10, 13
E	11, 12

Figure 17.-- Various ways to display data from example hypothetical spill at Island Ford.

In order to illustrate the superposition technique for dealing with a variable-rate or constant-rate spill, let us assume that the same 5,000 pounds of soluble, toxic material was spilled in the river. All conditions except the method of spill are assumed to be the same as in the previous problem. Let us further assume that the spill occurred at the rate of 200 pounds per hour for the first 10 hours and then at the rate of 100 pounds per hour for 30 hours (fig. 18A). The problem is to determine the response at the Front Royal water intake. The following information is available from the previous problem for the Front Royal site (site 11): T_{LE} = 234 hours, T_P= 280 hours, T_{TE} = 340 hours, D = 106 hours, Q_{F80} = 465 ft^3/s, and W_d = 5,000 pounds.

As the contaminant cloud required over 100 hours to pass the Front Royal intakes from an instantaneous injection, it should provide an adequate solution if each 5-hour increment of spill is treated as an instantaneous injection. The injection time will be assumed to be the midpoint of the 5-hour increment. The following table shows the information necessary to plot the triangular approximation (fig. 18B) of the time-concentration curve for each injection increment.

Injection increment no.	Weight injected (lb)	Time since injection began (h)	T_{LE} (+234) (h)	T_P (+280) (h)	T_{TE} (+340) (h)	$C_{up} = \frac{9,270}{D}$ (*)	$C_{P(con)} = \frac{C_{up}W_d}{Q}$ (µg/L)
1	1,000	2.5	236.5	282.5	342.5	87.5	188
2	1,000	7.5	241.5	287.5	347.5	87.5	188
3	500	12.5	246.5	292.5	352.5	87.5	94
4	500	17.5	251.5	297.5	357.5	87.5	94
5	500	22.5	256.5	302.5	362.5	87.5	94
6	500	27.5	261.5	307.5	367.5	87.5	94
7	500	32.5	266.5	312.5	372.5	87.5	94
8	500	37.5	271.5	317.5	377.5	87.5	94

* C_{up}, in micrograms per liter per pound per cubic foot per second.

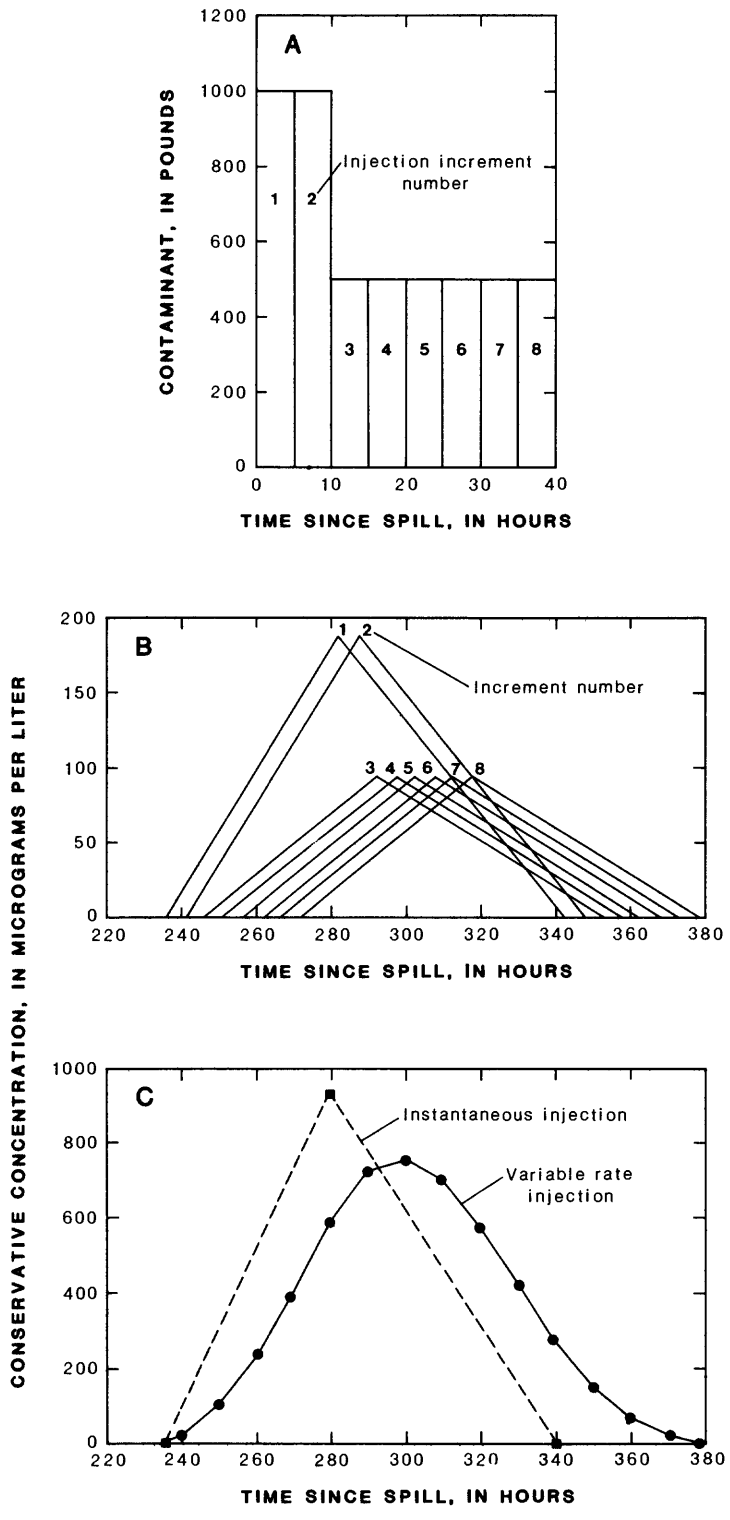


Figure 18.-- Computation of time-concentration curve for variable-rate injection by superposition method. (A) Variable-rate injection of contaminant in 5-hour increments: (B) Triangular responses to injection increments: and (C) Composite response curve for variable-rate injection and triangular response curve for instantaneous injection.

The composite time-concentration curve (fig. 18C) is the sum of the contributions of the eight triangular approximations summed at 10-hour intervals. The triangular approximation of the time-concentration curve at Front Royal for the instantaneous injection is also shown in figure 18C. The effects of the variable-rate injection are that it delays the arrival of the peak concentration by 20 hours and reduces the peak concentration by about 20 percent. It should be noted that the concentrations are conservative and reflect the transport of the total amount of the spilled contaminant.

ASSUMPTIONS AND LIMITATIONS

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). 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. When using the described procedures, and a significant flood wave is present in the system, added uncertainty will be introduced in the results.

In the example computation, steady flow rates were assumed to exist for a long period of time. Actually, steady flow seldom exists in a natural flow system. If precipitation is occurring or has recently occurred, the discharge usually is increasing. In the case of no precipitation, the discharge usually is decreasing. The data for this study generally 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. The index discharge most likely will be changing during the time a contaminant is moving downstream. As the traveltimes and concentrations are related to discharge, the user will need to reassess these values at periodic intervals based on the most curent discharge information.

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. Ideally, three measurements of velocities and associated discharges would be used to determine these relationships. Some studies have revealed a slightly curvilinear relation. However, the 50-percent increase in study cost for obtaining the third set of data did not seem warranted.

Complete lateral mixing was assumed to exist in the development of the concentration attenuation procedures. However, under the conditions prevailing during this study, complete lateral mixing was not continuously maintained because of large inflows of water from the two major tributaries.

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 may 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 under most circumstances. When lateral mixing is not complete, a localized peak concentration in the stream section may be higher than the average peak concentration determined from the relation. These two factors are at least partially compensating and the relations should provide a reasonable 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, the contaminant would tend to move more slowly at first than indicated by the traveltime relations. Under these circumtances, the contaminant also would be highly concentrated on one side of the stream. As indicated by the equations of mixing length on page 32, the distance for complete lateral mixing can be substantial, particularly in rivers that have a large width-to-depth ratio. The user should calculate the reach length required for total mixing. While the contaminant moves through this reach, the calculated average concentration would need to be adjusted for the uneven distribution in the cross section.

SUMMARY AND CONCLUSIONS

Dye-tracer studies on the Shenandoah River between Waynesboro, Va., and Harpers Ferry, W. Va., were made in September 1983 and June 1984 at discharges with flow durations of 85 and 45 percent, respectively. 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 method is most applicable to nearly steady or slowly decreasing rates of flow. The method allows the user to estimate the necessary data 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. The method is applicable to spills in which the contaminant is injected instantaneously, at a constant rate, or at a variable rate.

An example computation using the graphs and tables shows that, with flow conditions at the 80-percent duration level, an instantaneous spill of 5,000 pounds of water-soluble contaminant at Island Ford, Va., would have the following effect on the river (85 mi downstream) at the Front Royal water intakes: (1) The leading edge of the contaminant cloud would reach Front Royal in 9.75 days; (2) the peak concentration of contaminant would arrive in 11.7 days; (3) the magnitude of the peak concentration would be about 940 μg/L if the contaminant were conservative; and (4) the concentration of contaminant would be about 94 μg/L, or 10 percent of the peak, 14.2 days after the spill.

Under the same flow conditions, a variable-rate spill of 200 pounds per hour for 10 hours and 100 pounds per hour for 30 hours would delay the peak concentration by 20 hours and reduce the magnitude of the peak concentration by about 20 percent.

The methods presented in this report are intended to be used as a guide in monitoring the movement of a soluble substance in the Shenandoah River. Those responsible for managing and regulating water resources would generally monitor a situation such as that described in the sample problem. Extensive 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 will 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.

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 substantially from those described. The user also is advised that some subjective decisions may be required to adjust the results to reflect the field situation existing at the time a problem occurs.

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