TRAVELTIME AND DISPERSION OF A SOLUBLE DYE IN THE SOUTH BRANCH POTOMAC RIVER, PETERSBURG TO GREEN SPRING, WEST VIRGINIA

By Alvin R. Jack

U.S. GEOLOGICAL SURVEY
Water Resources Investigations Report 84-4167

Prepared in cooperation with the
INTERSTATE COMMISSION ON THE POTOMAC RIVER BASIN

Charleston, West Virginia
1986

UNITED STATES DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, *SECRETARY*

GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

For additional information write to:

District Chief
U.S. Geological Survey, WRD
603 Morris Street
Charleston, West Virginia 25301

Copies of this report can be purchased from:

Open-File Services Section
Western Distribution Branch
U.S. Geological Survey
Box 25425, Federal Center
Denver, Colorado 80225
(Telephone: (303) 234-5888)

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS—CONTINUED

TABLES

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

For the convenience of readers who may want to use International System of Units (SI), the data may be converted by using the following factors:

Multiply inch-pound units	By	To obtain SI units
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
ounce, fluid (fl. oz)	0.02957	liter(L)
pint (pt)	0.4732	liter (L)
quart (qt)	0.9464	liter (L)
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
mile per hour (m/h)	1.609	kilometer per hour (km/hr)
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	453.6	gram (g)
degree Fahrenheit (°F)	°C=5/9 (°F-32)	degree Celcius (°C)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

TRAVELTIME AND DISPERSION OF A SOLUBLE DYE IN THE SOUTH BRANCH POTOMAC RIVER, PETERSBURG TO GREEN SPRING, WEST VIRGINIA

By Alvin R. Jack

ABSTRACT

Traveltime studies, using rhodamine dyes, were made in 1970 and 1982 on the South Branch Potomac River from Petersburg, West Virginia, to the confluence with the North Branch Potomac River at Green Spring, West Virginia.

Flow-duration at the time of the studies was approximately 32 percent in November 1970 and 95 percent in September 1982.

Two studies, at discharges of 110 and 1,230 cubic feet per second, were used to define traveltime-distance relationships. A contaminant takes 386 hours to travel 69 miles from Petersburg, West Virginia, to the mouth of the river when streamflow is 110 cubic feet per second. The contaminant would, however, take only 89 hours when streamflow is 1,230 cubic feet per second. The traveltime data were interpolated and extrapolated for selected discharges from 70 to 1,500 cubic feet per second at the index gage near Springfield, West Virginia.

INTRODUCTION

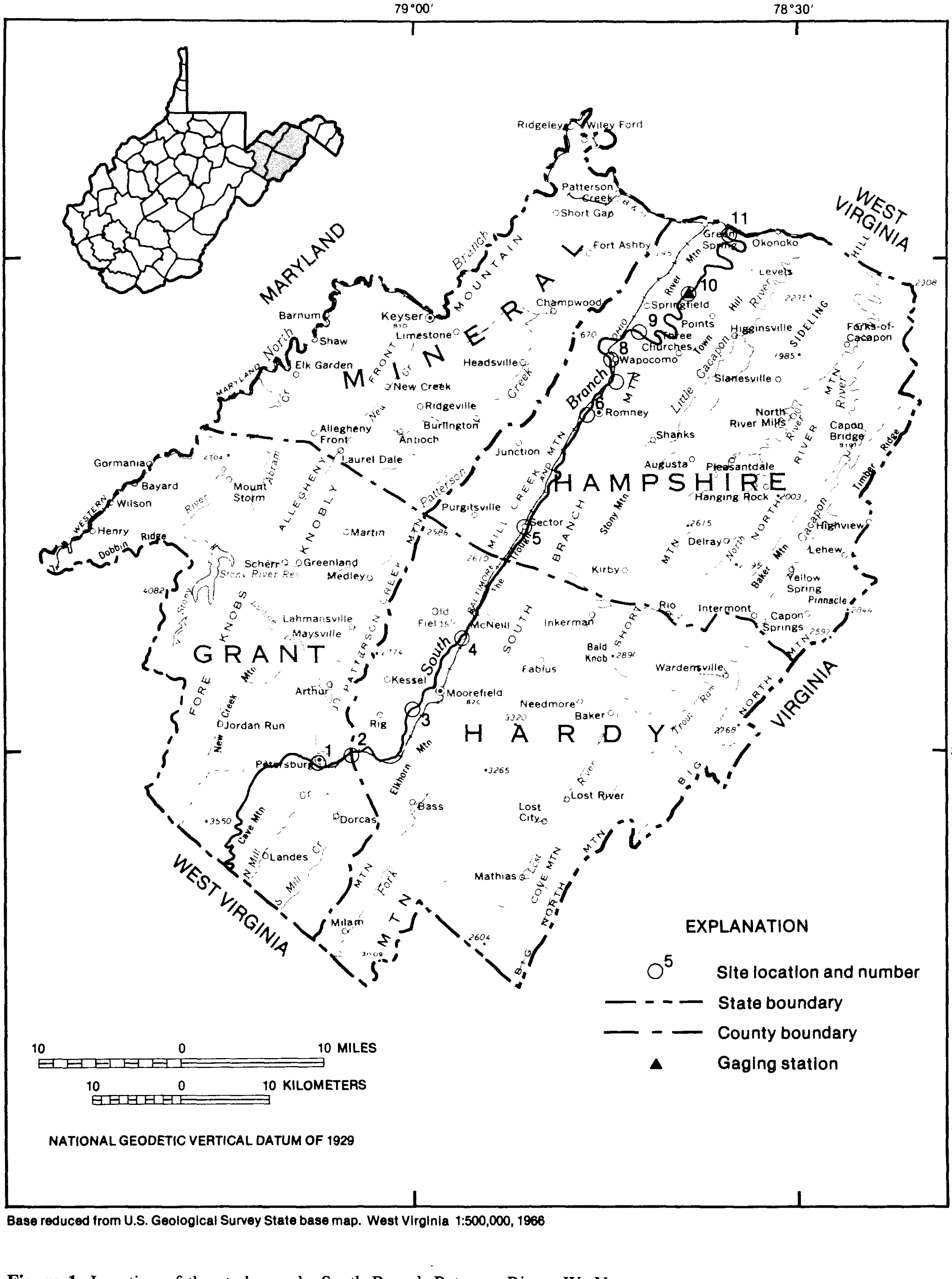
A major concern of surface-water users is the effect that a contaminant spilled upstream will have on their water supply. The purpose of this report is to enable water users in the South Branch Potomac River to predict (1) the time of passage of a contaminant and (2) the maximum level of concentration during passage of the contaminant. Graphs and data in this report will enable the user to predict the movement and concentration of a soluble contaminant spilled in the study reach for discharges between 70 and 1,500 ft^3/s.

This report combines the results of two studies: One in November 1970 (Hobba and others, 1972) at about mean annual flow, or 32 percent flow duration, and the other in September 1982 at 95 percent flow duration or low flow. Dye was injected instantaneously at the head of each subreach. Samples were collected at the same sites in each study.

DESCRIPTION OF THE REACH

The South Branch Potomac River is 135 mi long and has a total drainage area of 1,487 mi^2. The study reach between Petersburg, W. Va., and the mouth is 69 mi long and generally is free flowing and unobstructed by any significant impoundments. The drainage area at the Springfield, W. Va., index gage (site 10) is 1,471 mi^2 (fig. 1).

Moorefield and Romney, W. Va., at river miles 57 and 31 respectively, are the two principal towns and water users in the study reach. The reach from Petersburg to Romney is 38.3 mi long and has an average fall of 7.6 ft/mi. The reach from Romney to the confluence with the North Branch Potomac River is 30.7 mi long and has an average fall of 3.9 ft/mi.



Base reduced from U.S. Geological Survey State base map. West Virginia 1:500,000, 1966

Figure 1. Location of the study reach, South Branch Potomac River, W. Va.

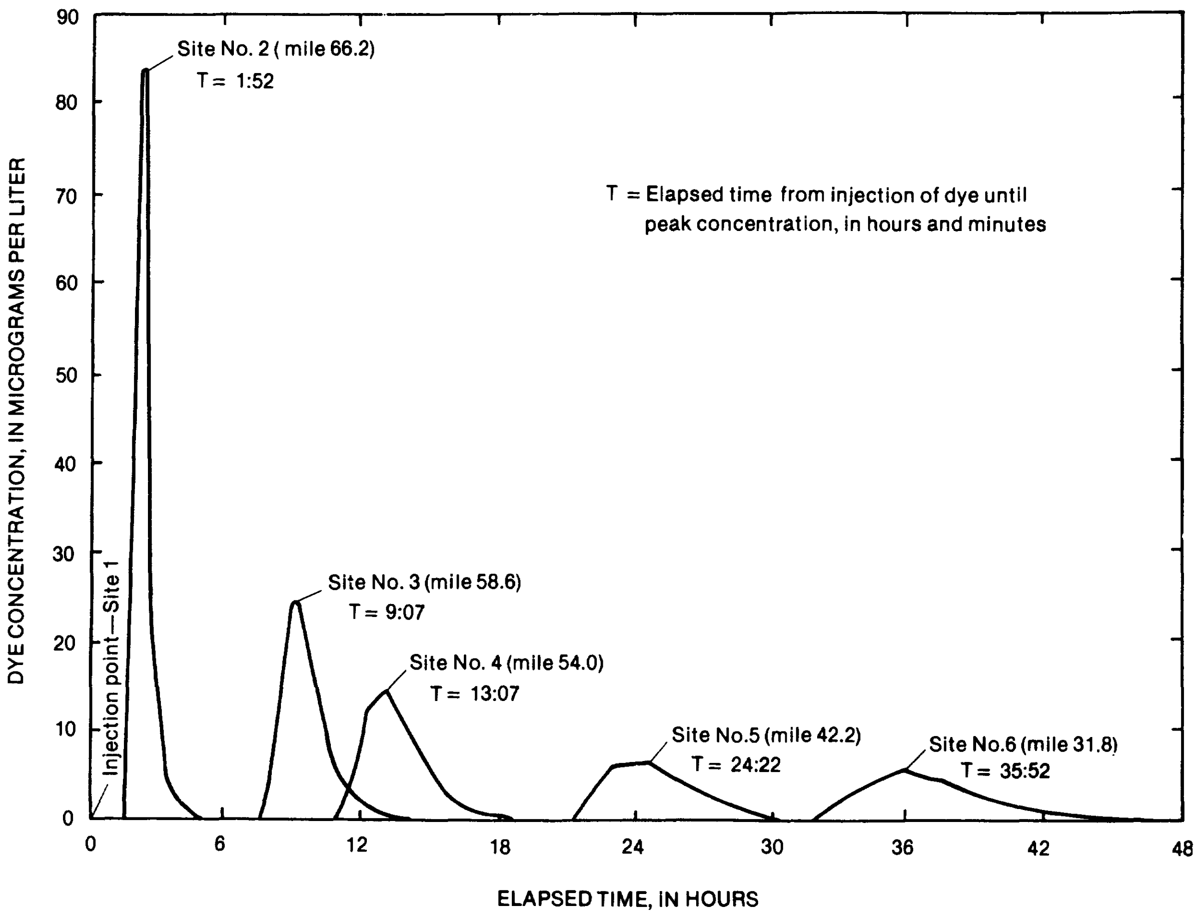


Figure 2. Observed time-concentration curves for South Branch Potomac River between Petersburg and Romney, November 1970 study (Hobba and others, 1972).

METHODS OF STUDY

Traveltime Determinations

The study reach was divided into subreaches to (1) shorten the overall sampling time, (2) reduce complications from inclement weather, and (3) reduce the change in discharge at the index station during the studies. Large fluctuations in discharge during the downstream movement of a contaminant can cause significant differences between actual and computed traveltimes.

The November 1970 study was done during a falling stage at approximately mean annual flow. The study reach was divided into two subreaches. The September 1982 low-flow study was divided into four subreaches. Precipitation occurred during the third and fourth day of the low-flow study, which increased the discharge and effectively reduced dye concentrations.

Rhodamine dye was injected instantaneously at the upper end of each subreach. Water samples were collected at selected time intervals at one to six sampling sites for each subreach either by hand sampler or syringe-boat sampler. Locations of the injection points, sampling sites, river crossings, and major tributary inflows are shown in table 1.

Fluorometers were used in the field to test each sample for dye and thus determine the leading edge, peak concentration, and trailing edge of the dye cloud to facilitate scheduling of sampling at successive downstream points. Sampling was continued at each sampling site until the concentration reached 5 percent of the peak.

All samples were reanalyzed under controlled temperatures and with a fluorometer calibrated with dye from the same batch used in each study. Plots of observed concentration (C_{obs}) versus elapsed time since injection resulted in the time-concentration curves shown in figures 2-7.

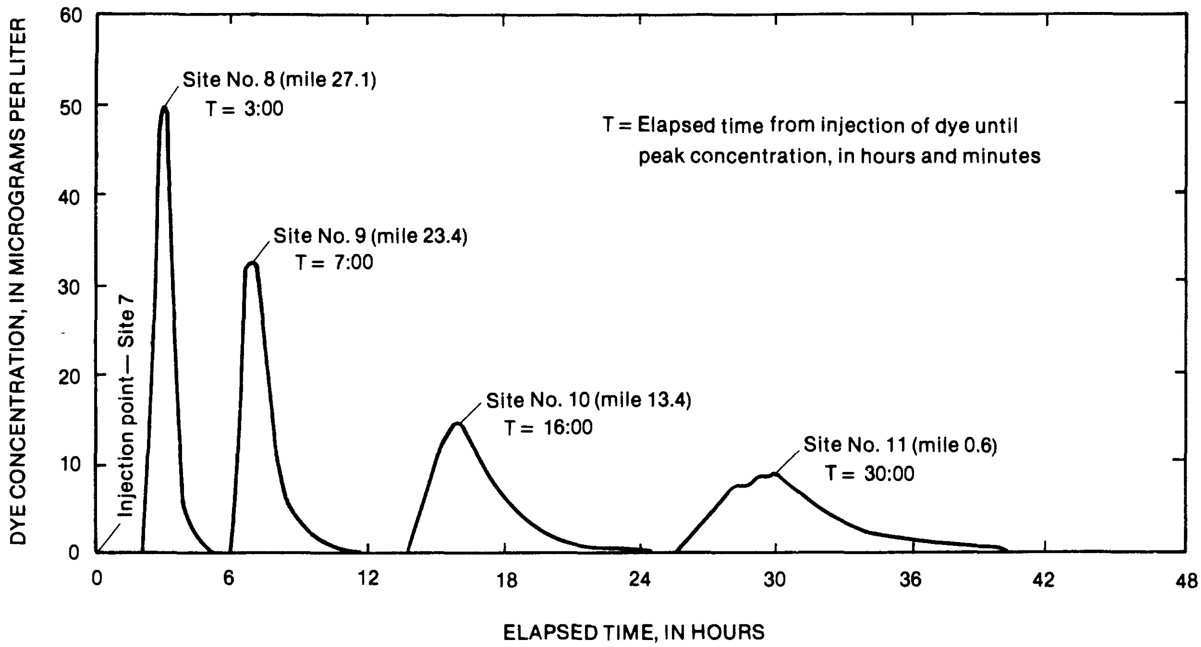


Figure 3. Observed time-concentration curves for South Branch Potomac River between Romney and the mouth, November 1970 study (Hobba and others, 1972).

Discharge Determinations

During the November 1970 study, discharge was computed from recorded stage at U.S. Geological Survey gaging stations on the South Branch Potomac River, measured at sampling sites during passage of the dye cloud, or estimated by drainage-area comparisons. During the 1982 study, in addition to the recorded stage at the gaging station, current-meter discharge measurements were made at each sampling site during the passage of the dye cloud.

TRAVELTIME ESTIMATION

Traveltime-estimation curves were drawn for the leading edge, peak concentration, and trailing edge of the dye by combining and interpolating the data from the two studies. (1) The traveltime and index-discharge data were plotted, and curves of relationship were drawn for each sampling site. (2) Travel-times for selected index discharges were determined for each site with these curves. (3) The traveltimes at each selected discharge and distance were then plotted. These curves of relationship are used to estimate traveltimes between any two points in the study reach for any of the selected index discharges. Traveltime-distance relationships for selected discharges from 70 to 1,500 ft^3/s are shown in figures 8 through 10.

Traveltimes for the individual subreaches were added, but only traveltime of the centroids of the time-concentration curves are truly additive. However, the time interval between passage of the peak concentration at two successive sites is virtually the same as the time interval between centroids of the time-concentration curves and may be added and plotted to approximate the pattern expected from a single injection (Hubbard and others, 1982, p. 28).

DISPERSION

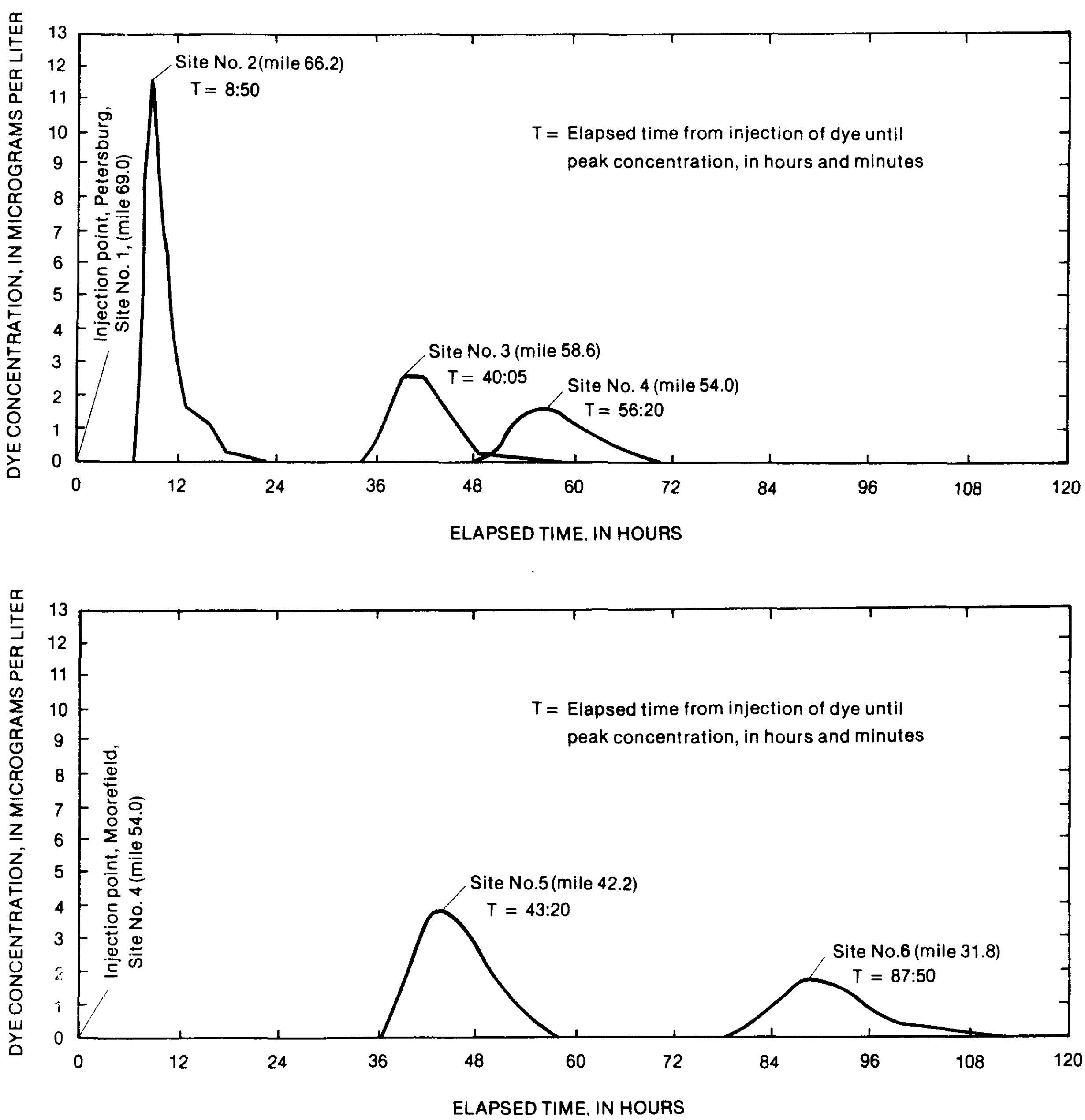
Dyes used as tracers usually have some loss due to various physical, chemical, and biological processes. The observed time-concentration curves have the proper shape, but concentrations are usually lower than those expected from a conservative solute (one representing 100 percent recovery of the total weight of the injected dye). The conservative-concentration values shown in table 2 were computed by adjusting the observed concentrations of dye upward to reflect 100 percent recovery of the dye or conservative solute. The percentage of recovery (R_p) is computed by using the equation:

$$R_p = (kQA_c) \div W_d \qquad (1)$$

Where:

k is a constant: 2.248×10^{-2};

Q is the discharge at the sampling point;



Figures 4-5. Observed time-concentration curves for South Branch Potomac River, September 1982 study.

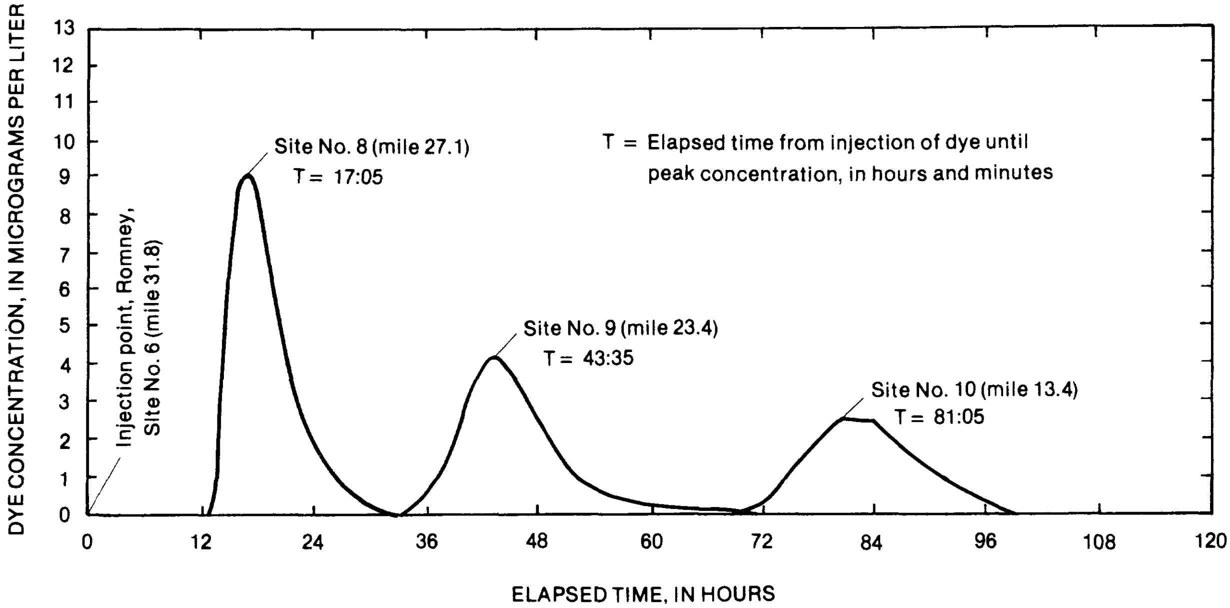
A_c is the mean area of the time-concentration curve in $\mu g/L \times$ hrs (micrograms per liter times hours); and

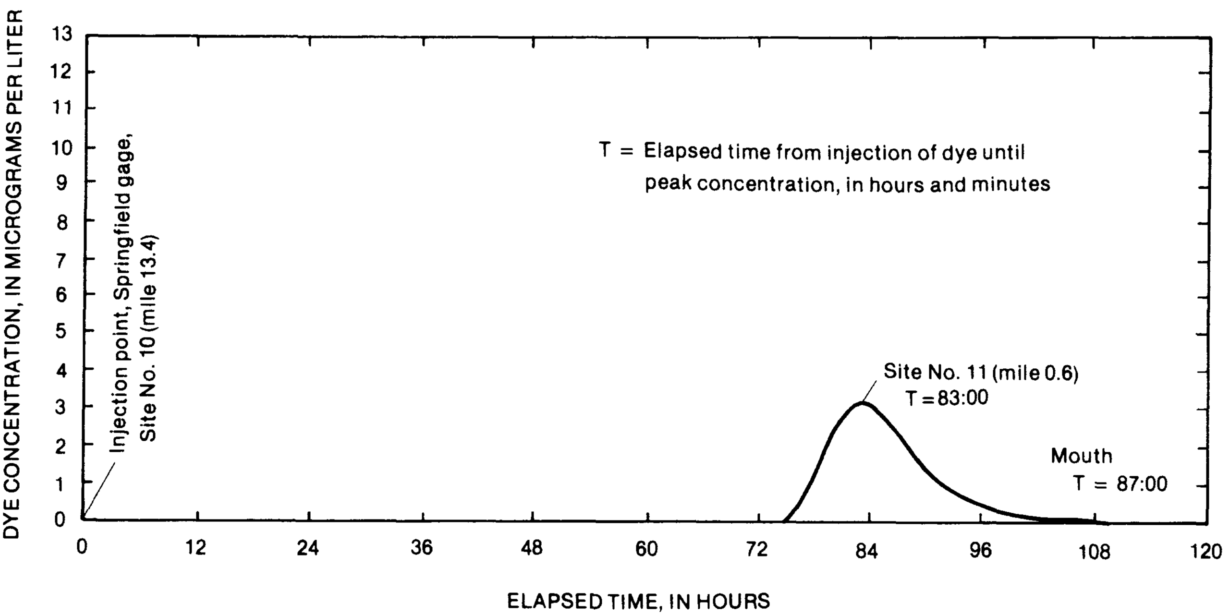
W_d is the weight, in pounds, of pure dye injected.

The effect of the dye loss as it moves downstream can be eliminated by using the unit-concentration concept. Unit peak concentration (C_{up}) is defined as the concentration produced in 1 ft^3/s flow by the injection of 1 lb of conservative contaminant. Unit peak concentration can be computed by the equation:

$$C_{up} = (C_p Q) \div W_d \qquad (2)$$

Where C_p is the conservative peak concentration computed as $(C_{obs} \div R_p) \times 100$;





Figures 6-7. Observed time-concentration curves for South Branch Potomac River, September 1982 study.

Observed-concentration data were used to compute unit concentrations for both studies. A more detailed discussion of the preceding paragraphs and development of the equations is presented in Hubbard and others (1982).

A best-fit curve was developed for the relationship between unit peak concentration and traveltime for a flow of 1,230 ft^3/s at sites 2 through 11. A similar curve was developed for a flow of 110 ft^3/s using sites 2 through 4 and 8 through 10. Only those sites where mixing had occurred were used to develop the curves.

The best-fit curves were extrapolated and interpolated to develop a family of unit peak concentration attenuation curves for selected discharges, shown in figure 11. This family of curves apply to general river conditions between Petersburg and the mouth.

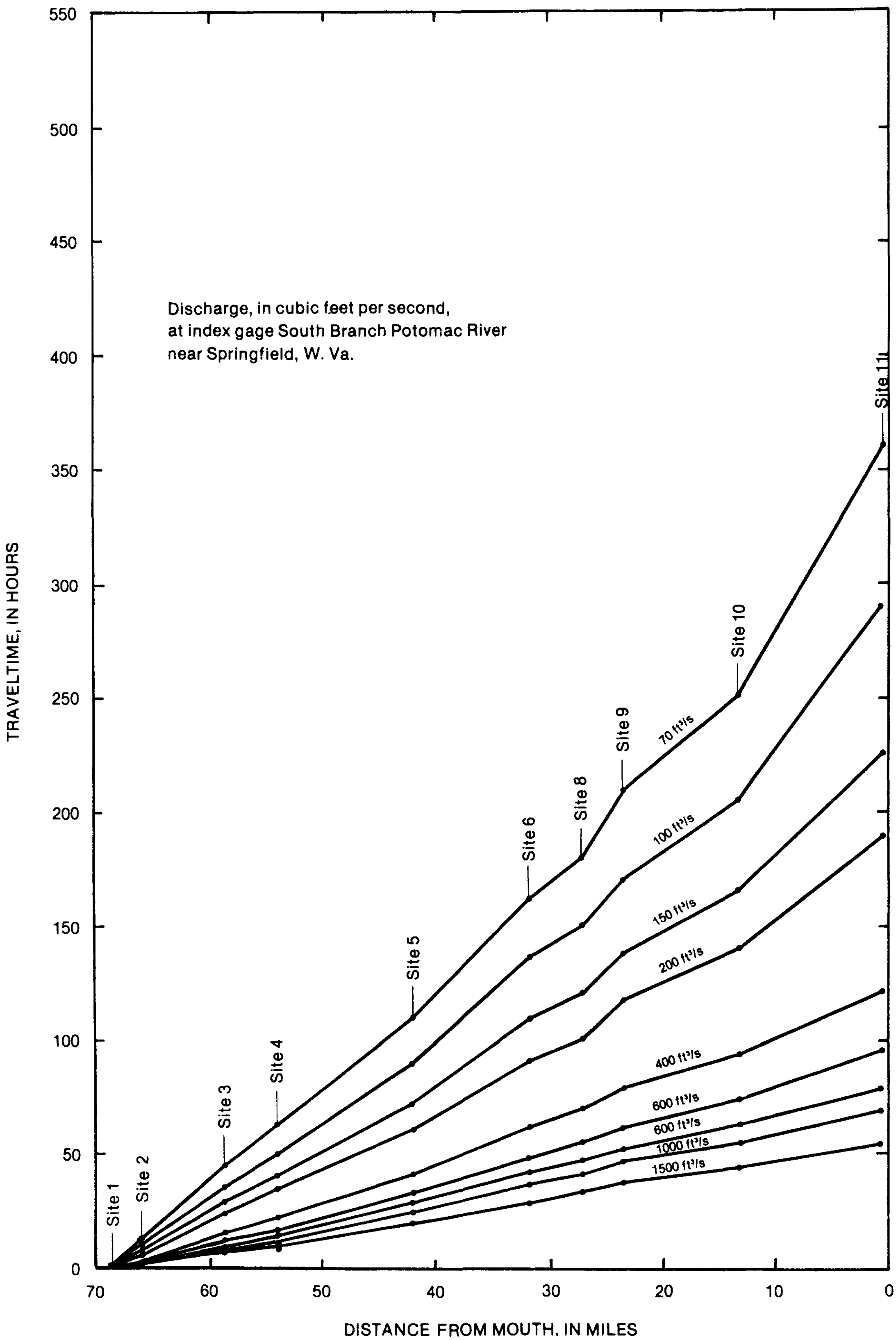


Figure 8. Traveltime-distance relationship of leading edge of dye cloud, South Branch Potomac River, Petersburg, W. Va., to the mouth.

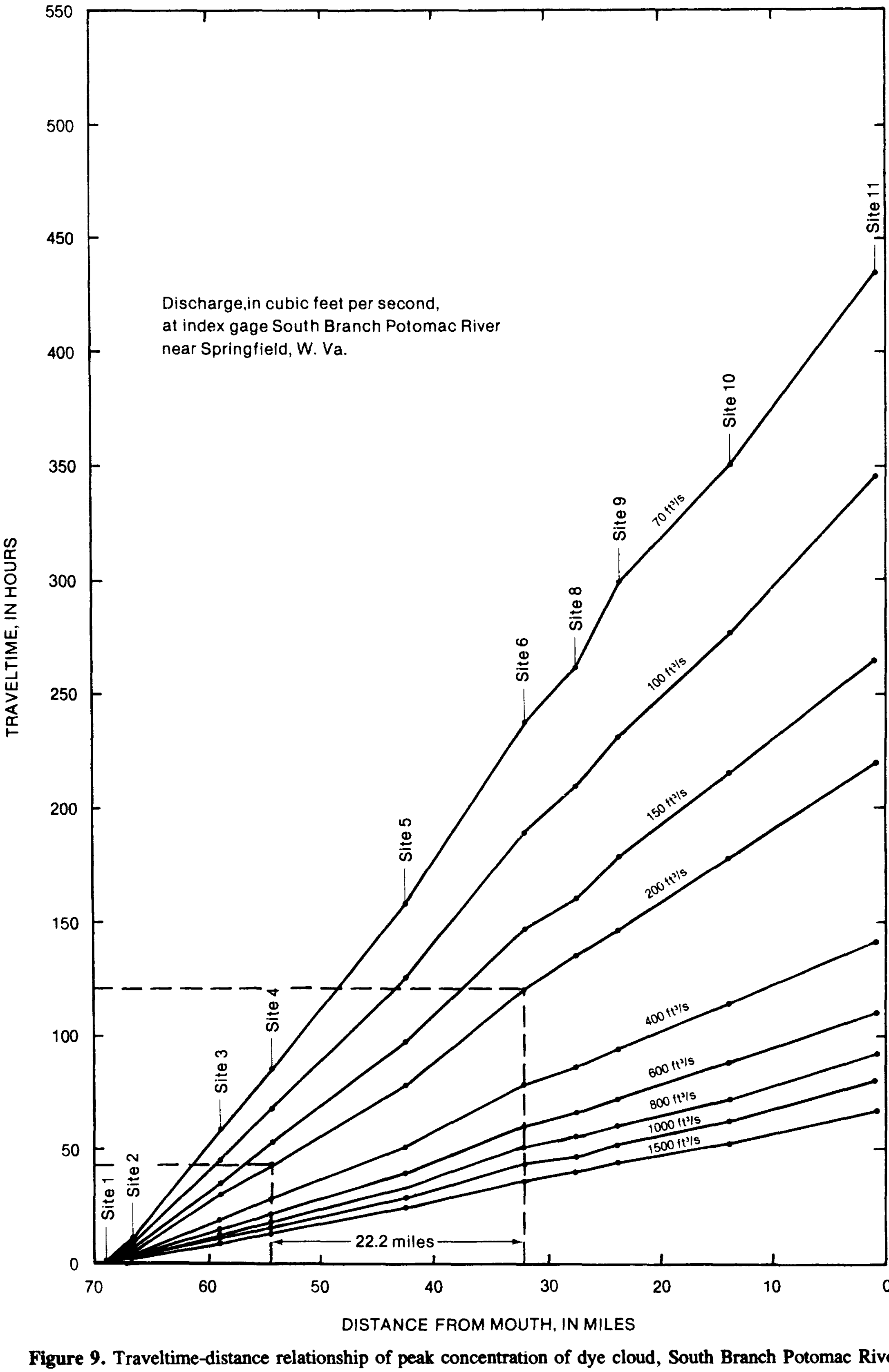


Figure 9. Traveltime-distance relationship of peak concentration of dye cloud, South Branch Potomac River, Petersburg, W. Va., to the mouth.

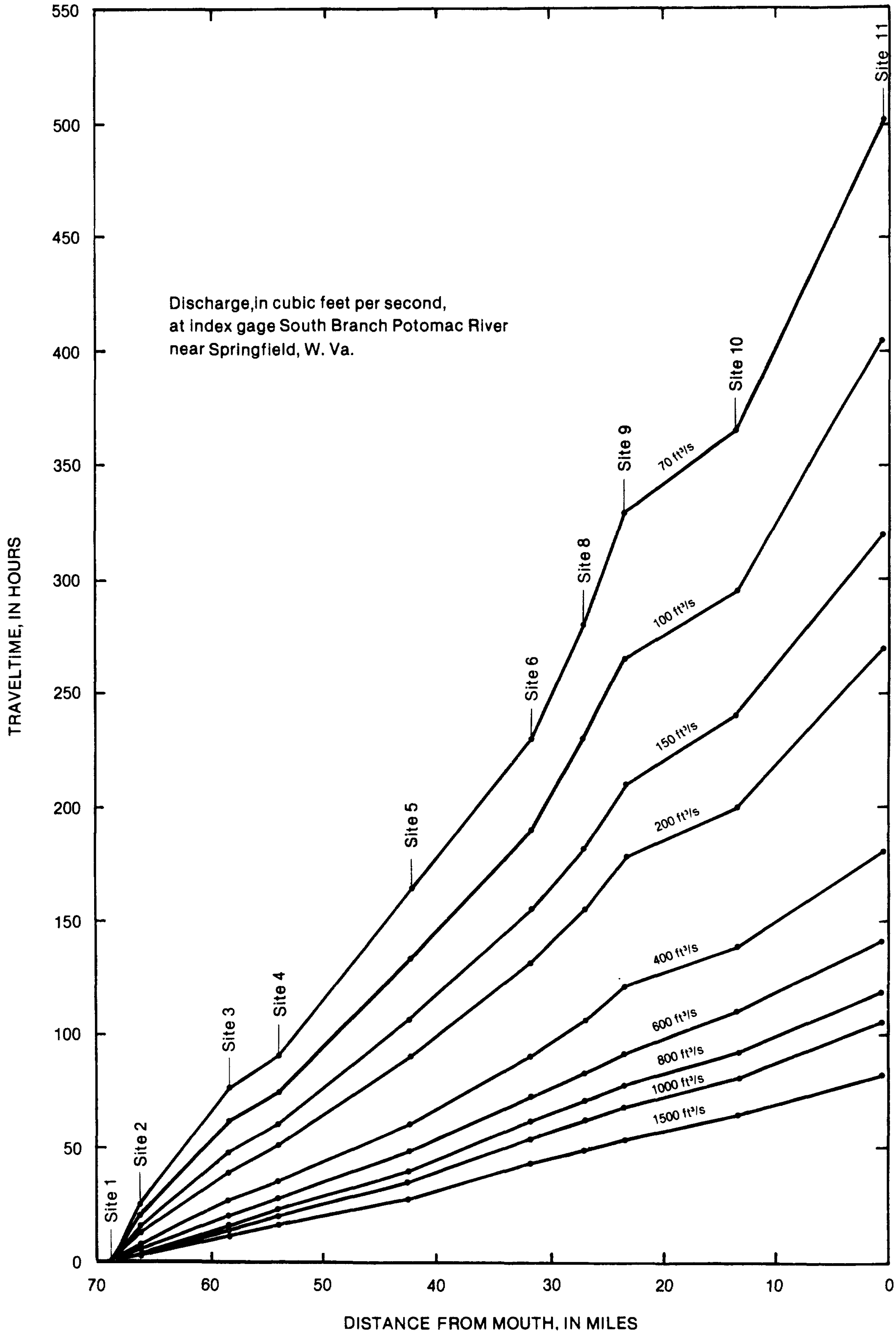


Figure 10. Traveltime-distance relationship of trailing edge of dye cloud, South Branch Potomac River, Petersburg, W. Va., to the mouth.

As an example, to demonstrate the use of figure 11, assume 500 lbs of a soluble contaminant was spilled into the South Branch Potomac River at U.S. Route 220 bridge east of Moorefield (fig. 1). A sample problem is to predict the resulting magnitude and arrival time of the peak concentration at the Romney water-supply intakes when the discharge is 200 ft^3/s at the index gage and the estimated discharge at the Romney water-supply intake is 210 ft^3/s. The spill site is at river mile 54 and the Romney intake is 22.2 mi downstream at river mile 31.8. From figure 9, when the discharge at the index gage is 200 ft^3/s, the peak will arrive 77 hours after the spill (120 minus 43 hours).

From figure 11, unit peak concentration would be approximately 200 µg/L when flow is 200 ft^3/s and traveltime is 77 hours. The peak conservative concentration, from equation 2, for the 500 lb spill would then be:

$$C_c = \frac{200\ \mu/L}{1\ lb} \times \frac{500\ lbs}{210\ ft^3/s} = 476\ \mu/L = \frac{W_d C_\mu}{Q}$$

The actual peak concentration is expected to be less than the value in figure 11 if the contaminant is not conservative. Health officials can determine if the concentration of a contaminant can be tolerated. If a concentration of 5 percent or more of the estimated peak concentration cannot be tolerated, then the leading- and trailing-edge traveltimes can be estimated by use of the curves in figures 8 and 10. For example, for an index flow of 200 ft^3/s, the leading edge would arrive 56 hours (90 minus 34) after the spill for 210 ft^3/s estimated flow at the Romney water plant. The trailing edge would be down to 5 percent or less of the estimated peak concentration about 130 hours after the spill therefore making the time of passage of the contaminant cloud (130 minus 56) 74 hours. Operational decisions could then be made concerning the closing and opening of the water intake at the Romney water-supply plant.

The time required for a given amount of solute to travel downstream and the corresponding concentration of the solute decreases with increased flow. For example, if 500 lbs of a soluble contaminant were spilled in the river at Petersburg, at flows of 70 ft^3/s and 1,500 ft^3/s, the peak concentration at site 2 would be about seven times greater for the lower flow. Peak concentrations at the mouth, however, would only be about twice as great, (see below).

	Site 2			At mouth		
Flow (ft^3/s)	Traveltime (hrs)	Unit concentration (C_{up})	Peak concentration (µg/L)	Traveltime (hrs)	Unit concentration (C_{up})	Peak concentration (µg/L)
70	12	1,700	12,100	440	33.5	240
1,500	3	5,000	1,700	68	425	140

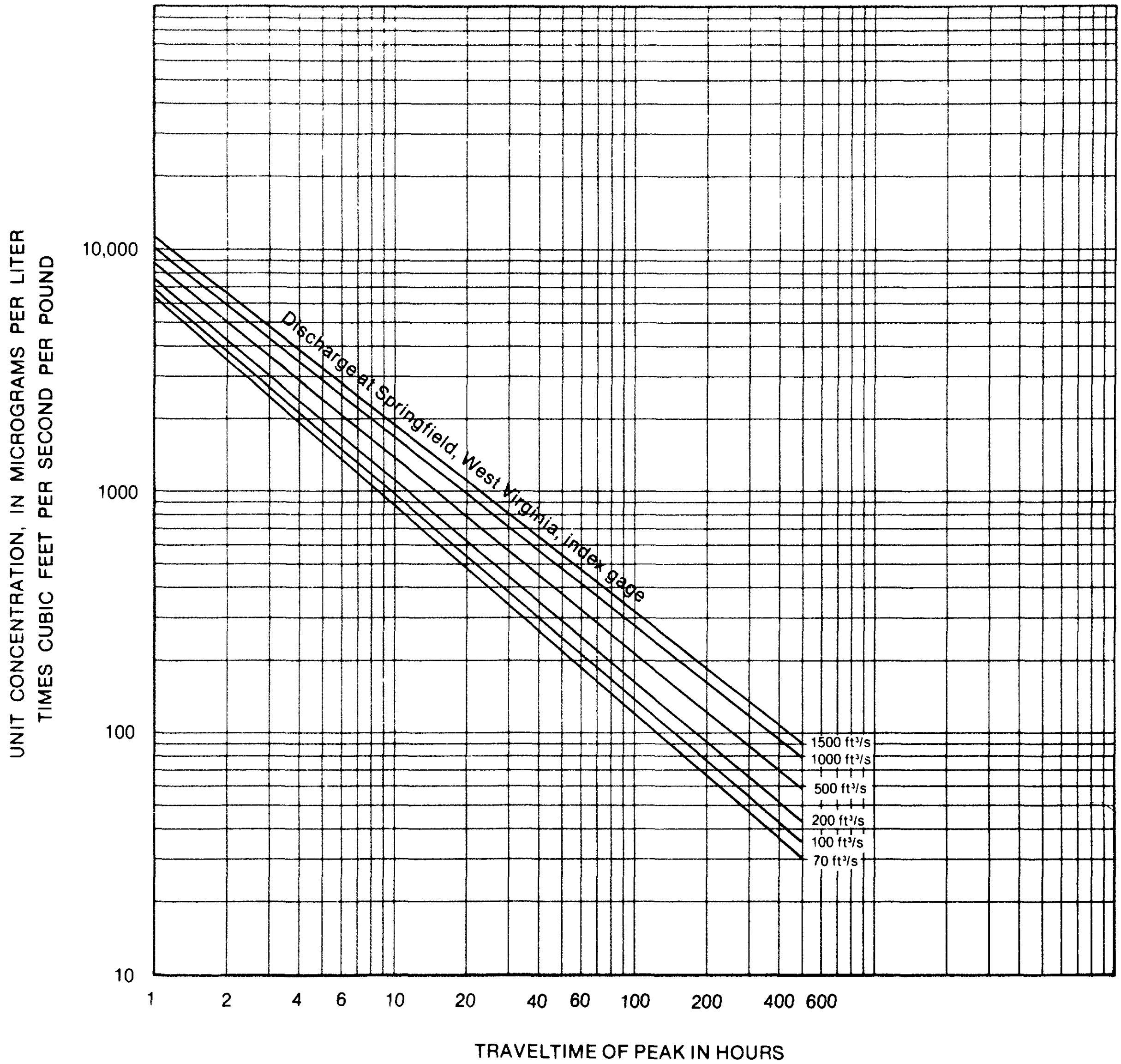


Figure 11. Attenuation of unit peak concentration with traveltime for selected discharges, South Branch Potomac River, Petersburg, W. Va., to the mouth.

SUMMARY

Two time-of-travel studies on the South Branch Potomac River, from Petersburg, W. Va., to the mouth, at flow durations of 32 and 95 percent, were used to define traveltime-distance relationships for discharges from 70 ft^3/s through 1,500 ft^3/s at the index gage near Springfield, W. Va. These data provide water users a method of estimating traveltimes of the leading edge, peak concentration, and trailing edge of soluble contaminants spilled into the studied reach. Users also can estimate the maximum peak concentration expected to occur at any point downstream from a spilled soluble contaminant of known quantity. This can be for any location in the reach and for any discharge from 70 through 1,500 ft^3/s.

Over 20 days would be required for the trailing edge of a soluble contaminant spilled into the river at Petersburg, W. Va., at an index discharge of 70 ft^3/s, to pass the mouth. About 3.5 days are required at a discharge of 1,500 ft^3/s.

If equal amounts of a soluble contaminant were spilled into the river at Petersburg, at flows of 70 ft^3/s and 1,500 ft^3/s, the peak concentrations would be about seven times greater at site 2 for the lower flow. Concentrations at the mouth, however, would only be about twice as great. Large changes in discharge during the downstream movement of a contaminant can cause significant differences between actual and computed traveltimes and concentrations.

GLOSSARY

Contaminant--Any substance that has an undesirable effect on water quality when discharged into a stream or water supply.

Cubic foot per second (ft^3/s)--The rate of discharge representing a volume of 1 cubic foot of water passing a given point during 1 second, equivalent to 7.48 gallons per second, 448.8 gallons per minute, or 0.028 cubic meters per second.

Discharge--The volume of water that passes a given place within a given period of time.

Drainage area--An area from which surface runoff is carried away by a single drainage system. Also called watershed and drainage basin.

Dye cloud--The form that a single injection of a fluorescent dye takes after mixing and dispersion.

Gaging station--A particular site on a stream where systematic observations of gage height and discharge are obtained. The station usually has a recording gage for continuous measurement of the elevation of the water surface in the channel.

Leading edge--The first or initial concentration of a dye cloud.

Natural flow--Streamflow unrestricted by dams, reservoirs, diversions, or other manmade hydraulic structures.

Peak concentration--The greatest concentration in a dye cloud.

Steady flow--The flow in a stream remains uniform with respect to time.

Trailing edge--That point in the dye cloud that has diminished to 5 percent of the peak concentration.

SELECTED REFERENCES

Hobba, W. A., Jr., Friel, E. A., and Chisholm, J. L., 1972, Water resources of the Potomac River basin, West Virginia: West Virginia Geological and Economic Survey, River Basin Bulletin 3, p. 48-58.

Hubbard, E. F., Kilpatrick, F. A., Martens, L. A., and Wilson, J. F., Jr., 1982, Measurement of time of travel and dispersion in streams by dye tracing: U.S. Geological Survey Techniques Water-Resources Investigations, book 3, Chapter A9, 44 p.

Taylor, K. R., 1970, Traveltime and concentration attenuation of a soluble dye in the Monocacy River, Maryland, 23 p.

Table 1.--Information on sites used in study

Site number	Landmark	River mile	Remarks[1]		
1.	Upstream from U.S. Rt. 220 bridge--Petersburg	69.0		0	X
	Lunice Creek (L)	68.3			
	Mill Creek (R)	67.2			
2.	U.S. Rt. 220 bridge	66.2	*		
	Walton	65.1			
	Durgon Creek (R)	63.6			
	Jenkins Run (R)	61.8			
3.	W. Va. Sec. Rt. 220/3 bridge	58.6	*		
	South Fork South Branch Potomac River (R), Moorefield	57.3			
	Dumpling Run (R)	56.0			
4.	U.S. Rt. 220 bridge	54.0	*		X
	Sycamore, B. & O. R.R. bridge	48.9			
	Sawmill Run (R)	42.8			
5.	Glebe Station (Sector)	42.2	*		
	Stony Run (R)	40.9			
	Johnson	39.1			
	Mill Run (R)	35.4			
6.	U.S. Rt. 50 bridge--Romney	31.8	*		X
7.	B. & O. R.R. bridge	30.7		0	
	Buffalo Creek (R)	29.6			
8.	Wapocomo	27.1	*		
	Fox Run (L)	26.0			
	Johns Run (L)	23.4			
9.	W. Va. Rt. 28 bridge--Grace	23.4	*		
	Millesons Mill	15.2			
10.	W. Va. Sec. Rt. 3 bridge--USGS gage near Springfield, W. Va.	13.4	*		X
11.	Along W. Va. Sec. Rt. 1/1	0.6	*		X
	B. & O. R. R. bridge and confluence with North Branch Potomac River	0			

(L) Stream enters from left side when facing downstream
(R) Stream enters from right side when facing downstream
[1] * Sampling site
0 Injection site 1970
X Injection site 1982

Table 2.--Traveltime, dispersion, and related data from the dye studies of November 1970 and September 1982 on the South Branch Potomac River from Petersburg, West Virginia to the mouth

Site number	Distance: From point of injection (miles)	Distance: From mouth (miles)	Distance: Distance between sites (miles)	Leading edge: Travel-time (hours)	Leading edge: Cumulative travel-time (hours)	Peak: Travel-time (hours)	Peak: Cumulative travel-time (hours)	Trailing edge: Travel-time (hours)	Trailing edge: Cumulative travel-time (hours)	Velocity of peak (mi/hr)	Time of passage of dye cloud (hours)	Discharge at sampling site (ft³/s)	Area T-C curve (µg/L-hr)	Percent recovery	Observed peak concentration C_{obs} (µg/L)	Conservative peak concentration C_p (µg/L)	Peak concentration produced by 1 lb of dye (1)	Unit peak concentration C_{up} (2)
Subreach 1-7																		
(Injected 29.6 lbs of rhodamine B dye at 1023 Nov. 18, 1970. Discharge at Springfield index gage: 1230 ft³/s)																		
1*	0	69.0	0	0	0	0	0	0	0	---	0	600	---	---	---	---	---	---
2	2.8	66.2	2.8	1.6	1.6	1.9	1.9	3.3	3.3	1.47	1.7	700	63.2	84	86	102	8.61	6030
3	10.4	58.6	7.6	6.0	7.6	7.2	9.1	9.5	12.8	1.06	5.2	800	54.7	83	25	30	2.53	2020
4	15.0	54.0	4.6	3.2	10.8	4.0	13.1	5.3	18.1	1.15	7.3	850	42.6	69	15	22	1.86	1580
5	26.8	42.2	11.8	10.3	21.1	11.3	24.4	12.1	30.2	1.04	9.1	880	35.7	60	6.7	11	0.93	820
6	37.2	31.8	10.4	11.3	32.4	11.5	35.9	17.6	47.8	0.90	15.4	900	37.0	63	5.2	8.3	0.70	630
7	38.3	30.7	1.1	1.2	33.6‡	1.9	37.8‡	1.2	49.0‡	0.58	15.4	900	---	---	---	---	---	---
Subreach 7-11																		
(Injected 50 lbs of rhodamine B dye at 0900 Nov. 18, 1970. Discharge at Springfield index gage: 1230 ft³/s)																		
7*	0	30.7	---	---	---	---	---	---	---	---	---	900	---	---	---	---	---	---
8	3.6	27.1	3.6	2.2	35.8	3.0	40.8	4.4	53.4	1.20	2.2	1180	51.8	69	53	77	3.85	4540
9	7.3	23.4	3.7	3.8	39.6	4.0	44.8	5.6	59.0	0.92	4.0	1150	52.3	68	33	49	2.45	2820
10	17.3	13.4	10.0	8.0	47.6	9.0	53.8	12.0	71.0	1.11	8.0	1000	50.8	57	14	25	1.25	1250
11	30.1	0.6	12.8	11.2	58.8	14.0	67.8	18.0	89.0	0.91	14.8	985	52.5	58	8.4	14	0.70	690
Subreach 1-4																		
(Injected 1,048 lbs of rhodamine WT dye at 1240 Sept. 20, 1982. Discharge at Springfield index gage: 110 ft³/s)																		
1*	0	69.0	0	0	0	0	0	0	0	---	0	70	---	---	---	---	---	---
2	2.8	66.2	2.8	7.1	7.1	8.8	8.8	18.3	18.3	0.32	11.2	75	39.5	63.4	12	18.8	17.9	1340
3	10.4	58.6	7.6	27.7	34.8	31.3	40.1	40.0	58.3	0.24	23.5	105	25.6	57.5	2.7	4.70	4.48	470
4	15.0	54.0	4.6	13.5	48.3	16.2	56.3	12.0	70.3	0.28	22.0	150	16.8	53.9	1.7	3.15	3.01	452
Subreach 4-6																		
(Injected 1,572 lbs of rhodamine WT dye at 1410 Sept. 20, 1982. Discharge at Springfield index gage: 110 ft³/s)																		
4*	0	54.0	---	---	---	---	---	---	---	---	---	100	---	---	---	---	---	---
5	11.8	42.2	11.8	36.6	84.9	43.3	99.6	57.0	127.3	0.27	20.4	115	39.4	64.6	3.9	6.04	3.84	442
6	22.2	31.8	10.4	41.7	126.6	44.5	144.1	54.8	182.1	0.23	33.5	165	25.5	60.0	1.9	3.17	2.02	333
Subreach 6-10																		
(Injected 2,096 lbs of rhodamine WT dye at 1525 Sept. 20, 1982. Discharge at Springfield index gage: 110 ft³/s)																		
6*	0	31.8	0	---	---	---	---	---	---	---	---	105	---	---	---	---	---	---
7	1.1	30.7	1.1	---	---	---	---	---	---	---	---	165	---	---	---	---	---	---
8	4.7	27.1	3.6	13.3	139.9	17.1	161.2	31.8	213.9	0.27	18.5	105	63.8	71.7	9.1	12.7	6.06	636
9	8.4	23.4	3.7	22.7	162.6	26.5	187.7	37.3	251.2	0.14	33.1	120	47.0	60.3	4.2	6.97	3.33	400
10	18.4	13.4	10.0	34.6	197.2	38.0	225.7	30.5	281.7	0.26	29.0	145	36.4	56.5	2.6	4.60	2.19	318
Subreach 10-11																		
(Injected 1,572 lbs of rhodamine WT dye at 1600 Sept. 20, 1982. Discharge at Springfield index gage: 110 ft³/s)																		
10*	0	13.4	0	---	---	---	---	---	---	---	---	110	---	---	---	---	---	---
11	12.8	0.6	12.8	75.3	272.5	83.0	308.7	104	385.7	0.15	28.7	150	39.8	85.2	3.3	3.87	2.46	369

* Dye injection site.

1 $C_p w_d$, in micrograms per liter per pound.

2 $C_{up} = \frac{C_p Q}{w_d}$, in micrograms per liter times cubic feet per second per pound.

‡ Estimated.