TRAVELTIME AND DISPERSION IN THE ILLINOIS RIVER, MARSEILLES TO PEORIA, ILLINOIS

by E. E. Zuehls

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 87-4106

Prepared in cooperation with

U.S. ARMY CORPS OF ENGINEERS,

ROCK ISLAND DISTRICT

Urbana, Illinois

1987

DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
Water Resources Division
102 E. Main Street, 4th Floor
Urbana, IL 61801

Copies of this report can be purchased from:

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

CONTENTS

ILLUSTRATIONS

TABLES

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

For the convenience of readers who may prefer to use metric (International System) units, the inch-pound values in this report 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)
pound, avoirdupois (lb)	453.6	gram (g)
gallon (gal)	3.785	liter (L)
mile per hour (mi/h)	1.609	kilometer per hour (km/h)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

GLOSSARY OF SYMBOLS

A_c	area under the observed time-concentration curve
C_c	conservative concentration
C_o	observed concentration
C_u	unit concentration
C_{pc}	conservative peak concentration
C_{po}	observed peak concentration
C_{pu}	unit peak concentration
D	passage time of the dye cloud
DA_{MAR}	drainage area at Marseilles
DA_{KING}	drainage area at Kingston Mines
DA_i	drainage area at point of interest
Q	stream discharge
Q_{MAR}	Illinois River discharge at Marseilles
Q_{KING}	Illinois River discharge at Kingston Mines
Q_i	stream discharge at point of interest
RM	river miles measured along the river channel
R_p	percent of dye or solute recovery
W_d	weight of pure dye or solute

TRAVELTIME AND DISPERSION IN THE ILLINOIS RIVER, MARSEILLES TO PEORIA, ILLINOIS

by E. E. Zuehls

ABSTRACT

Traveltime in 89.3 miles of the Illinois River between Marseilles Dam and Peoria Dam was measured using rhodamine-WT dye. On each of four subreaches, dye-tracer measurements were made at approximately 50- and 85-percent flow duration in 1978, 1979, and 1985.

The dye-tracer data were used to develop a method for estimating the traveltime and peak concentration of a solute spilled into the Illinois River. The estimates can apply to spills at any point within the study reach during a period of relatively steady discharge of low to medium streamflow. A sample problem to demonstrate the estimating methods is solved for a hypothetical situation in which 10,000 pounds of contaminant is spilled at a railroad crossing between Spring Valley and Hennepin, Illinois.

INTRODUCTION

The Illinois River is a source of municipal and industrial water supply and is a conveyance for the movement of commerce by barge. Demands for recreation are ever increasing. Consequently, there is a great awareness of the potential for accidental spills of toxic or harmful materials into the river.

Streamflow information has been obtained for the Illinois River since the early 1900's, and there are multitudes of publications where data, data summaries, and interpretative information can be reviewed. However, traveltime data for the river are meager and no known publications are available relating to traveltime.

The U.S. Army Corps of Engineers operates the structural controls on the Illinois River for navigational purposes. The Illinois Department of Transportation has responsibilities relative to the transportation of hazardous materials on and adjacent to the river. Knowledge of the streamflow and longitudinal dispersion characteristics of the river are needed to facilitate the development of hydraulic models applicable to streamflow regulation and for the control and abatement of accidental spills of pollutants.

This report describes results of a study by the U.S. Geological Survey, in cooperation with the U.S. Army Corps of Engineers, to measure time of travel and longitudinal dispersion of a reach of the Illinois River between

Starved Rock Dam and Peoria Dam. These measurements were combined with measurements between Marseilles Dam and Peoria Dam made in 1978-79 to develop predictive traveltime graphs or relations. The purpose of this report is to describe the procedures used to collect and analyze the traveltime data and to present the techniques by which the user of the report can estimate traveltime and dispersion in the river under a variety of streamflow conditions.

The scope of the traveltime relations are for streamflows from 40- to 95-percent flow durations, which translates to ranges in streamflow of about 4,000 to 10,000 ft^3/s (cubic feet per second) at Marseilles and about 4,000 to 14,000 ft^3/s at Peoria. Low-flow and medium-flow measurements, which relate to the above ranges in discharge, were made on eight segments in four subreaches of the river reach from Marseilles Dam to Peoria Dam. The data from the measurements were used to develop predictive relations for traveltime and dispersion at 5-percent increments of flow duration from 40 to 95 percent.

DESCRIPTION OF THE STUDY REACH

The study reach of the Illinois River was from Marseilles Dam to Peoria Dam, a distance of 89.3 miles. The reach was divided for measurement of time of travel into four subreaches, A to D (fig. 1), ranging in length from 16.0 to 27.3 miles.

Figure 1 shows 22 tributaries entering the study reach. The 10 largest tributaries have drainage areas ranging from 49.5 to 2,658 mi^2 (square miles) (Healy, 1979) and are large enough that a storm on a tributary basin could significantly affect the streamflow in the downstream subreaches. Locks and dams at Marseilles, Starved Rock, and Peoria are the only instream structures within the study reach that affect streamflow. The dams are used to maintain water levels sufficient to permit barge traffic throughout the year. Water is diverted from Lake Michigan to maintain streamflow adequate for barge traffic during low-flow periods.

Two long-term, continuous-record, streamflow-gaging stations are located within or near the study reach, one at Marseilles (05543500) and one at Kingston Mines (05568500). The gaging station at Marseilles has 66 years of discharge record showing an average discharge of 10,760 ft^3/s, a maximum discharge of 94,100 ft^3/s, and a minimum daily discharge of 1,460 ft^3/s. A gaging station just downstream of the study reach at Kingston Mines (05568500) has 46 years of record showing an average discharge of 15,190 ft^3/s, a maximum discharge of 88,800 ft^3/s and a minimum daily discharge of 1,700 ft^3/s. A third gaging station, at Henry (05558300), has only 4 years of record, which is insufficient for reliable statistics.

Table 1 lists the river miles for tributaries, dams, active gaging stations, highway and railroad crossings, and river sampling sites along the study reach. All river miles of the Illinois River are measured from its mouth located at the Mississippi River at Grafton, Illinois (Healy, 1979).

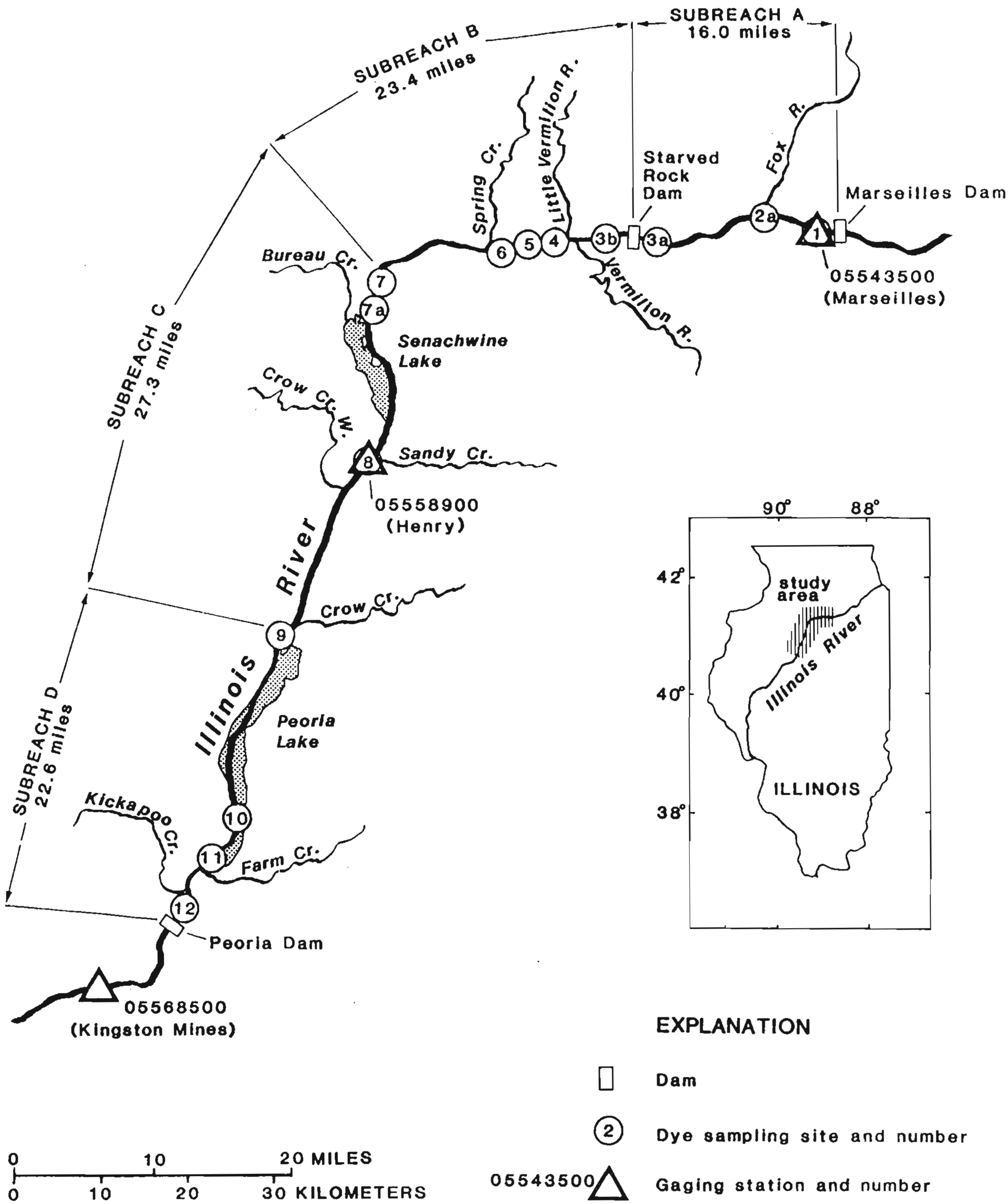

Figure 1.--Location of data-collection sites.

Table 1.--Study reach features including dams, tributaries, highway and railroad crossings, active gaging stations, and river sampling sites

[River miles and drainage areas from Healy (1979); mi^2, square miles; dashes indicate data not available]

River mile	Site number	Features	Drainage area (mi^2)	Ratio of drainage area at site to drainage area at Kingston Mines	Ratio of drainage area at site to drainage area at Marseilles
247.0	1	Marseilles Dam	--	--	--
246.9	-	County Highway bridge, Marseilles	--	--	--
246.5	-	05543500 Illinois River at Marseilles	8,259	0.52	1.00
244.5	-	Marseilles Lock	--	--	--
240.1	2a	Above Fox River	--	--	--
239.7	-	State Highway 23 bridge, Ottawa	--	--	--
239.6	2	Fox River	2,658	--	--
239.4	-	Burlington Northern Railroad bridge, Ottawa	10,949	.69	1.33
236.3	-	Coval Creek	--	--	--
231.8	3a	Above Starved Rock Dam	--	--	--
231.0	3	Starved Rock Dam	11,056	.70	1.34
229.6	3b	State Highway 178 bridge, North Utica	--	--	--
226.3	-	Vermilion River	1,331	--	--
225.7	-	Little Vermilion River	126	--	--
225.5	-	Burlington Northern Railroad bridge	--	--	--
225.4	-	Burlington Northern Railroad bridge	--	--	--
224.8	4	U.S. Highway 351 bridge, La Salle	12,572	.79	1.52
222.9	5	U.S. Highway 51 bridge, Peru	--	--	--
220.7	-	Cedar Creek	--	--	--
218.6	-	Spring Creek	[1]49.5	--	--
218.4	6	State Highway 89 bridge, Spring Valley	--	--	--
214.3	-	Negro Creek	--	--	--
214.0	-	Allfork Creek	--	--	--
213.9	-	Conrail Railroad bridge	--	--	--
207.8	-	Interstate Highway 180 bridge, Hennepin	--	--	--
207.6	7	State Highway 26 bridge, Hennepin	12,756	.81	1.54
207.2	7a	Public boat landing, Hennepin	--	--	--
207.0	-	Coffee Creek	--	--	--
199.0	-	Senachwine Lake and Bureau Creek	--	--	--
196.2	-	Sandy Creek	146	--	--
196.0	8	05558300 Illinois River at Henry and State Highway 18 bridge	[1]13,543	.86	1.64
191.6	-	Crow Creek (West)	81.7	--	--
189.2	-	State Highway 17 bridge, Lacon	[1]13,666	.86	1.65
189.1	-	Gimlet Creek	5.7	--	--
185.5	-	Strawn Creek	--	--	--
182.2	-	Crow Creek	130	--	--
181.9	-	Atchison, Topeka and Santa Fe Railroad bridge	--	--	--
181.6	-	Senachwine Creek	--	--	--
181.1	-	Snag Creek	--	--	--
180.4	-	Richland Creek	--	--	--
180.3	9	Chillicothe City Park	--	--	--
177.3	-	Partridge Creek	--	--	--
166.2	-	Tenmile Creek	--	--	--
166.1	10	Peoria Water Works	--	--	--
165.8	-	U.S. Highway 150 bridge, Peoria	--	--	--

Table 1.--Study reach features including dams, tributaries, highway and railroad crossings, active gaging stations, and river sampling sites--Continued

River mile	Site number	Features	Drainage area (mi²)	Ratio of drainage area at site to drainage area at Kingston Mines	Ratio of drainage area at site to drainage area at Marseilles
164.6	-	U.S. Army Corps of Engineers boat landing, Peoria	14,165	.90	1.72
162.6	-	Interstate Highway 74 bridge, Peoria	--	--	--
162.3	11	Franklin Street bridge, Peoria	--	--	--
162.0	-	Farm Creek	61.3	--	--
161.6	-	Cedar Street bridge, Peoria	--	--	--
160.7	-	Peoria and Pekin Union Railroad bridge, Peoria	--	--	--
159.5	-	Kickapoo Creek	306	--	--
157.9	12a	Interstate Highway 474 bridge, Peoria	--	--	--
157.7	12	Peoria Dam	[1]14,550	.92	1.76
144.4	-	05568500 Illinois River at Kingston Mines	[1]15,818	--	--

[1] From U.S. Geological Survey drainage area file.

METHODS OF STUDY

General Concepts

Traveltime refers to the duration of movement of water and dissolved substances from point to point in a stream. Dispersion refers to the lateral, vertical, and longitudinal spreading of a dissolved substance. Lateral and vertical dispersion is limited by the width and depth of the stream and is generally complete within some finite distance of travel depending on the width and depth of the stream. Longitudinal dispersion continues indefinitely and is characterized by an attenuation of concentrations of a dissolved substance.

Traveltime and dispersion are generally considered to be stable characteristics of a stream for given streamflow conditions. Moreover, if these characteristics are known for different streamflow conditions, relations to streamflow can be used to interpolate traveltime and dispersion for intervening streamflow conditions.

Traveltime and dispersion are measured by injecting a soluble substance, usually a dye, into a stream and measuring the times of arrival and concentrations of the dissolved substance at downstream locations. The following assumptions are made:

(1) Streamflow conditions are steady,

(2) the substance is water soluble,

(3) the solute is uniformly mixed in the stream water,

(4) the solute is conservative in nature, and

(5) there is a linear relation between the logarithms of stream velocity and discharge.

The peak concentration of a dye cloud will diminish as it moves downstream due to dilution and longitudinal dispersion. "The shape and magnitude of a time-concentration curve that is the response to a dye injection is determined by (1) the amount of the dye injected, (2) the losses undergone by the dye, (3) the discharge that serves to dilute the cloud in the reach, and (4) the longitudinal dispersion." (Hubbard and others, 1982, p. 34).

Traveltime

Traveltime was measured by injecting a fluorescent tracer dye, rhodamine WT, into the Illinois River upstream of each reach to be measured. For dye-tracer measurements made in 1978 and 1979, the dye was injected at the upstream end of each subreach. The dye was slug injected at a single point at midchannel. Samples were collected at the downstream end and at an intermediate location. For the medium-flow dye-tracer measurements conducted in 1985, rhodamine-WT dye was injected into the river 1 to 2 miles upstream from each subreach to allow for mixing across the channel before the dye entered the subreach. To expedite lateral dispersion, the dye was injected from a boat moving across the central two-thirds of the stream channel. Water-sampling sites in these subreaches (fig. 1) were located near the beginning, at the end, and at one or more intermediate locations.

The dye cloud behaved in the same manner as the water particles and dispersed longitudinally as it moved downstream. Water samples were collected at two or more sites in each stream subreach at sampling frequencies from 10 minutes near the time of peak concentration up to 60 minutes near the time of the trailing edge. The time at which each sample was obtained was recorded and each sample was analyzed for dye concentration.

A fluorometer was used to detect and measure the dye in the water samples. Fluorometer readings were converted to dye concentrations in micrograms per liter (μg/L) from a calibration curve prepared with standard dye solutions. Dye-concentration graphs were plotted for each sampling site as shown in figure 2 for the site near Starved Rock Dam for May 28, 1985. The arrival times of the leading edge, trailing edge, and peak concentration, and the value of the peak concentration, were read from the graphs. The leading edge of the cloud was considered to be the first detection of the dye at a sampling site. The trailing edge was defined as the dye concentration after the peak that was equal to 10 percent of the peak concentration.

Flow duration is defined as the percentage of time that the historic mean-daily discharges equaled or exceeded a specified discharge. Flow duration curves were prepared for the gaging stations at Marseilles and Kingston Mines (fig. 3), which are the stations used as index stations in this report. Flow-duration information for the station at Henry was not used because the period of continuous streamflow record was insufficient for reliable flow-duration values. Two measurements were made in each subreach, one at low flow (80- to 90-percent flow duration) and another at medium flow (40- to 60-percent flow duration). The measurements were conducted under conditions of no significant precipitation to avoid significant increases in streamflow during the measurement. Streamflow was measured near each sampling site when the dye cloud was present.

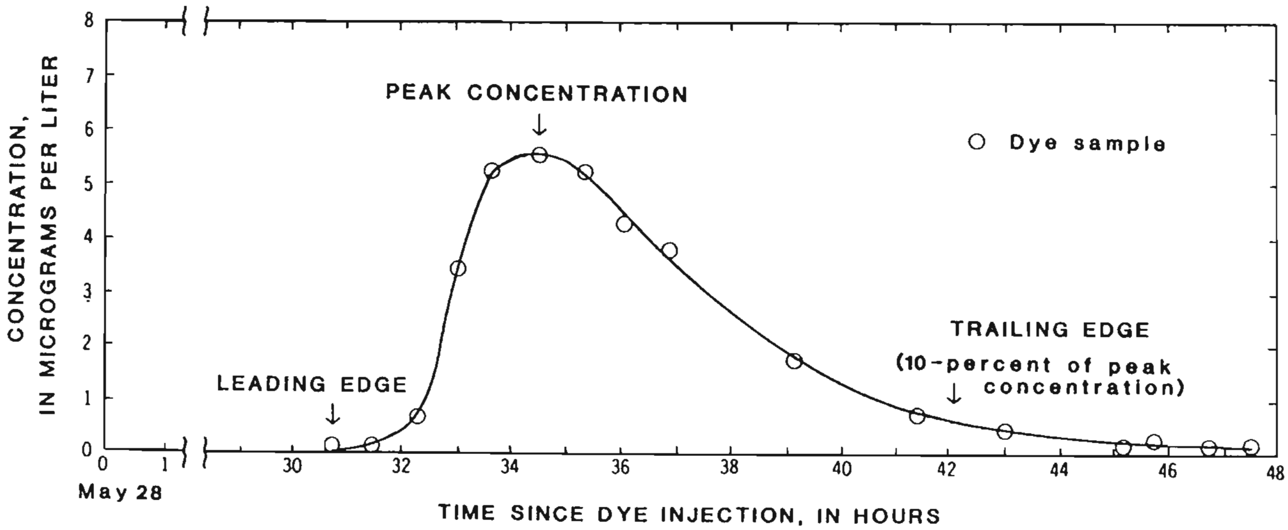

Figure 2.--Time-concentration curve of rhodamine-WT dye injected into the Illinois River near Starved Rock Dam on May 28, 1985, at 1340 hours and sampled at Hennepin.

The average velocities between successive sampling sites of the leading edge, peak concentration, and trailing edge of the dye cloud were calculated by dividing the segment length by the measured traveltime (tables 2 and 3). These velocities and the average streamflow at each index gage occurring at the sampling times were plotted on logarithmic graph paper, and straight lines were drawn through the points representing the leading edge, peak, and trailing edge of the dye cloud.

Velocities were read for discharge values at each 5-percent flow duration from 40 to 95 percent for each index gage. The velocities read from the graph for the two index gages were averaged to obtain the average velocity between each successive sampling site for the leading edge, peak, and trailing edge of a dye cloud for each value of flow duration.

Traveltimes for each river segment at each flow duration were computed by dividing the segment length by the average velocities obtained above. The cumulative traveltimes for the entire reach from Marseilles Dam to Peoria Dam were plotted against cumulative river miles to prepare families of traveltime graphs for all flow-duration values. Separate families of curves were prepared for the leading edge, the peak concentration, and the trailing edge of the dye clouds.

Dispersion

The time difference between the arrivals of the leading edge and the trailing edge of a dye cloud is the passage time of the dye cloud and is an index of longitudinal dispersion. A reduction in peak concentration is characteristic of increased duration and is a second index of dispersion.

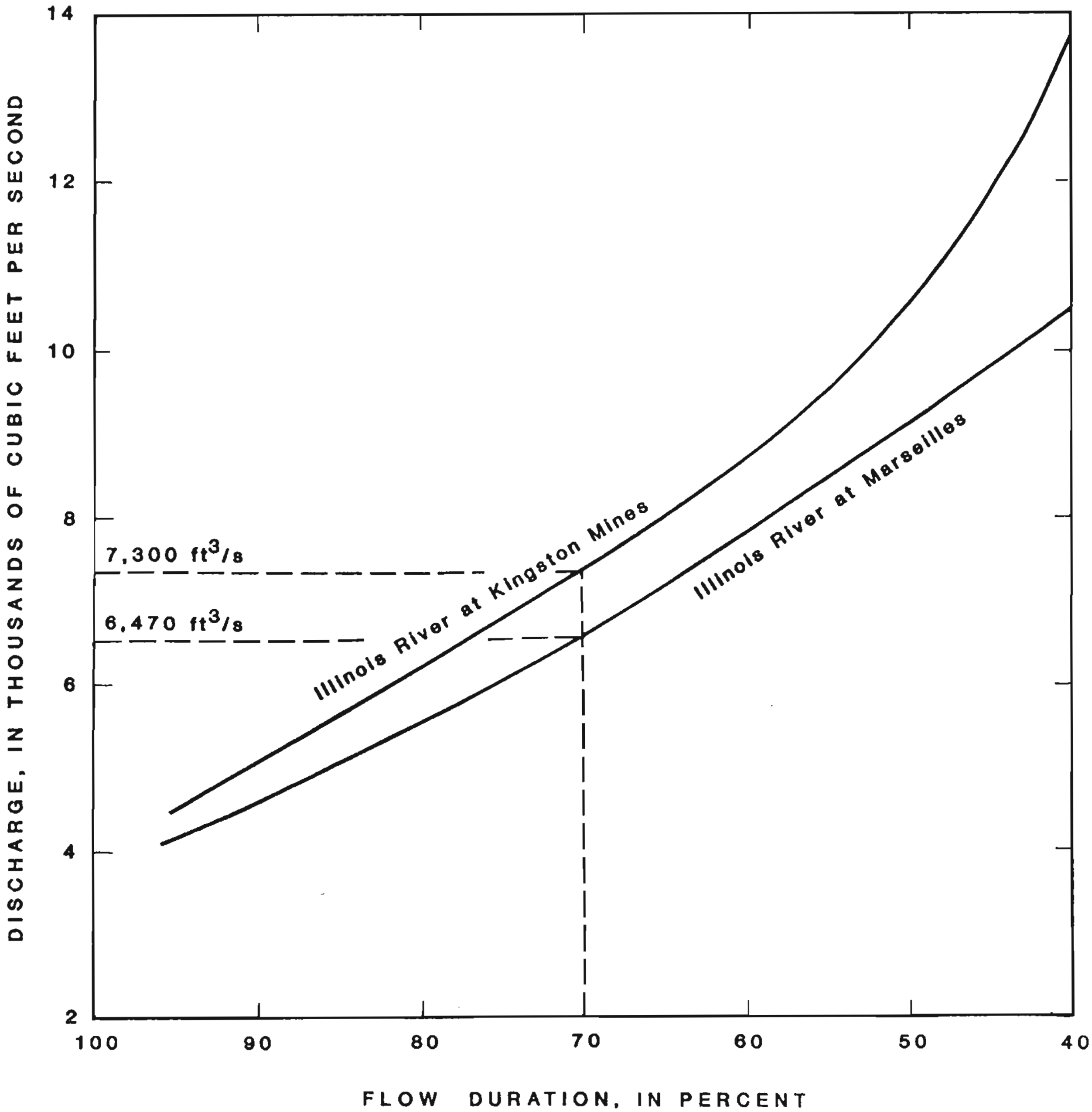

Figure 3.--Relation of flow duration to discharge at Illinois River index gaging stations.

Table 2.--Traveltime, dispersion, and related data for dye study of low streamflow in the Illinois River

[mi, mile; h, hour; mi/h, mile per hour; dashes indicate not applicable]

Site number	River mile	Distance		Leading edge			Peak concentration			Trailing edge		
		Between adjacent sites (mi)	From injection point (mi)	Time of travel (h)	Cumulative time of travel (h)	Velocity (mi/h)	Time of travel (h)	Cumulative time of travel (h)	Velocity (mi/h)	Time of travel (h)	Cumulative time of travel (h)	Velocity (mi/h)
Subreach A - Injected 19.1 liters of 20-percent rhodamine-WT dye at river mile 247.0 at 1055 hours on October 30, 1979												
1	247.0	0	0	0	0	-	0	0	-	0	0	-
2a	240.1	6.9	6.9	9.5	9.5	0.73	10.4	10.4	0.66	16.3	16.3	0.42
3a	231.8	8.3	15.2	23.8	33.3	.35	33.9	44.3	.24	44.7	61.0	.19
Subreach B - Injection 57.2 liters of 20-percent rhodamine-WT dye at river mile 229.8 at 1300 hours on October 13, 1978												
3b	229.8	0	0	0	0	-	0	0	-	0	0	-
6	218.4	11.4	11.4	20.0	20.0	0.57	22.2	22.2	0.51	29.0	29.0	0.39
7a	207.2	11.2	22.6	23.1	43.1	.48	26.3	48.5	.43	35.0	64.0	.32
Subreach C - Injected 76.2 liters of 20-percent rhodamine-WT dye at river mile 207.6 at 1200 hours on October 3, 1978												
7	207.6	0	0	0	0	-	0	0	-	0	0	-
8	196.0	11.6	11.6	17.0	17.0	0.68	19.5	19.5	0.59	30.0	30.0	0.38
9	180.3	15.7	27.3	30.5	47.5	.51	34.5	54.0	.46	45.5	75.5	.35
Subreach D - Injected 95.3 liters of 20-percent rhodamine-WT dye at river mile 181.9 at 1800 hours on September 11, 1978												
9	180.3	0	1.6	0	0	-	0	0	-	0	0	-
10	166.1	14.2	15.8	23.0	23.0	0.69	30.0	30.0	0.53	46.0	46.0	0.34
12	157.7	8.4	24.2	16.0	39.0	.53	20.5	50.5	.41	27.0	73.0	.31

Table 3.--Traveltime, dispersion, and related data for dye study of medium streamflow in the Illinois River

[mi, mile; h, hour; mi/h, mile per hour; NS, no sample collected; dashes indicate not applicable]

Site number	Distance			Leading edge			Peak concentration			Trailing edge		
	River mile	Between adjacent sites (mi)	From injection point (mi)	Time of travel (h)	Cumulative time of travel (h)	Velocity (mi/h)	Time of travel (h)	Cumulative time of travel (h)	Velocity (mi/h)	Time of travel (h)	Cumulative time of travel (h)	Velocity (mi/h)
Subreach A - Injected 38.1 liters of 20-percent rhodamine-WT dye at river mile 247.0 at 1220 hours on July 9, 1979												
1	247.0	0	0	0	0	-	0	0	-	0	0	-
2a	240.1	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
3a	231.8	15.2	15.2	18.7	18.7	0.81	24.7	24.7	0.61	32.7	32.7	0.46
Subreach B - Injected 95.3 liters of 20-percent rhodamine-WT dye at river mile 230.8 at 1340 hours on May 28, 1985												
3b	229.6	0	1.2	0	0	-	0	0	-	0	0	-
6	218.4	11.2	12.4	14.8	14.8	0.76	16.2	16.2	0.69	21.1	21.1	0.53
7a	207.2	11.2	23.6	14.1	28.9	.79	16.1	32.3	.70	20.5	41.6	.55
Subreach C - Injected 95.3 liters of 20-percent rhodamine-WT dye at river mile 209.4 at 1530 hours on May 20, 1985												
7	207.6	0	1.8	0	0	-	0	0	-	0	0	-
8	196.0	11.6	13.4	13.5	13.5	0.86	16.5	16.5	0.70	22.3	22.3	0.52
9	180.3	15.7	29.1	24.0	37.5	.65	27.5	44.0	.57	36.5	58.8	.43
Subreach D - Injected 114 liters of 20-percent rhodamine-WT dye at river mile 182.2 at 0715 hours on May 14, 1985												
9	180.3	0	1.9	0	0	-	0	0	-	0	0	-
10	166.1	14.2	16.1	18.1	18.1	0.78	23.2	23.2	0.61	79.0	79.0	0.18
12	157.7	8.4	24.5	14.3	32.4	.59	17.5	40.7	.48	22.2	101.2	.38

The cumulative passage times for each sampling site between Marseilles Dam and Peoria Dam were determined for the values of flow duration used in computing traveltimes. These passage times were then plotted with river miles to obtain a family of curves representing the passage time of dye clouds at different flow-duration values.

The concept of unit concentrations was formulated (Hubbard and others, 1982, p. 34) to exclude all of the influences affecting the shape and magnitude of the time-concentration curve except longitudinal dispersion. Unit concentration (C_u) is the concentration produced in one unit of flow rate by the injection of one unit weight of substance, provided the substance is conservative and no losses occur:

$$C_u = \frac{Q}{W_d} C_c \qquad (1)$$

where Q = the observed discharge,

W_d = the weight of the pure substance injected, and

C_c = the conservative concentration assuming that none of the substance is lost.

Some losses are usually reflected in the observed time-concentration curves. The percent of recovery (R_p) of the substance measured at the sampling site provides a measure of these losses. The conservative concentration (C_c) is related to the observed concentration (C_o) by the percent recovery:

$$C_c = \frac{100}{R_p} C_o \, . \qquad (2)$$

Taylor and others (1985, p. 17-18) use these relations to show that the unit peak concentration (C_{pu}) is proportional to the observed peak concentration (C_{po}) divided by the area under the observed time-concentration curve (A_c):

$$C_{pu} = 4{,}440 \frac{C_{po}}{A_c} \, . \qquad (3)$$

They also show a relation between the area under the observed time-concentration curve (A_c) and the area of a triangle that has the observed peak concentration (C_{po}) as the height of the triangle and the passage time (D) as the base:

$$A_c = K \, 0.5 \, (D \, C_{po}) . \qquad (4)$$

The proportionality constant (K) computed for measurements on the Illinois River was determined to be 0.965. When equations 3 and 4 are combined, unit peak concentration is shown to be inversely related to passage time (D), a measure of longitudinal dispersion:

$$C_{pu} = \frac{9{,}200}{D} \, . \qquad (5)$$

Table 4.--Example of measured dye cloud velocities between site 8 and site 9 for two flow conditions

	Flow condition[1]	Average velocity from site 8 to site 9 (miles per hour)	Average discharge at index gaging station (cubic feet per second)	
			Marseilles	Kingston Mines
Leading edge	low	0.51	4,230	8,730
	medium	.65	6,120	11,600
Peak	low	.46	4,230	8,730
	medium	.57	6,120	11,600
Trailing edge	low	.35	4,230	8,730
	medium	.43	6,120	11,600

[1] Period of low flow is October 4-6, 1978, and period of medium flow is May 21-23, 1985.

TRAVELTIME AND DISPERSION

Figure 2 is a time-concentration curve for one site typical of curves plotted from samples collected at the middle and downstream sampling site for each segment, eight sites during low-flow conditions (table 2), and seven sites during medium-flow conditions (table 3). The measured velocities ranged from 0.35 to 0.86 mi/h (miles per hour) for the leading edge, 0.24 to 0.70 mi/h for the peak, and 0.18 to 0.55 mi/h for the trailing edge of the dye cloud.

Subreach D (fig. 1) was affected by high winds blowing upstream across shallow Peoria Lake during the medium-flow measurement (table 3). The wind caused an extended dye-cloud passage time at the intermediate and downstream sites. However, the water did flow normally down the deepened shipping channel; the leading edge and peak concentration arrived near the expected times.

Tables 2 and 3 list the dye-cloud velocities measured for each segment in each subreach for both the low and medium streamflow conditions, respectively. The velocities, along with average discharge and flow duration data for the index stations, were used to develop traveltime data for streamflow between Marseilles Dam and Peoria Dam.

As an example, the velocities were computed from site 8 to site 9. It was necessary to also determine the average discharge at the index gages during the passage of the dye cloud. These data (table 4) were then plotted on logarithmic graph paper (fig. 4) and lines representing the leading edge, peak, and trailing edge were drawn through the pairs of points for each index gage.

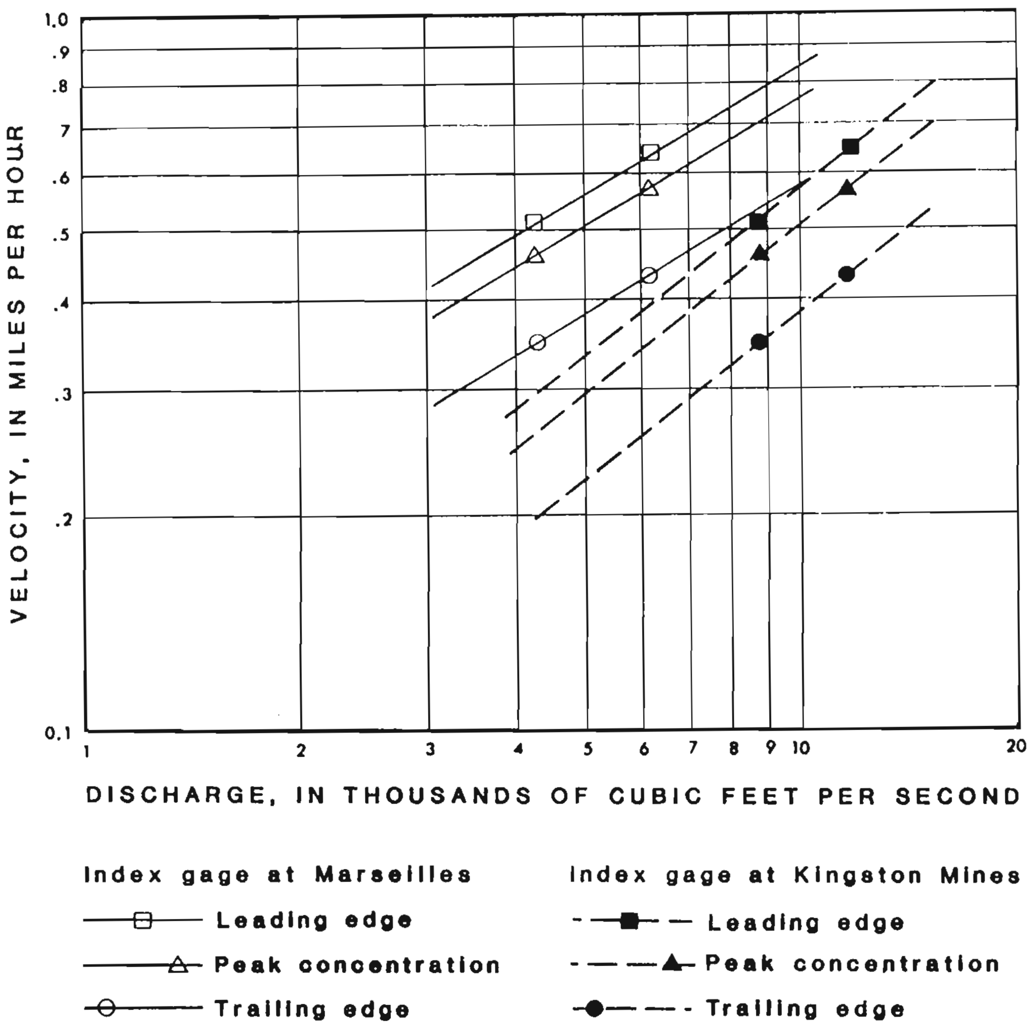

Figure 4.--Relation of average stream velocity between site 8 and site 9 to discharge at the index gages.

Flow duration at each 5-percent increment from 40 to 95 percent was then determined from figure 3 for each index gage. The flow duration was then related to velocity for each index gage using the relation shown in figure 4. The velocities for each flow duration were averaged and tabulated (table 5). Traveltime was then computed by dividing the distance between sites by the average velocity for each flow duration.

Computations similar to those for the stream segment between sites 8 and 9 were made for all subreaches and converted to traveltime using the average velocities and segment distances computed from the river miles in table 1. The cumulative traveltimes from Marseilles Dam to Peoria Dam for the leading edge, peak concentration, and trailing edge are given in tables 6, 7, and 8, respectively.

Figures 5, 6, and 7 show families of curves for traveltime developed from the data in tables 6, 7, and 8, respectively. These figures can be used to estimate traveltime within the study reach for any given flow duration between 40 and 95 percent.

The cloud passage time caused by longitudinal dispersion of rhodamine-WT dye injected at Marseilles and measured at selected downstream sites (table 9) were estimated for each 5-percent increment in flow duration by the difference in the arrival of the leading edge (table 6) and the arrival of the trailing edge (table 8). Figure 8, a plot of the passage time values with river miles, can be used to quickly estimate the passage time of a solute passing any point on the reach for flow-duration values from 40 to 95 percent. Time-concentration curves (fig. 9) show a lower observed peak concentration and a longer passage time from site to site as the dye cloud moved downstream. The observed peak concentration is generally lower than the peak computed for a conservative solute because there are chemical, physical, and biological processes that decrease the effective mass of a solute as it moves downstream.

Figure 10 was prepared by plotting values of C_{pu}, computed by using equation 5 and values of D from table 9 and traveltime of the peak concentration from table 7 for selected values of flow duration. The figure illustrates the attenuation of the unit peak concentration with time from injection at Marseilles Dam for the selected flows.

USE OF TRAVELTIME RELATIONS--AN EXAMPLE

A generalized method can be followed to estimate times of travel and peak concentrations resulting from a spill of a solute into the Illinois River between Marseilles Dam and Peoria Dam. The following hypothetical example is presented to demonstrate the use of the method.

An accident at the railroad bridge located between Spring Valley and Hennepin, Illinois, at RM (river mile) 213.9 spills 10,000 pounds of a water-soluble contaminant into the river. Downstream, the city of Peoria uses water from the river and needs the following information at the U.S. Highway 150 bridge (RM 165.8):

Table 5.--Computed Illinois River velocities between site 8 and site 9 using 5-percent increments of flow-duration discharge from index gages at Marseilles and Kingston Mines

Per-cent	Flow duration: Discharge, in cubic feet per second		Velocity, in miles per hour: Leading edge			Peak			Trailing edge		
	Marseilles	Kingston Mines	Marseilles	Kingston Mines	Average	Marseilles	Kingston Mines	Average	Marseilles	Kingston Mines	Average
40	10,400	13,700	0.86	0.73	0.80	0.78	0.65	0.72	0.59	0.49	0.54
45	9,750	11,900	.83	.66	.75	.75	.58	.66	.56	.44	.50
50	9,130	10,600	.80	.60	.70	.72	.53	.63	.54	.41	.47
55	8,500	9,440	.76	.56	.66	.69	.49	.59	.53	.37	.45
60	7,810	8,610	.73	.51	.62	.66	.46	.56	.50	.35	.42
65	7,120	7,910	.69	.48	.59	.62	.42	.52	.47	.34	.40
70	6,470	7,300	.65	.45	.55	.59	.40	.50	.44	.30	.37
75	5,930	6,750	.61	.42	.52	.55	.37	.46	.42	.29	.36
80	5,440	6,210	.59	.40	.50	.53	.35	.44	.40	.27	.34
85	4,990	5,650	.56	.37	.46	.50	.33	.41	.38	.25	.32
90	4,570	5,020	.53	.34	.43	.48	.30	.39	.36	.23	.30
95	4,060	4,330	.50	.30	.40	.45	.27	.36	.34	.20	.27

Table 6.--Traveltime for the leading edge of a dye cloud from Marseilles Dam to Peoria Dam

Site number	River mile	Subreach length (miles)	Flow duration, in percent											
			40	45	50	55	60	65	70	75	80	85	90	95
			Discharge at Marseilles, in cubic feet per second											
			10,400	9,750	9,130	8,500	7,810	7,120	6,470	5,930	5,440	4,990	4,570	4,060
			Accumulative time of travel, in hours											
1	247.0	-	0	0	0	0	0	0	0	0	0	0	0	0
3	231.0	16.0	17	18	19	21	23	25	27	29	31	34	37	41
6	218.4	12.6	31	33	35	37	39	42	45	48	51	55	58	64
7	207.6	10.8	39	42	45	48	51	55	59	64	69	74	79	86
8	196.0	11.6	50	54	58	62	67	72	77	82	87	94	102	113
9	180.3	15.7	70	75	80	85	91	97	104	112	120	129	140	152
10	166.1	14.2	86	92	98	104	110	117	124	132	140	150	160	175
12	157.7	8.4	96	102	109	116	123	131	139	147	155	166	178	195

Table 7.--Traveltime for the peak concentration of a dye cloud from Marseilles Dam to Peoria Dam

Site number	River mile	Subreach length (miles)	Flow duration, in percent											
			40	45	50	55	60	65	70	75	80	85	90	95
			Discharge at Marseilles, in cubic feet per second											
			10,400	9,750	9,130	8,500	7,810	7,120	6,470	5,930	5,440	4,990	4,570	4,060
			Accumulative time of travel, in hours											
1	247.0	-	0	0	0	0	0	0	0	0	0	0	0	0
3	231.0	16.0	22	25	27	29	31	33	36	38	40	44	48	55
6	218.4	12.6	37	40	43	46	49	52	55	58	62	67	73	81
7	207.6	10.8	47	51	54	58	62	68	72	76	80	87	95	106
8	196.0	11.6	60	65	70	75	80	86	92	98	104	113	122	136
9	180.3	15.7	82	89	95	101	108	116	124	132	140	151	163	180
10	166.1	14.2	103	111	117	124	132	140	149	158	167	178	190	210
12	157.7	8.4	117	125	132	141	150	159	168	178	188	201	214	235

Table 8.--Traveltime for the trailing edge of a dye cloud from Marseilles Dam to Peoria Dam

Site number	River mile	Subreach length (miles)	Flow duration, in percent											
			40	45	50	55	60	65	70	75	80	85	90	95
			Discharge at Marseilles, in cubic feet per second											
			10,400	9,750	9,130	8,500	7,810	7,120	6,470	5,930	5,440	4,990	4,570	4,060
			Accumulative time of travel, in hours											
1	247.0	-	0	0	0	0	0	0	0	0	0	0	0	0
3	231.0	16.0	30	33	35	38	41	45	49	53	57	62	67	73
6	218.4	12.6	48	52	56	60	64	69	74	79	84	91	98	107
7	207.6	10.8	60	66	71	76	82	88	94	101	108	118	128	139
8	196.0	11.6	80	87	93	99	107	115	124	133	142	154	167	183
9	180.3	15.7	109	118	126	135	144	154	165	178	191	204	220	239
[1]10	166.1	14.2	141	150	159	169	179	190	202	216	229	244	261	282
[1]12	157.7	8.4	158	169	179	190	200	213	227	243	256	274	294	316

[1] Estimated, see page __ of text for explanation.

Table 9.--Passage time of the dye cloud at Illinois River sites for selected flow durations

Site number	River mile	Subreach length (miles)	Flow duration, in percent											
			40	45	50	55	60	65	70	75	80	85	90	95
			Discharge at Marseilles, in cubic feet per second											
			10,400	9,750	9,130	8,500	7,810	7,120	6,470	5,930	5,440	4,990	4,570	4,060
			Accumulative time of travel, in hours (passage time)											
1	247.0	-	0	0	0	0	0	0	0	0	0	0	0	0
3	231.0	16.0	13	15	16	17	18	20	22	24	26	28	30	32
6	218.4	12.6	17	19	21	23	25	27	29	31	34	36	40	43
7	207.6	10.8	21	24	26	28	31	33	35	37	39	44	49	53
8	196.0	11.6	30	33	35	37	40	43	47	51	55	60	65	70
9	180.3	15.7	39	43	46	50	53	57	61	66	71	75	80	87
10	166.1	14.2	55	58	61	65	69	73	78	84	89	94	101	107
12	157.7	8.4	62	67	70	74	77	82	88	96	101	108	116	121

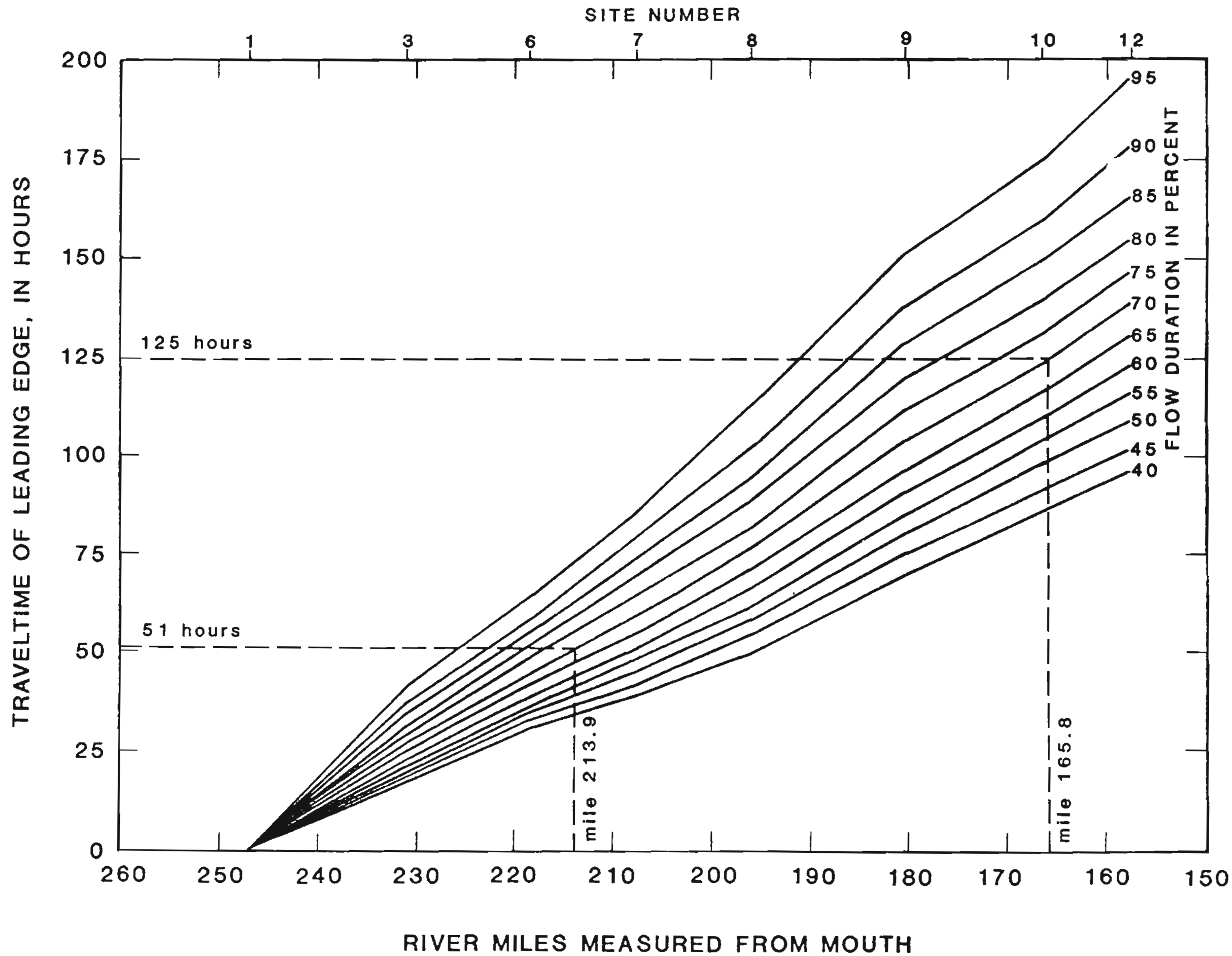

Figure 5.--Traveltime from Marseilles Dam for the leading edge of the dye cloud at selected flow durations.

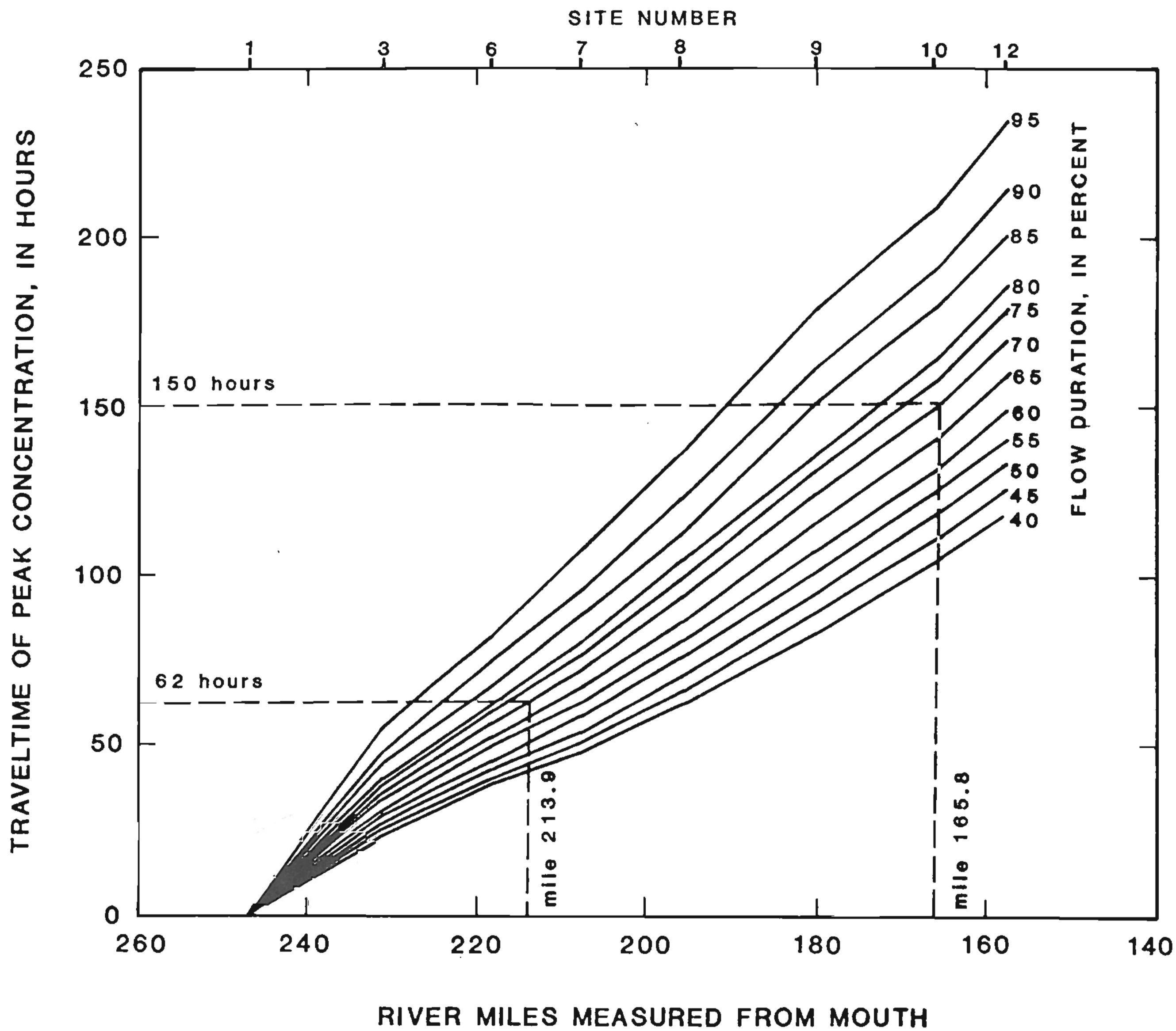

Figure 6.--Traveltime from Marseilles Dam for the peak concentration of the dye cloud at selected flow durations.

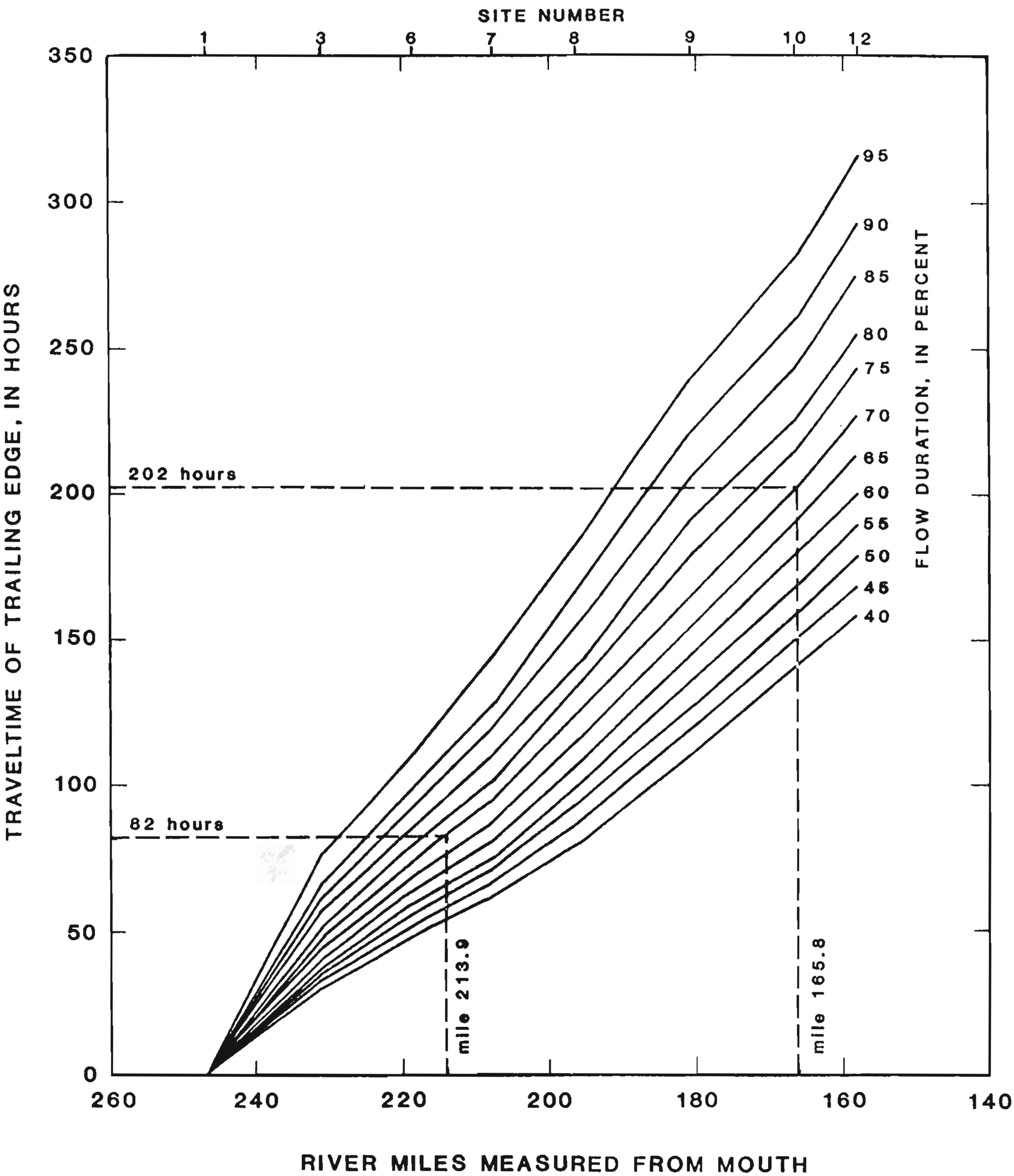

Figure 7.--Traveltime from Marseilles Dam for the trailing edge of the dye cloud at selected flow durations.

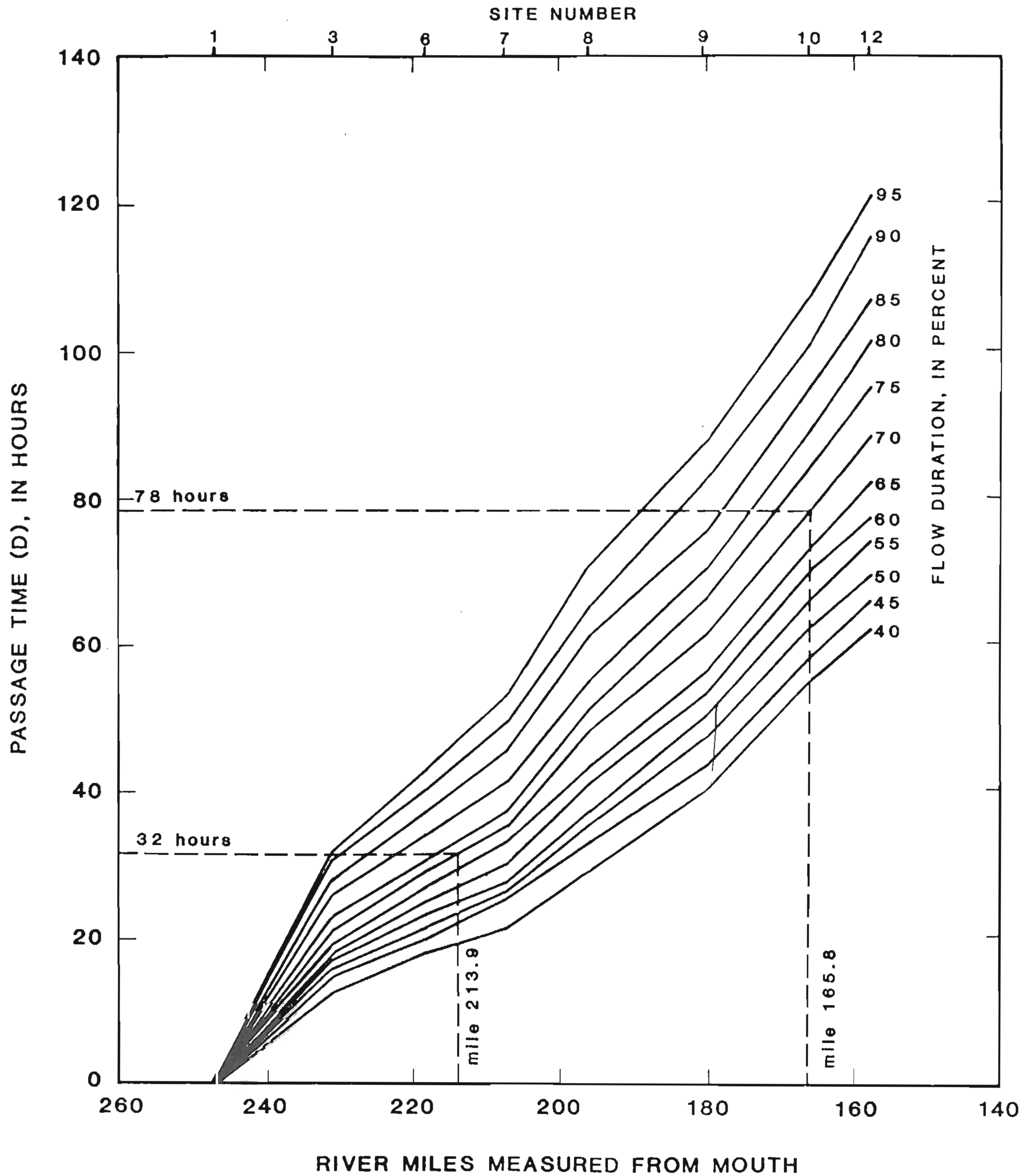

Figure 8.--Relation of cloud passage time to distance traveled at selected flow durations for the Illinois River.

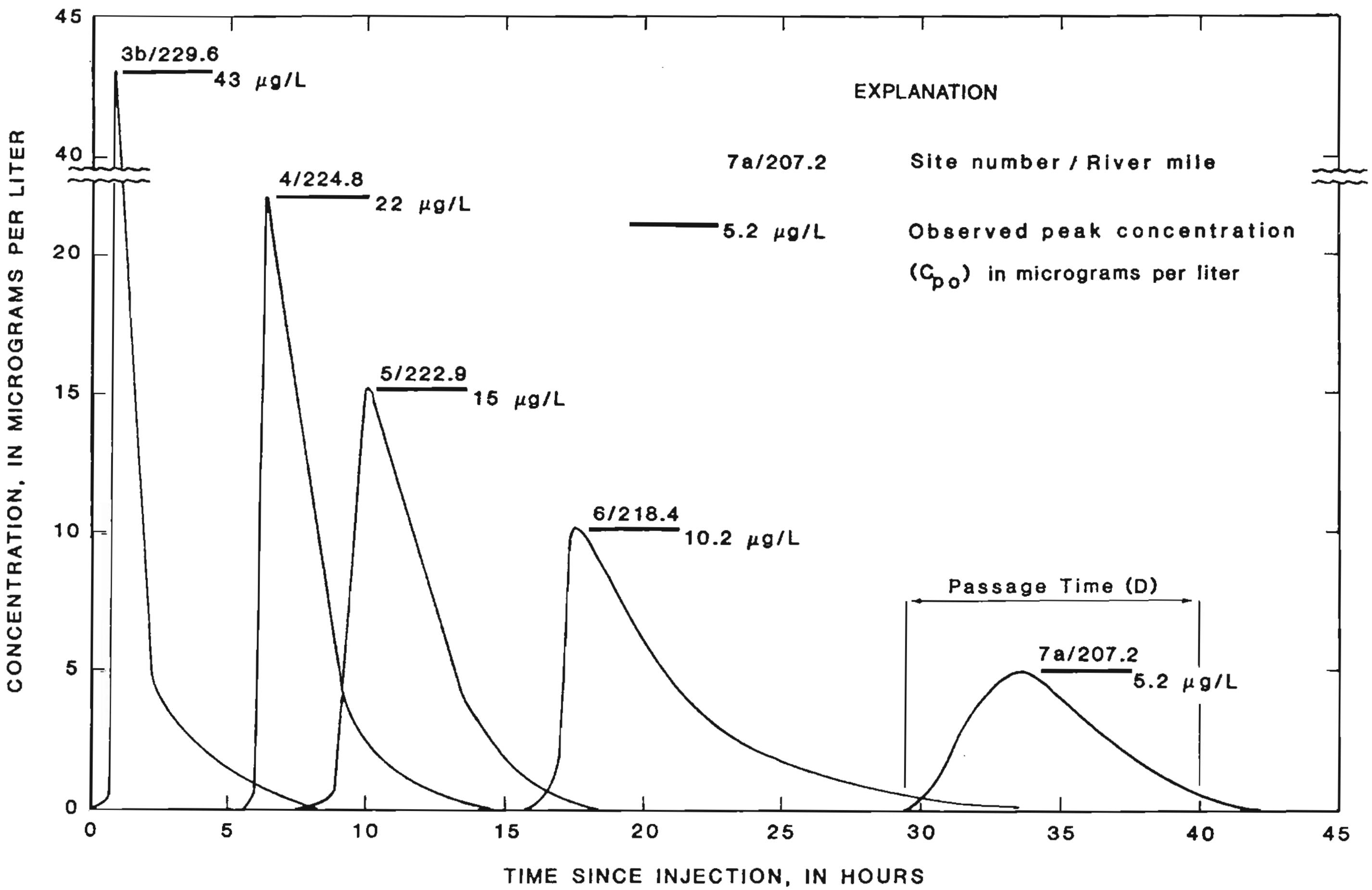

Figure 9.--Observed time-concentration curves of the dye cloud in subreach B for the medium-flow study, May 28-31, 1985.

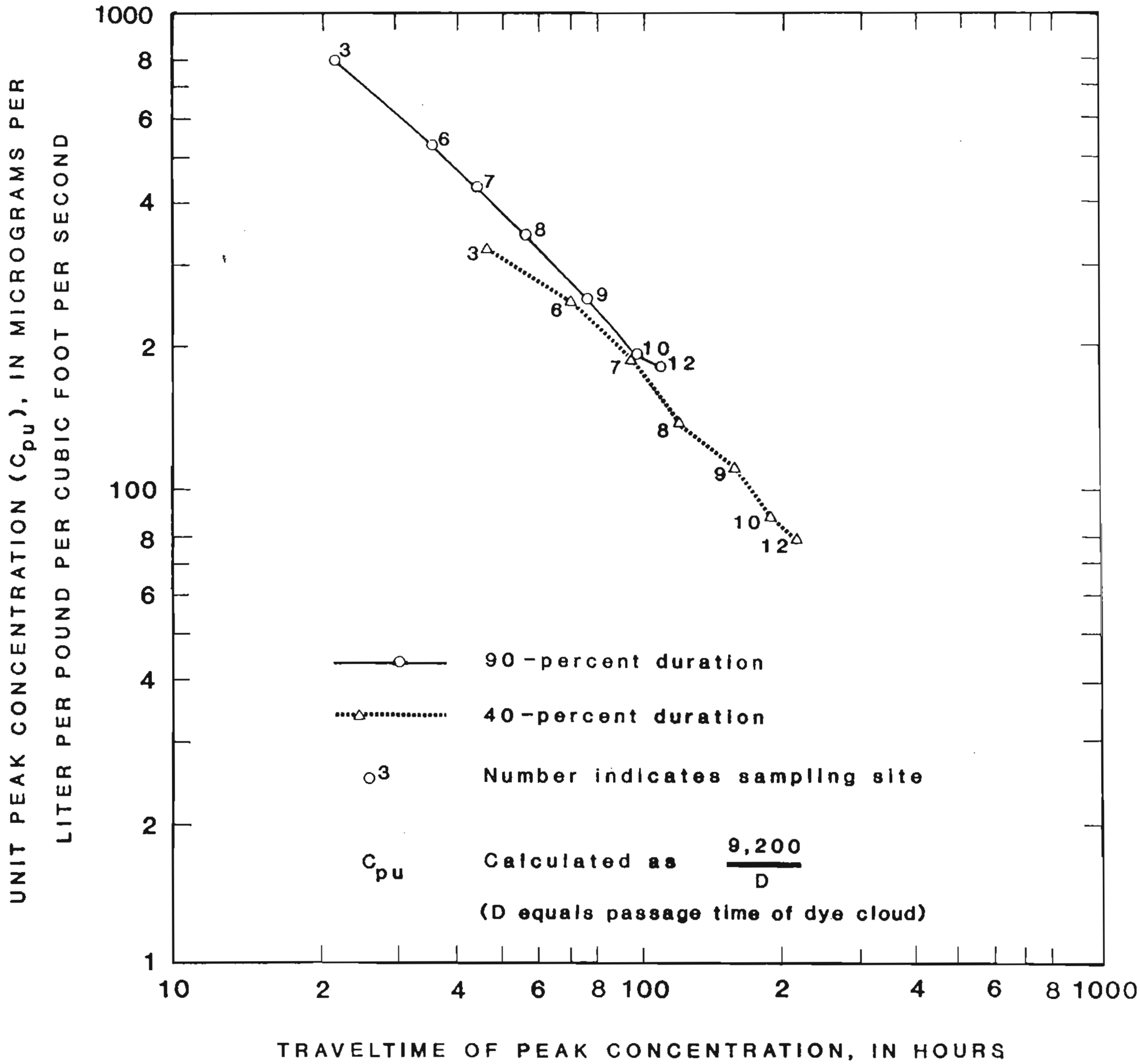

Figure 10.--Relation of unit peak concentrations to traveltime of the peak concentrations at the 40- and 90-percent flow durations for a solute introduced into the Illinois River at Marseilles.

(1) When will the leading edge of the contaminant arrive;

(2) when will the peak arrive;

(3) what will the peak concentration be; and

(4) when will the trailing edge of the contaminant be essentially past the highway bridge and what will the concentrations be?

Several additional bits of information are needed. (1) When did the spill occur? Established as May 13 at 1000 hours. (2) What is the flow in the river? Flow at the Kingston Mines index gage is 7,300 ft^3/s.

The discharge at the U.S. Highway 150 bridge, the point of interest, must be measured or may be estimated using the following equation:

$$Q_i = Q_{MAR} + [(Q_{KING} - Q_{MAR})(DA_i - DA_{MAR})/(DA_{KING} - DA_{MAR})] \qquad (6)$$

The discharge at the index gages, Marseilles (Q_{MAR}) and Kingston Mines (Q_{KING}), are required to compute the estimated discharge at the point of interest (Q_i). However, if the discharge at only one index gage is known, the discharge at the other gage can be determined using figure 3 and the equivalent flow duration for both gages. Q_{KING} is given as 7,300 ft^3/s and is a flow duration of 70 percent. Using figure 3, Q_{MAR} is 6,470 ft^3/s at the same flow duration.

The drainage areas needed are for the index gages--Marseilles (DA_{MAR}) equals 8,259 mi^2 and Kingston Mines (DA_{KING}) equals 15,818 mi^2 and for the point of interest (DA_i). Determining the drainage area DA_i requires the use of figure 11 which gives the drainage area at any point between Marseilles Dam and Peoria Dam. Using figure 11, DA_i is 14,160 mi^2 and Q_i is then calculated to be 7,120 ft^3/s.

Traveltime and concentration computations are made as follows:

(1) When will the leading edge of the contaminant arrive at the U.S. Highway 150 bridge?

Procedure:

From figure 3, the flow duration for a discharge of 7,300 ft^3/s at the Kingston Mines index gage, which is closest to point of interest, is 70 percent. Using figure 5 and a flow duration of 70 percent, the leading-edge traveltime at the railroad bridge (RM 213.9) is approximately 51 hours and at the U.S. Highway 150 bridge (RM 165.8) is approximately 125 hours. Therefore, the estimated traveltime from the railroad bridge to the U.S. Highway 150 bridge is 125 hours minus 51 hours or 74 hours (3 days and 2 hours). The leading edge would arrive at the U.S. Highway 150 bridge in Peoria at approximately 1200 hours on May 16.

(2) When will the peak arrive?

Procedure:

Using figure 6 and a flow duration of 70 percent, traveltime of the peak at the railroad bridge (RM 213.9) is approximately 62

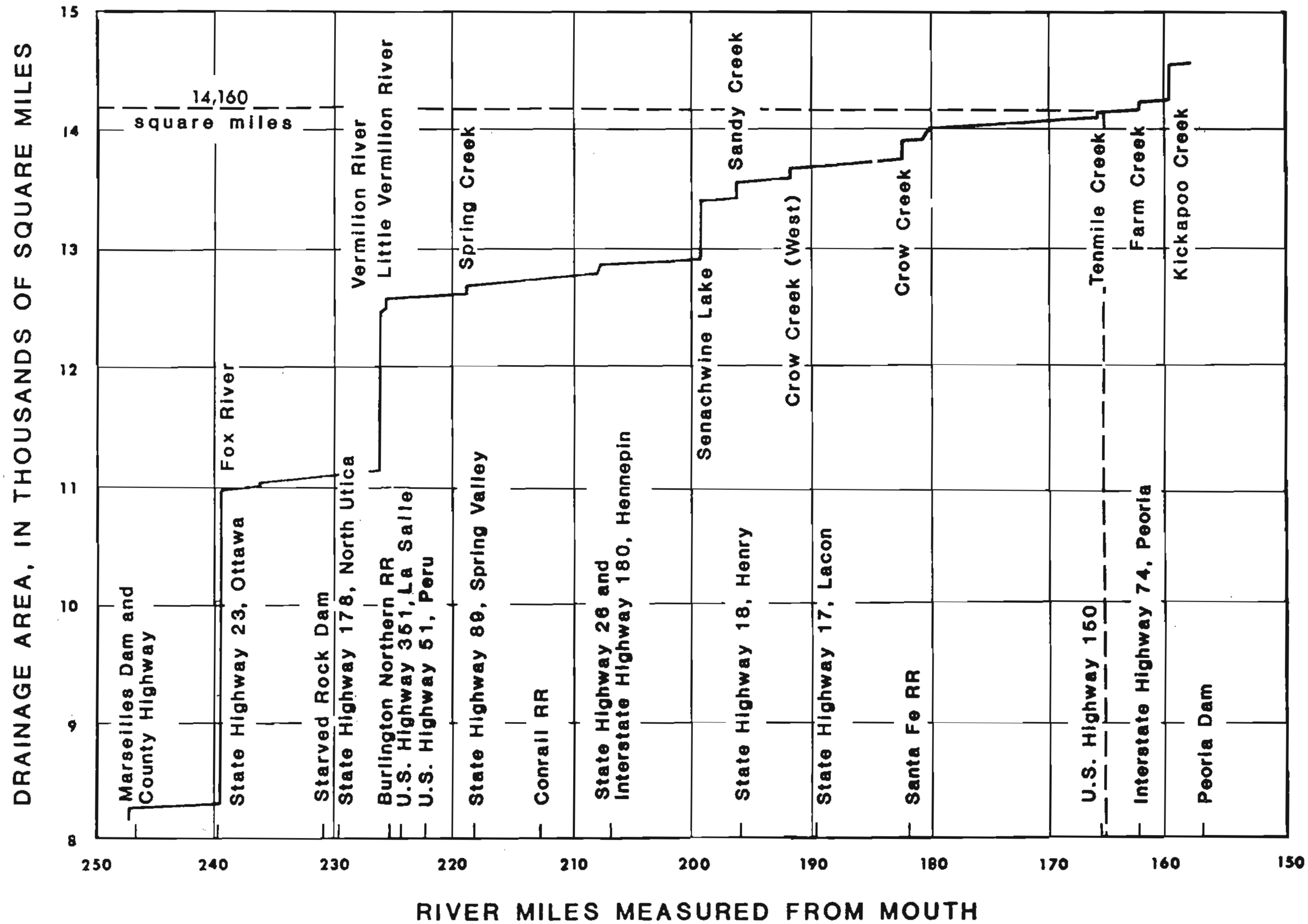

Figure 11.--Relation of river miles to drainage area for the study reach of the Illinois River.

hours and at the U.S. Highway 150 bridge (RM 165.8) is approximately 150 hours. The peak is estimated to arrive in 150 hours minus 62 hours or 88 hours (3 days and 16 hours). Therefore, the peak would arrive at the U.S. Highway 150 bridge at about 0200 hours on May 17.

(3) What will the peak concentration be (assuming a conservative contaminant)?

Procedure:

Rearrange equation 1 to estimate the peak concentration at the U.S. Highway 150 bridge:

$$C_{pc} = C_{pu} \frac{W_d}{Q} .$$

C_{pu} is estimated using equation 5 and the passage time of the contaminant cloud. From figure 9 and a flow duration of 70 percent, the passage time at the railroad bridge (RM 213.9) is approximately 32 hours and at the U.S. Highway 150 bridge (RM 165.8) is approximately 78 hours. The estimated passage time is 78 hours minus 32 hours or 46 hours and

$$C_{pu} = \frac{9,200}{D} = \frac{9,200}{46} = 200 \frac{\mu g/L \times ft^3/s}{lb}$$

and the peak concentration is

$$C_{pc} = C_{pu} \frac{W_d}{Q} = 200 \frac{10,000}{7,120} = 280 \ \mu g/L.$$

(4) When will the trailing edge of the contaminant be essentially past the U.S. Highway 150 bridge and what will the concentration be?

Procedure:

Using figure 7, the trailing edge traveltime at the railroad bridge (RM 213.9) is approximately 82 hours and at the U.S. Highway 150 bridge (RM 165.8) is approximately 202 hours. The trailing edge of the contaminant cloud is estimated to pass the U.S. Highway 150 bridge 202 hours minus 82 hours or 120 hours (5 days) after the spill or at about 1000 hours on May 18.

The trailing edge is defined as the time the concentration decreases to a level of 10 percent of the peak concentration of 280 μg/L and is equal to 28 μg/L. Therefore, relatively small and diminishing concentrations of the contaminant will be passing the site of interest for many more hours.

In summary, the available information for the hypothetical spill to pass the U.S. Highway 150 bridge is as follows:

(1) The leading edge will arrive at approximately 1200 hours on May 16.

(2) The peak concentration will arrive at approximately 0200 hours on May 17.

(3) The peak concentration will be approximately 280 μg/L (assuming a conservative contaminant).

(4) The trailing edge concentration will pass at approximately 1000 hours on May 18 and will be approximately 28 μg/L.

The above information is sufficient to construct an approximate time-concentration curve at U.S. Highway 150. Computations, similar to the above, can be made at any intervening point between the point of a spill and the point of interest. Thus, the behavior of a contaminant cloud as it moves downstream can be predicted as it relates to time, distance, or concentration for any discharge between 40- and 95-percent flow duration.

LIMITATIONS OF THE METHOD

In this report, methods used in estimating traveltime and longitudinal dispersion assume steady streamflow conditions and may be subject to potentially large errors if applied to an unsteady flow condition such as a flood wave. Streamflow during the dye measurements was generally characterized as slowly decreasing; no significant precipitation occurred to introduce concern for the presence of a flood wave.

The traveltime and mixing relations apply only to substances dissolved in stream water. The movement of a substance such as oil, which floats on the water surface, or a particulate substance, which may settle, cannot be estimated by using these relations. Unit-peak-concentration relations give the change in concentration caused only by mixing. If other processes, such as chemical reaction or biological uptake, are acting to greatly change solute concentrations, the relations presented in this report will not be sufficient to estimate concentrations with a reasonable degree of accuracy.

A solute is considered conservative if it can be fully recovered; conservative solutes are assumed, in this method, for all estimates relating to concentrations. Because no loss of solute is assumed, the estimated concentrations should be generally higher than the observed concentrations if the solute is not actually conservative. Also, if inflow from a tributary is incompletely mixed at the measuring section, the observed concentrations may be higher or lower than the estimated concentrations depending on the location of the sampling site within the measuring section.

The relations presented are applicable only to the reaches measured. Downstream reaches of the Illinois River differ in channel geometry and other characteristics that control flow; therefore, the relations are probably not applicable for estimating flow rate or dispersion for those reaches. The relations should not be used outside the flow-duration frequencies of 40 to 90 percent.

Measurements of longitudinal dispersion require that the tracer dye be fully mixed at the beginning of the subreach and at all measuring sections. For the measurements made during 1978 and 1979, the dye was slug-injected at the center of flow at the beginning of each subreach and, therefore, the dye concentration at the first measuring section cannot be used to calculate a true measure of dispersion. For the measurements made during 1985, the tracer dye was injected, from a moving boat, throughout the middle two-thirds of the river, 1 to 2 miles upstream of each subreach, assuring that it was well-mixed at the beginning of each subreach. All measurements made during 1985 were considered to accurately measure longitudinal dispersion.

It is much more likely that an accidental spill would occur near the edge of the river bank, or from a small tributary entering the Illinois River. The method does not consider mixing length and, therefore, both traveltime and dispersion would be atypical, with respect to the injections made for this study, until the solute reaches the main channel and becomes well mixed. The main river channel is maintained for navigation and is relatively uniform throughout the study reach. Once the solute has reached the main channel, the estimating methods are applicable and their use should result in only minimal traveltime error.

SUMMARY

Traveltime measurements on four subreaches of the Illinois River between Marseilles Dam and Peoria Dam were made in 1978, 1979, and 1985 using rhodamine-WT dye. The measurements were used to document traveltime and to develop a method for estimating traveltime and concentration attenuation of a soluble substance spilled into the river between the two dams.

Each subreach was measured during medium- and low-discharge conditions. For interpolation to other discharges, a linear relation was assumed between the logarithmic values for velocity of the leading edge, peak, and trailing edge of the dye cloud and the average discharge for each index gage. This assumption is more credible for the peak and the leading edge than for the trailing edge because of the truncation of the trailing edge at an arbitrary 10 percent of peak concentration.

The method is applicable during periods of nearly steady or slowly decreasing rates of flow. The user can estimate parameters used to construct an approximate time-concentration curve for a spill of a solute at any point in the study reach under a wide range of flow conditions.

An example computation that uses streamflow at the 70-percent flow duration shows that a spill of 10,000 pounds of water-soluble conservative contaminant at the railroad bridge between Spring Valley and Hennepin, Illinois, would have the following results at the U.S. Highway 150 bridge in Peoria, Illinois: (1) The leading edge of the contaminant cloud would reach the U.S. Highway 150 bridge approximately 3 days after the spill; (2) the peak would occur about 3 2/3 days after the spill; (3) the magnitude of the peak would be about 280 μg/L; and (4) the trailing edge of the cloud would pass about 5 days after the spill, and its concentration would then be about 28 μg/L.

The method is intended primarily as a tool for use by water managers and regulatory authorities. It will allow the user to rapidly assess the seriousness of a spill and more effectively plan and execute a program to mitigate its effects. Equally important, the report provides the means to understand, in advance of a serious spill, how the Illinois River transports, disperses, and dilutes a water-soluble substance.

REFERENCES CITED

Healy, R. W., 1979, River mileages and drainage areas for Illinois streams - Volume 2. Illinois River Basin: U.S. Geological Survey Water-Resources Investigations 79-111, 302 p.

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 of Water-Resources Investigations, Book 3, Chapter A9, 44 p.

Taylor, K. R., James, R. W., Jr., and Helinsky, B. M., 1985, Traveltime and dispersion in the Potomac River, Cumberland, Maryland, to Washington, D.C.: U.S. Geological Survey Water-Supply Paper 2257, 30 p.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1987—744-456/62009