TIME OF TRAVEL AND DISPERSION OF SOLUTES IN A 36.4-MILE REACH OF THE NORTH PLATTE RIVER DOWNSTREAM FROM CASPER, WYOMING

By G. W. Armentrout, Jr. and L. R. Larson

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply inch-pound units by the factors shown to obtain the corresponding metric equivalents:

Multiply	By	To obtain
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
gallon (gal)	3.785	liter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
mile per hour (mi/h)	1.609	kilometer per hour
pound (lb)	0.4536	kilogram
foot per second (ft/s)	0.3048	meter per second
foot per foot (ft/ft)	1.0	meter per meter

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level.

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ABSTRACT

Time-of-travel and dispersion measurements made during a dye study November 7-8, 1978, are presented for a reach of the North Platte River from Casper, Wyoming, to a bridge 2 miles downstream from the Dave Johnston Power Plant. The dye study simulates an accidental spill of a soluble contaminant into the river. Rhodamine WT dye was injected into the river at Casper, and the resultant dye cloud was traced by sampling as it moved downstream. Samples taken in three equal-flow sections of the river's lateral transect at three sites were analyzed by fluorometer. The flow in the river was 940 cubic feet per second. The data consist of measured stream mileages and time, distance, and concentration graphs of the dye cloud. The peak concentration traveled through the reach in 24 hours, averaging 1.5 miles per hour; the leading edge took about 22 hours, averaging 1.7 miles per hour; and the trailing edge took 35 hours, averaging 1.0 mile per hour. Results from this study compared favorably with values calculated from equations for estimating time of travel for a range of stream discharges.

INTRODUCTION

The North Platte River is an important water source for the semiarid region through which it flows, providing water for agriculture, industry, municipalities, recreation, fish, and wildlife. Downstream from the city of Casper (a center for the production of energy minerals in northeastern Wyoming) to Glendo Reservoir, the North Platte is especially susceptible to spills of contaminants. Between Casper and Glendo Reservoir both a railroad and a busy interstate highway are adjacent to the river. Oil pipelines cross the river and its tributaries at several locations.

The purpose of this study was to define time of travel, travel rate, and dispersion rate of solutes in the 36.4-mile reach of the North Platte River from Casper to a bridge 2 miles downstream from the Dave Johnston Power Plant when the river is flowing about 1,000 ft^3/s. Traveltime and dispersion information is useful for assessing the effects of an accidental spill of soluble contaminants into the river and for warning water users downstream. The location of the study reach is shown in figure 1.

The flow in this reach of the river is almost totally regulated by reservoirs upstream from Casper. Channel conditions within the study reach are relatively uniform because the banks and channel have adjusted to the range of release, which normally is about 700 to 4,000 ft^3/s. The river flow is fairly uniform for long periods each year, commonly 700 to 1,100 ft^3/s from October through March, and 1,000 to 4,000 ft^3/s during the irrigation season from April through September. Occasional flooding occurs some years in May and June. Such flooding originates from tributaries that have no large reservoirs.

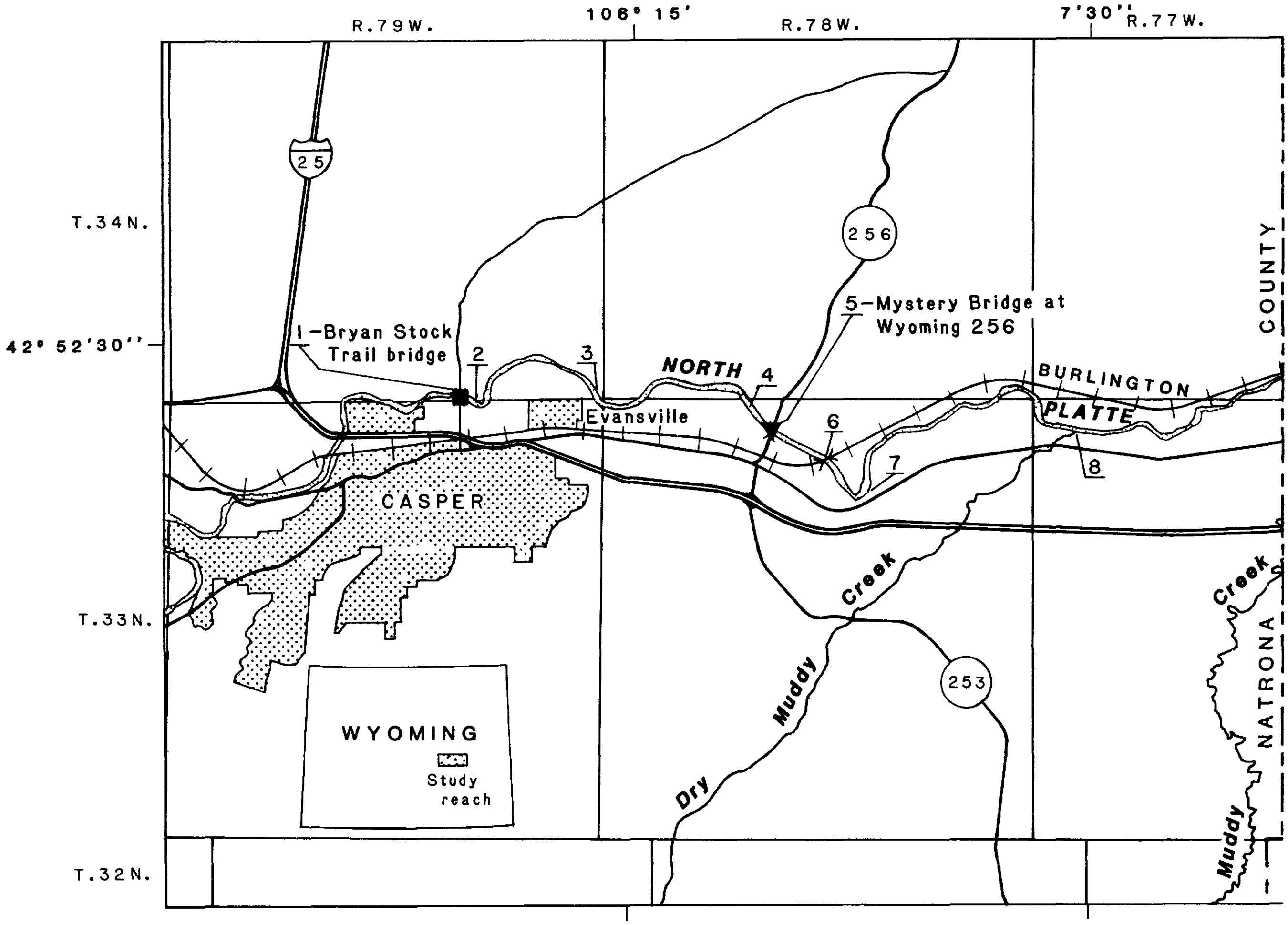
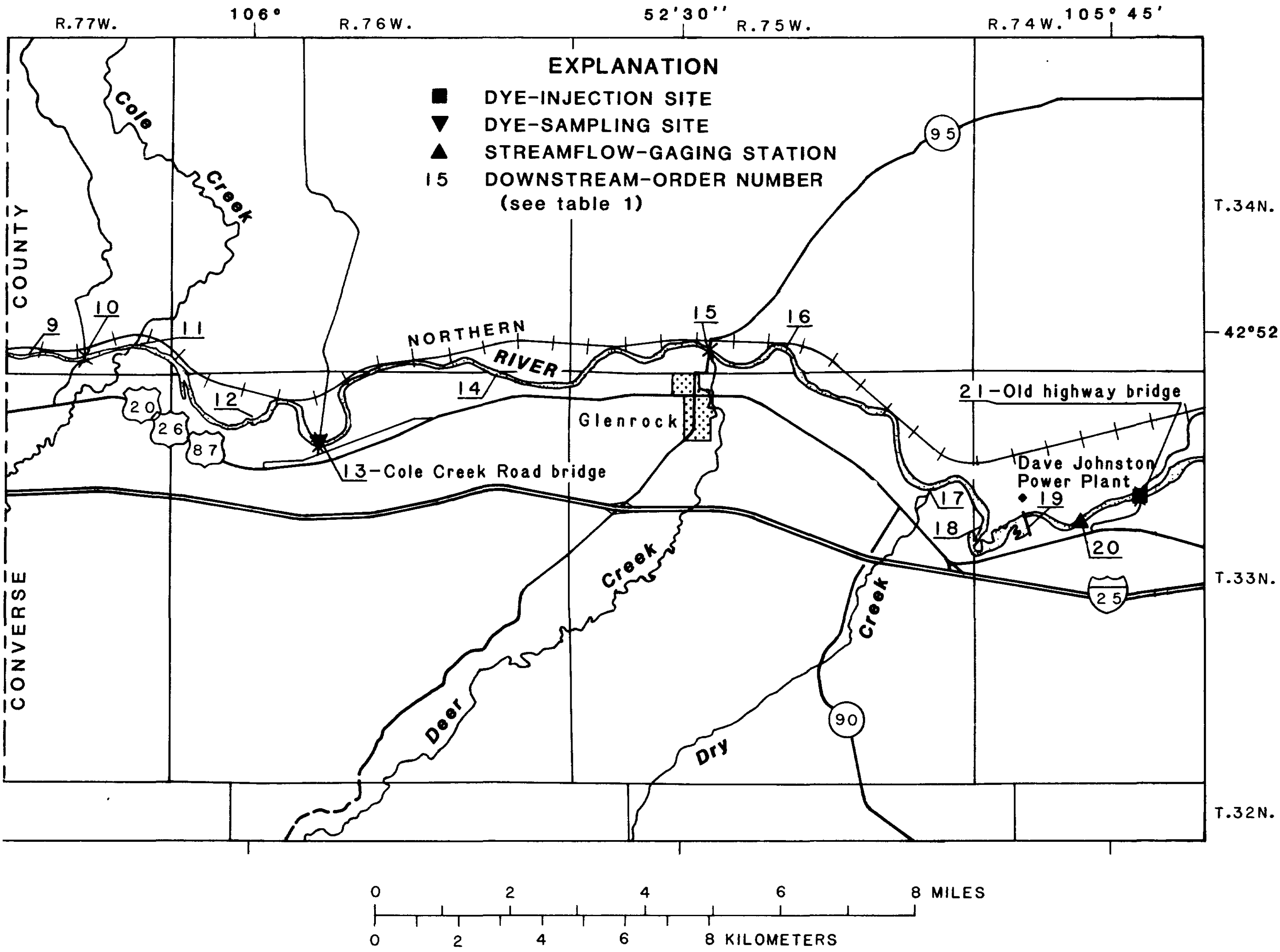


Figure 1.--The 36.4-mile study reach.



R.77W.
106°
R.76W.
52'30''
R.75W.
R.74W.
105° 45'
EXPLANATION
DYE-INJECTION SITE
DYE-SAMPLING SITE
STREAMFLOW-GAGING STATION
15 DOWNSTREAM-ORDER NUMBER (see table 1)
T.34N.
42°52'30"
T.33N.
T.32N.
CONVERSE COUNTY
Cole Creek
NORTHERN RIVER
Glenrock
13-Cole Creek Road bridge
21-Old highway bridge
Dave Johnston Power Plant
Deer Creek
Dry Creek
0 2 4 6 8 MILES
0 2 4 6 8 KILOMETERS

The only hydraulic structure in the reach is a dam at the Dave Johnston Power Plant (34.5 river miles downstream from injection site). As this dam only diverts water and does not store it, the dam has a negligible effect on the average velocities of water in the reach.

River mileages were measured on U.S. Geological Survey 7½-minute topographic maps between easily identifiable features, such as bridges and tributaries; other features that may be of interest, such as sewage treatment plants and industrial plants; and points where topographic contours cross the river. The features were numbered in downstream order and are shown in figure 1. The downstream-order number, the description and location, and the river mile for each feature are listed in table 1.

ACKNOWLEDGMENT

The authors would like to thank Carlton Hunter of the Wyoming State Engineer's Office for his assistance in the collection of data for this study.

METHOD OF STUDY

Dye tracing is a widely accepted method of measuring time of travel, dispersion rates, and dilution of solutes in streams. The technique described by Hubbard and others (1982) was used in this study. It involves the addition of a known amount of fluorescent dye that is water-soluble, easily detected, harmless in low concentrations, relatively inexpensive, and reasonably stable in a normal stream environment. Subsequent fluorometer measurements of the concentration of the dye cloud with time as it moves downstream determine the rate of travel, dispersion, and dilution (Wilson, 1968).

Previous time-of-travel measurements using dye in Wyoming have been made on the Wind/Bighorn River (Lowham and Wilson, 1971; Lowry and others, 1976), on the Little Snake River (Bauer and others, 1979), and on the upper Green River and its tributaries (Lowham, 1982).

The study began with the injection of 19.85 pounds of rhodamine WT dye (20-percent solution) into the river at the Bryan Stock Trail bridge (fig. 1) at 0500 hours November 7, 1978. Samples were collected November 7-8 at Mystery Bridge on Wyoming Highway 256, the bridge on Cole Creek Road, and an old highway bridge 2 miles downstream from the Dave Johnston Power Plant (fig. 1). The estimated lateral distribution of streamflow at each sampling site was subdivided into 3 increments of approximately equal discharge, so that representative samples could be collected from the left or north-bank flow, the center flow, and the right or south-bank flow. Samples were collected near the surface from the center of each one-third of the streamflow at the bridges.

An average flow of 940 ft^3/s during the measurements was determined from streamflow-gaging-station records. This flow was typical of a normal release for the winter of 1978-79. Inflow into the reach from tributaries was estimated to be less than 50 ft^3/s.

Table 1.--Downstream-order numbers, description, location, and river miles for selected features in the study reach

[Streambed altitudes are in feet above National Geodetic Vertical Datum of 1929]

Down-stream-order number	Description and location	Distance from dye-injection site (river mile)
1	Bryan Stock Trail bridge (SW¼SW¼ sec. 35, T. 34 N., R. 79 W.).	0.0
2	Casper sewage treatment plant (NW¼NW¼ sec. 2, T. 33 N., R. 79 W.).	0.3
3	Streambed altitude 5,080; Evansville sewage treatment plant (SE¼SE¼ sec. 36, T. 34 N., R. 79 W.).	2.4
4	Former site of Mystery Bridge (NW¼NW¼ sec. 4, T. 33 N., R. 78 W.).	4.9
5	Water-quality station *06645000, Mystery Bridge at Wyoming Highway 256 (SE¼NW¼ sec. 4, T. 33 N., R. 78 W.).	5.4
6	Railroad bridge (SW¼SW¼ sec. 3, T. 33 N., R. 78 W.).	6.2
7	Streambed altitude 5,060 (SW¼NE¼ sec. 10, T. 33 N., R. 78 W.).	7.0
8	Streambed altitude 5,040; Dry Muddy Creek (SW¼NE¼ sec. 6, T. 33 N., R. 77 W.).	11.0
9	Streambed altitude 5,020 (NE¼SW¼ sec. 34, T. 34 N., R. 77 W.).	15.1
10	Big Muddy Creek bridge (SW¼SE¼ sec. 35, T. 34 N., R. 77 W.).	15.5
11	Muddy Creek; Cole Creek (NE¼SW¼ sec. 36, T. 34 N., R. 77 W.).	16.3
12	Streambed altitude 5,000 (NE¼SW¼ sec. 5, T. 33 N., R. 76 W.).	18.6
13	Cole Creek Road bridge (NE¼NW¼ sec. 9, T. 33 N., R. 76 W.).	20.1
14	Streambed altitude 4,980 (NE¼NE¼ sec. 2, T. 33 N., R. 76 W.).	23.7
15	Glenrock Bridge; Deer Creek (NW¼SW¼ sec. 33, T. 34 N., R. 75 W.).	27.1
16	Streambed altitude 4,960 (NW¼SW¼ sec. 34, T. 34 N., R. 75 W.).	28.3
17	Dry Creek (NW¼SW¼ sec. 12, T. 33 N., R. 75 W.).	31.8
18	Streambed altitude 4,940 (SW¼NW¼ sec. 18, T. 33 N., R. 74 W.).	33.1
19	Dave Johnston Dam (NE¼NE¼ sec. 18, T. 33 N., R. 74 W.).	34.5
20	Gaging station *06646800 (NW¼NE¼ sec. 17, T. 33 N., R. 74 W.).	35.5
21	Old highway bridge below Dave Johnston Power Plant (SE¼SW¼ sec. 9, T. 33 N., R. 74 W.). Water-quality samples for station *06646800 are collected at this location.	36.4

* U.S. Geological Survey station-identification number.

DYE MOVEMENT AND DATA ANALYSIS

The dye dispersed vertically, laterally, and longitudinally after injection. Vertical dispersion occurred almost immediately due to the shallowness of the river. Lateral dispersion was much slower; the dye cloud was observed to take about 3 hours to reach the banks. Longitudinal dispersion continued indefinitely. There was a rapid increase in concentration of dye from the leading edge to the peak. The concentration then decreased gradually into a long trailing edge as the dye cloud slowed after reaching the banks and was deflected back towards the center of the stream. The rate of lateral dispersion is graphically depicted by three curves showing concentration of dye and time at sampling sites (figs. 2-4). Curves were drawn for each one-third of the streamflow at each of the three sampling sites. Although the three curves at Mystery Bridge (fig. 2) show considerable differences in their shapes and between their peaks, lateral dispersion was almost complete at this point. There is only an 11.4-percent difference in the areas beneath these curves.

Dye recovery was calculated to be 98 percent at Mystery Bridge, 92 percent at Cole Creek Road bridge, and 89 percent at the bridge downstream from the Dave Johnston Power Plant. The method of calculation is described by Hubbard and others (1982, p. 33). The reason for the dye loss is not known, but the losses may have been due to adsorption on vegetation and sediment, photochemical decay, or chemical reactions with substances in the water. Losses do not seriously affect the computations of traveltime and rate but do prevent accurate assessment of the concentrations of contaminants that might not have the same loss or decay characteristics as the dye. All dye concentrations in this report have been adjusted for the amount of solute injected and for dye loss by converting the data to conservative concentrations. This was done by dividing measured concentrations by the recovery ratio (0.98 at Mystery Bridge, 0.92 at Cole Creek Road bridge, and 0.89 at the bridge downstream from the Dave Johnston Power Plant).

The data were converted to unit concentrations to adjust for varying discharges. Unit concentration (C_u) is defined as the concentration produced in 1 unit of flow rate by the injection of 1 unit weight of a conservative solute (Hubbard and others, 1982, p. 34-35). A conservative solute is one which retains its original injected weight as it disperses and is transported downstream; that is, 100 percent of the solute cloud will be detected during any subsequent downstream sampling. Unit concentration (C_u) may be computed by the equation:

$$C_u = \frac{CQ}{Rw} \qquad (1)$$

where C = measured concentration, in micrograms per liter;
Q = flow rate, in cubic feet per second;
R = recovery ratio; and
w = weight of conservative solute, in pounds (for rhodamine WT, w = weight of dye solution injected x 0.2, the solution concentration).

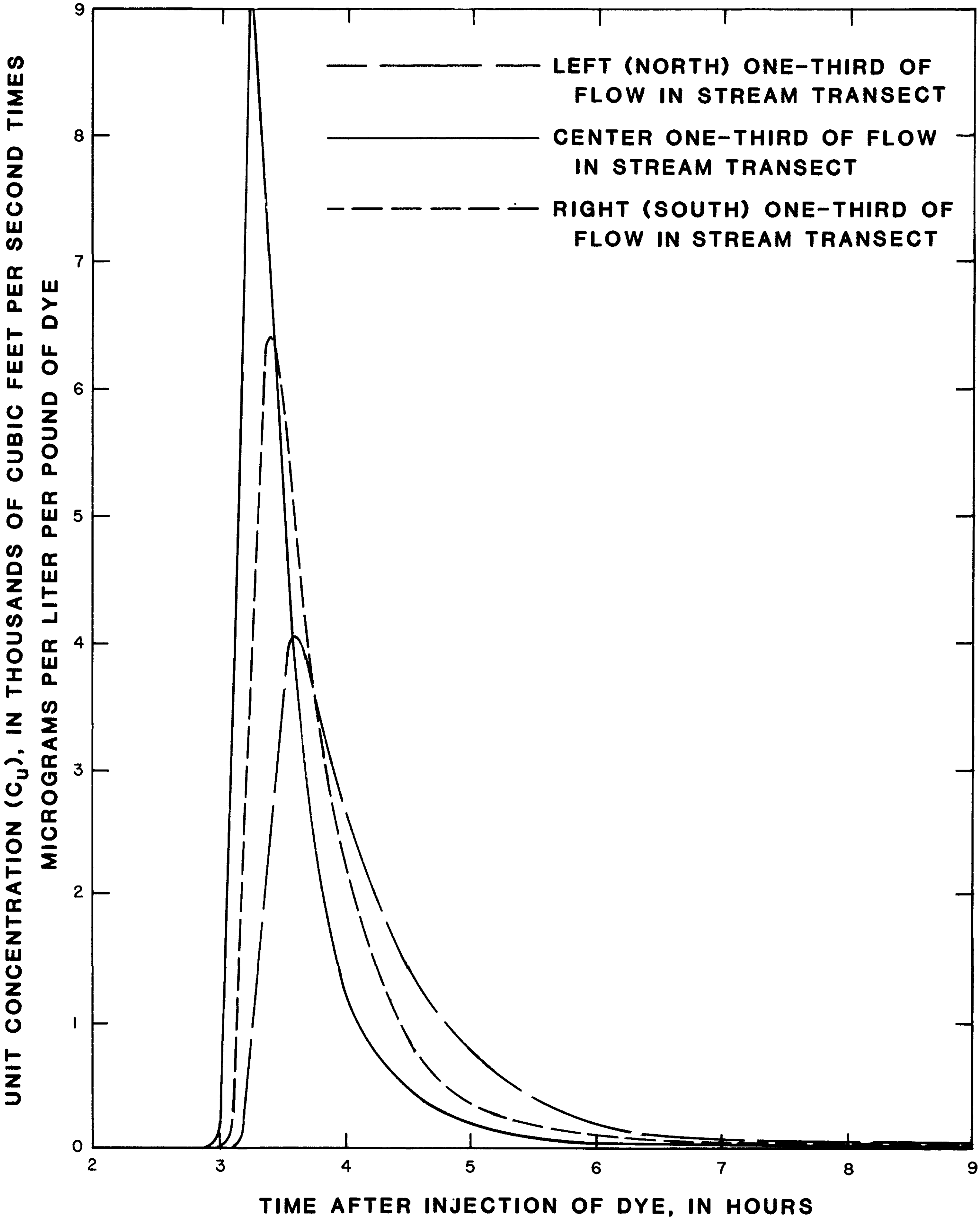


Figure 2.--Unit concentration and time after injection of dye at Mystery Bridge (site 5, 5.4 river miles downstream from injection site).

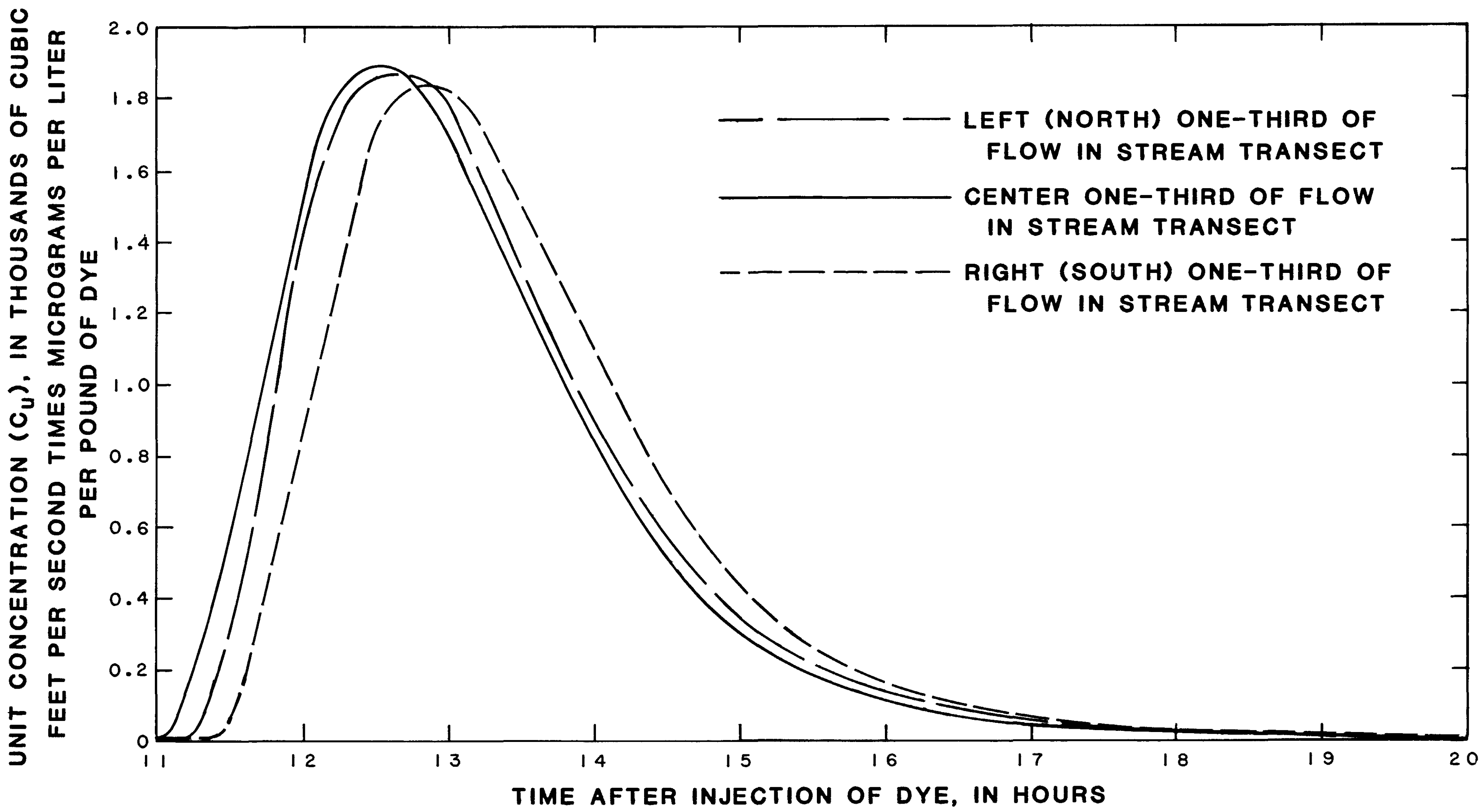


Figure 3.--Unit concentration and time after injection of dye at Cole Creek Road bridge (site 13, 20.1 river miles downstream from injection site).

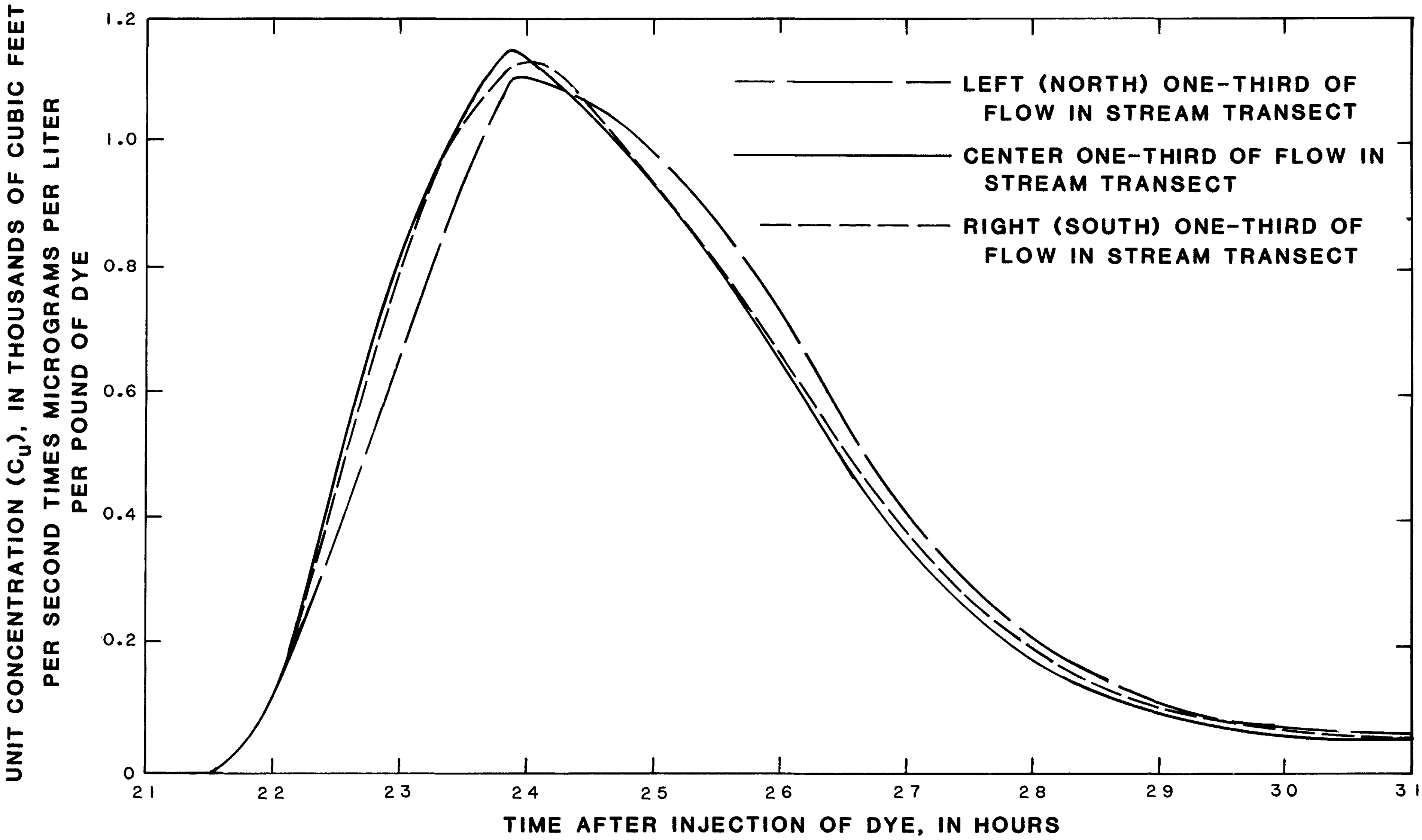


Figure 4.--Unit concentration and time after injection of dye at bridge downstream from Dave Johnston Power Plant (site 21, 36.4 river miles downstream from injection site).

By using unit concentration, only variation due to longitudinal dispersion remains (Hubbard and others, 1982, p. 34). Unit concentrations obtained during one discharge, therefore, would be applicable for a range of discharges limited only by the rate at which the longitudinal dispersion of the dye varies.

A total of 15 background samples were collected at the sampling sites prior to the arrival of the dye cloud. The mean fluorometer reading for the 15 samples was 0.036 fluorometer unit, with a standard deviation of 0.027 unit. Background readings greater than zero are common in most streams. Such readings do not indicate the presence of dye, but rather are indicative of the inability of a fluorometer to screen out all light not due to fluorescence of dye. The mean background reading was subtracted from all readings for samples containing dye. For the purposes of this study, the trailing edge of the dye cloud at a sampling site was defined as the point in time when the background reading of the water (measured at all three sections of the site) returned to 0.036 fluorometer unit or less.

Traveltimes and rates of travel for the leading edge, the peak concentration and the trailing edge of dye injected at Bryan Stock Trail bridge for selected reaches are shown in table 2. The dye was injected at 0500 hours on November 7, 1978, when the river was flowing at 940 ft^3/s.

The distance downstream from the injection point and the time after injection of dye are shown in figure 5 for the leading edge, the peak concentration, and the trailing edge of the dye. The length of the dye cloud at a given time or the duration (time of passage) of the dye cloud at a given place in the study reach may be determined from figure 5. For example, at 20 hours after injection the dye cloud extended from about 20 to about 34 river miles downstream, or the cloud was 14 miles long. In addition, at 20 river miles downstream from the injection point the dye cloud passed in 9 hours. (The leading edge arrived 11 hours after injection and the trailing edge 20 hours after injection.)

According to Hubbard and others (1982, p. 34), Nobuhiro Yotsukura (U.S. Geological Survey) has shown that once mixing is complete, a log-log plot of peak concentration versus traveltime tends to be a straight line. However, a line through the peak concentrations at Cole Creek Road bridge (site 13) and at the old highway bridge downstream from the Dave Johnston Power Plant at site 21 is above the maximum dye concentrations of supplementary samples collected by a member of the Wyoming State Engineer's Office at points 45.6 and 54.1 river miles downstream from Bryan Stock Trail bridge (graph A, fig. 6). The supplementary points seem to be near the maximum dye concentration, but data collected at these locations were not sufficient to determine the peak concentration. The peak concentration at Mystery Bridge (site 5) plots above the line (graph A, fig. 6) because lateral dispersion was incomplete at that location. Therefore, only the peak concentrations at Cole Creek Road bridge and at the old highway bridge may be used to determine the relation between peak concentration and time. The relation between unit peak concentration (C_{up}) and time is shown in graph B, figure 6. The relation between C_{up} and peak traveltime (T_p) is

$$C_{up} = 14{,}000\ T_p^{-0.78}. \tag{2}$$

Table 2.--Measured traveltimes and rates of travel of dye

[h = hours; mi/h = miles per hour]

Reach (river miles)	Leading edge of dye		Peak of dye concentration		Trailing edge of dye	
	time (h)	rate (mi/h)	time (h)	rate (mi/h)	time (h)	rate (mi/h)
0 to 5.4	3.0	1.80	3.17	1.70	9.0	0.60
0 to 20.1	11.1	1.81	12.6	1.60	20	1.0
0 to 36.4	21.6	1.69	24.0	1.52	35	1.0
5.4 to 20.1	8.1	1.81	9.43	1.56	11	1.3
20.1 to 36.4	10.5	1.55	11.4	1.43	15	1.1

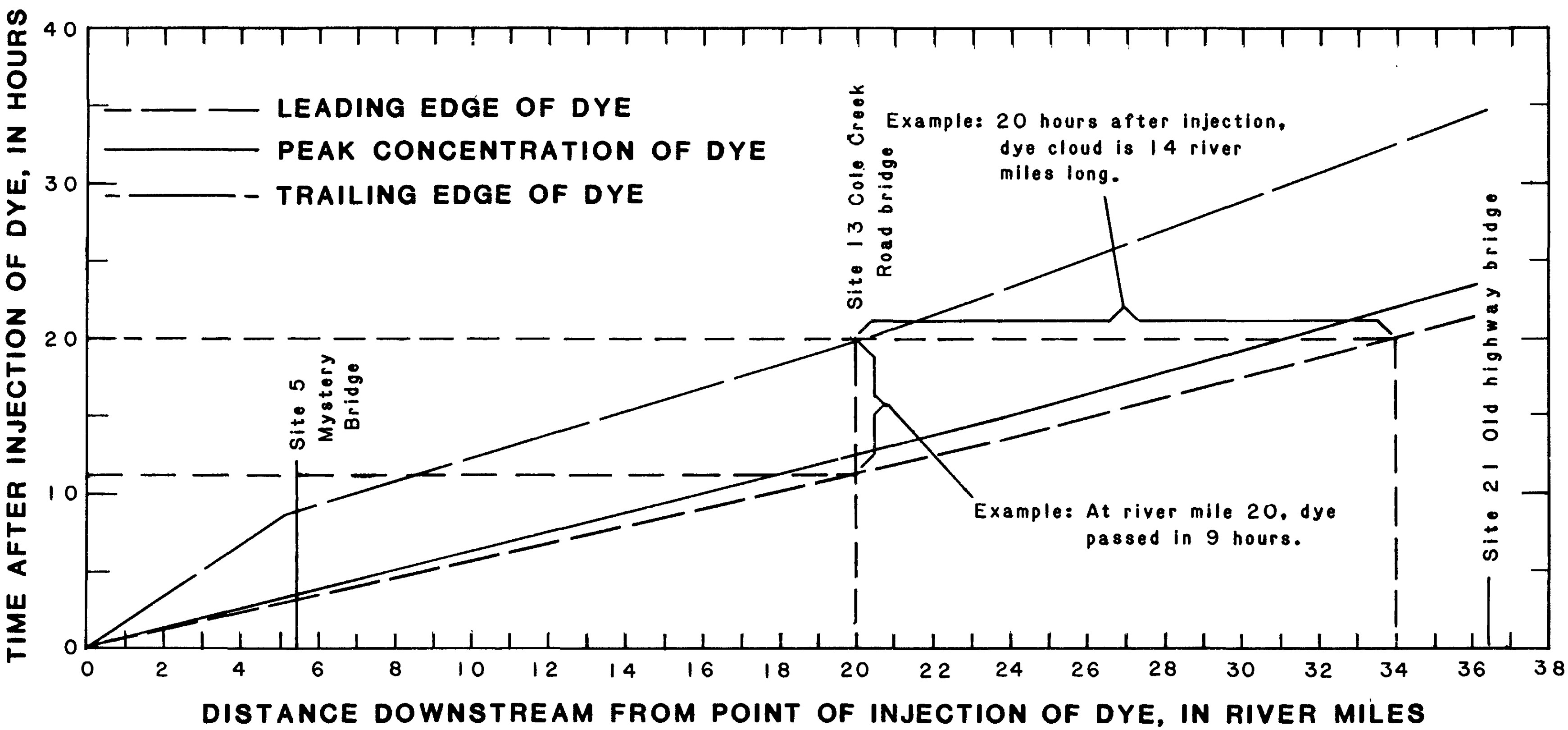


Figure 5.--Traveltime-distance relations for study reach.

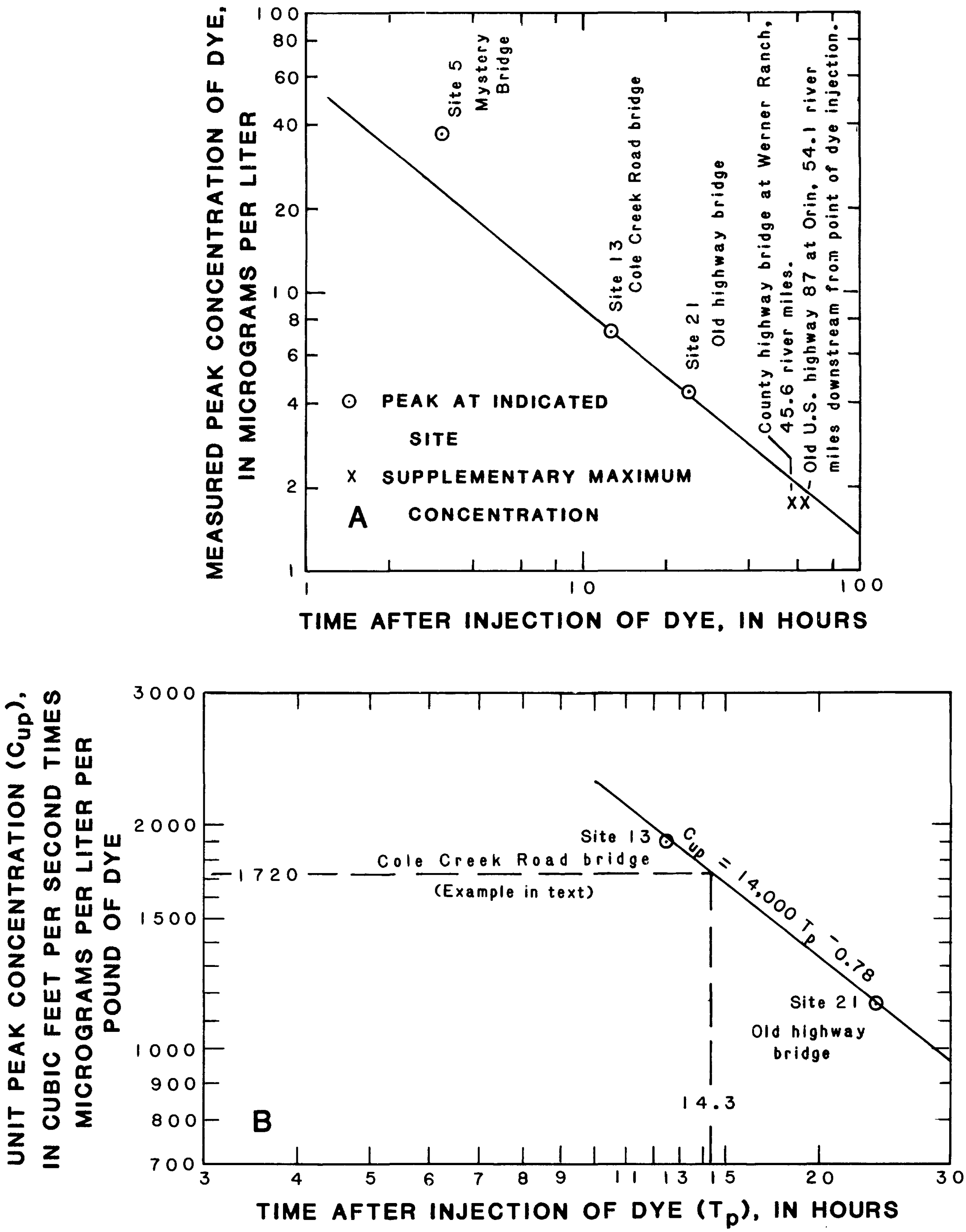


Figure 6.--Concentration-traveltime relations for selected sites. A, measured peak concentrations; B, unit peak concentrations.

APPLICATION

The concentration-time graphs (figs. 2-4) can be used to estimate the downstream concentration of any quantity of a conservative soluble contaminant spilled into the river within the study reach if the quantity of contaminant is known, the location of spill is known, and the river discharge is about 940 ft^3/s. (River-discharge data are available from the U.S. Geological Survey, Casper, Wyo., and the U.S. Bureau of Reclamation, Mills, Wyo.) The traveltime-distance graph (fig. 5) and the table of river mileages (table 1) can be used to estimate distances traveled and times between locations as the contaminant moves downstream. Contaminants that are not conservative will have different transport characteristics, and insoluble contaminants, such as oil, will also have different transport characteristics. Estimates obtained from these graphs are valid only in the study reach.

Estimating Peak Concentrations

In a hypothetical situation, suppose that 100 pounds of a conservative contaminant has spilled into the North Platte River near the Bryan Stock Trail bridge, and the river discharge is 1,000 ft^3/s. To find the peak concentration at Cole Creek Road bridge, equation 1 (p. 6) can be used by solving for C, assuming a value of 1 for R, and obtaining a unit peak concentration of 1,890 $(ft^3/s)(\mu g/L)$ for each pound of contaminant from figure 3. The resultant equation and calculations are as follows:

$$C = \frac{C_u w}{Q} \qquad (3)$$

$$= \frac{1{,}890 \ \frac{(ft^3/s)(\mu g/L)}{lb} \times 100 \text{ lbs}}{1{,}000 \ ft^3/s}$$

$$= 189 \ \mu g/L.$$

The peak concentration of 189 $\mu g/L$ at Cole Creek Road bridge occurs 12.6 hours after the spill (fig. 3). Duration and velocity of the cloud may be obtained using the traveltime-distance curve (fig. 5).

Figures 2, 3, and 4 (p. 7-9) give values of unit concentration for contaminant travel distances of 5.4, 20.1, and 36.4 river miles. Values of unit concentration for other contaminant travel distances within the study reach would require estimations.

Estimating Time of Travel and Unit Concentration

In another hypothetical situation, suppose that a contaminant is being pumped into the river at Mystery Bridge, and the river is flowing at 900 ft^3/s. If the point of concern is a water intake near Glenrock, the downstream distances of both locations can be obtained from table 1 and applied to figure 5 (p. 12). Mystery Bridge is at river mile 5.4 downstream from Bryan Stock Trail bridge, and Glenrock is at river mile 27.1. When applied to the traveltime-distance graph (fig. 5), these mileages give peak-concentration times of 3.2 hours at Mystery Bridge and 17.5 hours at Glenrock. The difference of 14.3 hours represents the time of travel estimated for the peak concentration of the contaminant to reach Glenrock. The 14.3-hour traveltime is sufficient for complete mixing. By applying the traveltime to graph B in figure 6 (p. 13), a unit peak concentration of about 1,720 (ft^3/s)(μg/L) is obtained for each pound of conservative contaminant being pumped into the river. (Unit peak concentration may then be converted to peak concentration as explained in the preceeding section on estimating peak concentrations.)

Estimates of Time of Travel for Different Discharge Rates

Time of travel varies inversely with discharge. The relationship of time of travel to discharge usually is determined by making dye studies at two or three discharges covering as wide a range of discharge as possible. Because only one dye study was made on the reach described in this report, the following discussion may be useful if estimates of time of travel are needed for a discharge significantly different from that of this study (940 ft^3/s).

Boning (1974) analyzed the data from 873 time-of-travel measurements made throughout the United States. He applied regression analyses to obtain sets of equations for estimating time-of-travel information for streams that have not been measured with dye. Boning's equations for channel-controlled reaches were used to estimate time of travel for the study reach of the North Platte River. The calculated values are shown below and are compared to the values obtained from the dye study. (Note--Boning's symbols have been modified to agree with those used in this report.)

1. Time of travel of peak concentration of dye (Tp) at the old highway bridge, site 21 (river mile 36.4).

   a. Calculated: $v_p = 2.69Q^{0.26}\, s^{0.28}$,

   where v_p = velocity of peak concentration, in feet per second;

   Q = discharge, in cubic feet per second; and

   s = channel slope, in feet per foot.

   Channel slope(s) was determined from topographic maps to be 169 ft/36.4 mi = 0.00088 ft/ft.

$$v_p = 2.69(940)^{0.26}(0.00088)^{0.28} = 2.22 \text{ ft/s},$$

$$T_p = 1.467\ L/v_p,$$

where L = reach length, in river miles,

$$T_p = 1.467(36.4)/(2.22) = 24.1 \text{ hours}.$$

b. Observed (table 2): 24.0 hours

2. Time of travel of leading edge of dye (T_l) at site 21.

a. Calculated: $v_l = 2.86Q^{0.27}\ s^{0.28}$,

where v_l = velocity of leading edge of dye,

$$v_l = 2.86(940)^{0.27}(0.00088)^{0.28} = 2.53 \text{ ft/s},$$

$$T_l = 1.467\ L/v_l = 1.467(36.4)/(2.53) = 21.1 \text{ hours}.$$

b. Observed (table 2): 21.6 hours

3. Unit peak concentration (C_{up}) at site 21.

a. Observed: $C_{up} = 139{,}000\ L^{-0.88}Q^{0.27}\ s^{0.51}$

$$= 139{,}000(36.4)^{-0.88}(940)^{0.27}(0.00088)^{0.51}$$

$$= \frac{1{,}032\ (\text{ft}^3/\text{s})(\mu\text{g/L})}{\text{lb}}.$$

b. Observed (fig. 4): $1{,}140\ \frac{(\text{ft}^3/\text{s})(\mu\text{g/L})}{\text{lb}}$

4. Duration (passage time) of dye (D) at site 21 at 10 percent of C_{up}:

a. Calculated: $D = 0.062L^{0.89}Q^{-0.28}s^{-0.53}$

$$= 0.062(36.4)^{0.89}(940)^{-0.28}(0.00088)^{-0.53}$$

$$= 9.3 \text{ hours}.$$

b. Observed (fig. 4): approximately 7 hours

The calculated values (except duration) are within one standard error of the observed values. In an emergency, such as an accidental spill of hazardous material, Boning's equations could be used to provide managers with information needed to make decisions. The fact that the equations overestimated duration of dye passage and underestimated unit peak concentration at 940 ft^3/s need to be taken into account.

In the foregoing comparison, the entire dye-study reach was used. Boning's equations can be applied to any subreach by substituting appropriate values for Q, s, and L.

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