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GEOLOGICAL SURVEY

DETERMINATION OF REAERATION-RATE COEFFICIENTS OF THE WABASH RIVER, INDIANA, BY THE MODIFIED TRACER TECHNIQUE

By Charles G. Crawford

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The inch-pound units used in this report can be converted to metric (International System) units, as follows:

Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
ounce, fluid (fl. oz)	29.574	milliliter (ml)
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.0283	cubic meter per second (m^3/s)
pound per minute (lb/min)	453.6	gram per minute (g/min)

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows:

$$°F = 1.8° C + 32$$

Time in hours and minutes is reported in military time (24-hour clock) for the Eastern Standard Time Zone; for example, 0122 is 1:22 am, eastern time; 1322 is 1:22 pm, eastern time.

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ABSTRACT

The modified tracer technique was used to determine reaeration-rate coefficients in the Wabash River in reaches near Lafayette and Terre Haute, Indiana, at streamflows ranging from 2,310 to 7,400 cubic feet per second. Chemically pure (CP grade) ethylene was used as the tracer gas, and rhodamine-WT dye was used as the dispersion-dilution tracer. Reaeration-rate coefficients determined for a 13.5-mile reach near Terre Haute, Indiana, at streamflows of 3,360 and 7,400 cubic feet per second (71 and 43 percent flow duration) were 1.4 and 1.1 day^{-1} at 20° Celsius, respectively. Reaeration-rate coefficients determined for a 18.4-mile reach near Lafayette, Indiana, at streamflows of 2,310 and 3,420 cubic feet per second (70 and 53 percent flow duration), were 1.2 and 0.8 day^{-1} at 20° Celsius, respectively.

None of the commonly used equations found in the literature predicted reaeration-rate coefficients similar to those measured for reaches of the Wabash River near Lafayette and Terre Haute. The average absolute prediction error for 10 commonly used reaeration equations ranged from 22 to 154 percent. Prediction error was much smaller in the reach near Terre Haute than in the reach near Lafayette. The overall average of the absolute prediction error for all 10 equations was 22 percent for the reach near Terre Haute and 128 percent for the reach near Lafayette. Confidence limits of results obtained from the modified tracer technique were smaller than those obtained from the equations in the literature.

INTRODUCTION

The Wabash River in western Indiana, the largest free-flowing tributary to the Ohio River (fig. 1), is economically important for agricultural, municipal, and industrial uses. Land use in the basin is predominantly agricultural although the basin contains several urban areas, chemical factories and other manufacturing plants. Many of the municipalities and industries withdraw water from the Wabash River and discharge wastewater directly into the river. Within the 150 mile long middle basin, 4 electrical generating stations withdraw and return to the river approximately 2,500 ft^3/s (cubic foot per second) of cooling water, 10 major industries discharge approximately 60 ft^3/s of cooling and process water, and 6 municipal wastewater-treatment facilities discharge approximately 65 ft^3/s of effluent. The electrical generating station at Cayuga

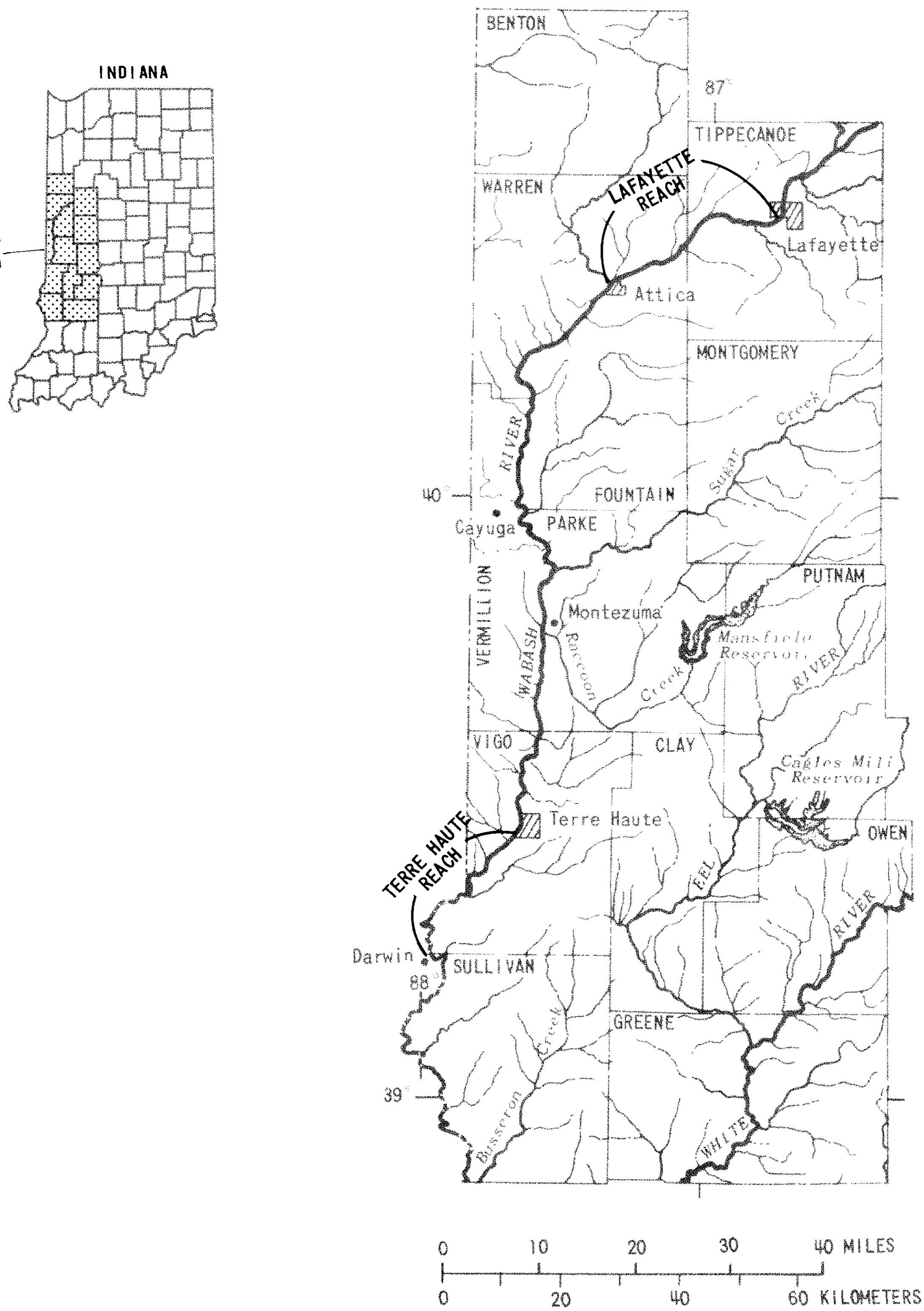


Figure 1.-- Locations of the study area and reaches of the Wabash River where reaeration was determined.

uses virtually all the 851 ft^3/s 10-year, 7-day low flow (Stewart, 1983, p. 83) at the Montezuma gaging station as cooling water. Development in the basin, if it is not properly managed, may adversely affect the Wabash River.

A study was done to determine reaeration-rate coefficients in two different reaches of the Wabash River. Reaeration is the process of oxygen absorption in streamwater from the atmosphere. This process is the primary means by which streams and lakes replace oxygen, and consequently, is a very significant factor in determining the amount of biodegradable waste that can be assimilated by a stream without damaging the aquatic life. The reaeration or oxygen gas-transfer coefficient is a measure of the rate at which the oxygen absorption or transfer takes place from the atmosphere to the stream.

The Indiana State Board of Health coordinated a series of multidisciplinary studies to evaluate the assimilative capacity of the Wabash River in the early 1980's. The work described in this report was part of that series. The information should be helpful to State and local managers of water resources in the Wabash River basin.

Purpose and Scope

This report 1) describes reaeration-rate coefficients for the Wabash River in reaches near Lafayette and Terre Haute, Indiana, determined by the modified-tracer technique at two different steady-state low-flow conditions, 2) describes the techniques and method of data collection and analysis, 3) summarizes the results obtained using this technique and compares them with results obtained from using predictive equations to calculate reaeration-rate coefficients, and 4) compares reaeration-rate coefficients in the Lafayette and Terre Haute reaches of the Wabash River.

Acknowledgments

This study was done in cooperation with the Indiana State Board of Health. The author thanks Stephen H. Boswell of the Indiana State Board of Health for assistance with planning and data collection.

METHODS OF STUDY

Modified Tracer Technique

This technique involves (1) injecting two tracers, rhodamine-WT dye and ethylene gas, into the river concurrently, (2) sampling the tracers at two or more locations downstream of the injection location, (3) determining their concentrations, (4) calculating the ethylene gas-transfer coefficient, and (5) converting the ethylene gas-transfer coefficient to the reaeration-rate or oxygen gas-transfer coefficient. The procedure used for the Wabash River is discussed in the following paragraphs. Additional information about the method is given in Rathbun and others (1975) and Rathbun and Grant (1978).

Chemically pure (CP grade) ethylene (99.5 percent pure) was bubbled into the river through a series of Zimpro passive diffusers[1]. The pore size of these flat-plate diffusers is 1.5 to 2.0 micrometers. Each diffuser (41 in. by 3 in. by 0.75 in.) consisted of 12 plates epoxied in a fiberglass channel. Diffusers were assembled into racks of four, and the individual diffusers were connected in parallel by plastic tubing (Tygon). Ethylene was released into the diffusers from high-pressure cylinders through two-stage regulating valves (Linde model UP-E). Plastic tubing was used to connect the gas cylinders to the diffusers. The gas flow rate was measured by a flowmeter (Linde model 150K) connected to the outlet of the regulating valve. One gas cylinder, regulating valve, and flowmeter were used for each rack of four diffusers. A diagram of the injection apparatus is shown in figure 2.

An injection point 1 to 2 hours time of travel upstream from each reach (1.5 mi at Terre Haute and 0.8 mi at Lafayette) was selected as it was desirable to have the tracers mixing in the flow at both downstream sampling sites. The diffusers were placed parallel to the flow on the bottom of the river at the deepest part of the channel near the center of flow. The racks were placed 15 to 50 ft apart. Eight diffuser racks were used for the high-flow measurement in the reach near Terre Haute, and five racks were used for all other reaches. Ethylene was injected at 0.16 to 0.22 lb/min from each gas cylinder. The ethylene cylinders were placed on the river bank near the location of the diffusers. Except at the point where the tubing entered the water over the diffuser, the tubing was suspended out of the water from a steel wire stretched across the river.

A 20-percent solution of rhodamine-WT dye was injected through plastic tubing into the river by one to two pumps manufactured by FMI Corp., and operated by 12-volt batteries. Two to four tubes from the pumps were fastened to each of the diffuser racks so that the distribution of the dye and the ethylene would be similar and mixing downstream for both tracers would be virtually the same.

[1]Use of brand and firm trade names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

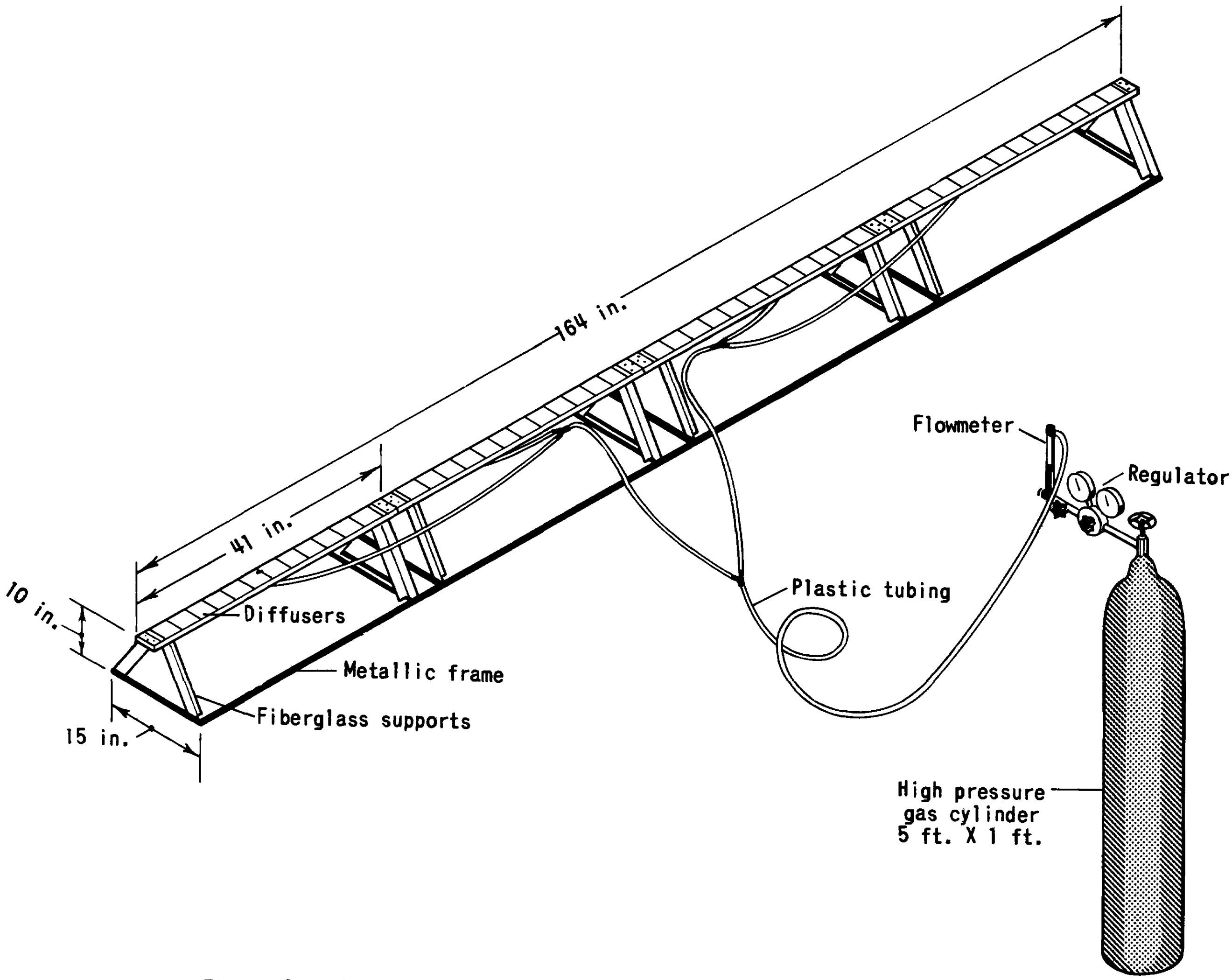


Figure 2.-- Injection apparatus used for the modified tracer technique.

The ethylene and the dye were injected for approximately 2 hours during each measurement. Injection rates were estimated by procedures described by Rathbun (1979). The procedure for ethylene was modified to account for the pressure drop of the Zimpro diffusers (R. E. Rathbun, written commun., 1981).

Water samples for determining concentrations of ethylene and rhodamine-WT were collected at three to five points in each cross section at the upstream and downstream ends of each reach.

Samples for determining concentrations of ethylene were collected at approximately mid-depth of the sampling point in a dissolved-oxygen sampler (Hach model 1962) equipped with septum vial sampling bottles of 1.4 oz capacity.

Samples were preserved for laboratory analysis by adding 0.03 oz (1 mL) of formalin to each sample bottle. Ethylene concentrations were determined by the procedure described by Shultz and others (1976). Ethylene concentrations were determined with a gas chromatograph that was calibrated to a commercial-gas standard. Because of the small quantity of gas involved in preparing the standard, the accuracy of the stated concentration of the standard with respect to the actual gas concentration in the standard is only ±10 percent. However, all samples were analyzed relative to the ethylene standard. Replicate measurements of the concentration of ethylene in water samples from the Wabash River were within ±2 percent. Only the ratio of the upstream and downstream ethylene concentrations were used to compute the ethylene gas-transfer coefficient. Consequently, the consistency of the analytical method is more critical than the absolute magnitude of the actual ethylene concentrations. Ethylene concentrations in the Wabash River samples were well above the detection limit and in the optimal range of the instrument used.

Water samples for determining concentrations of dye were collected in 1.1 oz bottles for analysis in the laboratory. Dye concentrations were determined by a fluorometric method described by Wilson (1968).

Concentrations of rhodamine-WT dye can be accurately determined within ±1 or 2 percent of the actual concentration by a fluorometer. All replicate readings from the Wabash River samples collected during the surveys of the Terre Haute and Lafayette reaches were within 1 percent of each other. Analytical error in determination of the dye concentrations is probably negligible.

The ethylene gas-transfer coefficients were computed by the peak concentration method (Rathbun and Grant, 1978):

$$K_E = \frac{1}{T_D - T_U} \ln \frac{E_U/D_U}{E_D/(D_D)(DCF)} \qquad (1)$$

where

K_E is the ethylene gas transfer coefficient at the ambient stream temperature, in minute^{-1};

T_U the time between the start of the dye injection and the plateau-dye concentration at upstream cross section, in minutes;

T_D the time between the start of the dye injection and the peak-dye concentration at downstream cross section, in minutes;

ln the natural logarithm;

E_U plateau ethylene concentration, at upstream cross section, in micrograms per liter;

D_U plateau dye concentration, at upstream cross section, in micrograms per liter;

E_D peak ethylene concentration at downstream cross section, in micrograms per liter;

D_D peak dye concentration at downstream cross section, in micrograms per liter;

and

DCF the dye-loss correction factor.

For this study, flow-weighted peak gas and dye concentrations were used in all calculations.

The dye-loss correction factor, which is based on the concept of conservation of mass, ensures that the dye mass, QA, is constant throughout the reach,

where

Q is the water discharge at the sampling site, and
A the area under the time-concentration dye curve.

The factor is derived as follows:

$$Q_U A_U = Q_D A_D \times DCF \qquad (2)$$

$$\text{or} \quad DCF = \frac{Q_U A_U}{Q_D A_D}, \qquad (3)$$

where

U and D are subscripts referring to the upstream and downstream cross sections.

The area under the dye time-concentration curve is determined by plotting the observed dye concentrations against time and integrating the area under the curve. The resulting units are minutes-microgram per liter.

The reaeration coefficient can be calculated from the ethylene gas-transfer coefficient by multiplying the latter by an experimentally determined coefficient ratio for oxygen and ethylene. This coefficient ratio, C, is the ratio of the rate at which oxygen absorbs into a body of water and the rate at which ethylene desorbs from the same body.

$$C = \frac{Ka}{K_E}, \qquad (4)$$

where

Ka is the oxygen gas-transfer coefficient,
K_E the ethylene gas-transfer coefficient.

Rathbun and others (1978), experimentally determined the value of C to be 1.15. All reaeration and ethylene gas-transfer coefficients presented in this paper are given to the base e (natural logarithim base, e=2.7183).

Another gas-tracer technique described by Rathbun and Grant (1978), the area method, was not used because it requires considerably more data and does not offer better accuracy than the method used.

Hydraulic Measurements and Wind Velocity

Streamflow and average velocity measurements are necessary to calculate the reaeration coefficient by the modified tracer technique. Average stream width and depth were determined so that the computed reaeration coefficients could be compared with those estimated from the predictive equations reported in the literature.

Streamflow was measured by the current meter method (Rantz and others, 1982) at each end of the two reaches studied. Average stream width was computed as the average of width measurements taken at approximately 1,000-ft intervals along each reach. Width at each point was measured with an optical range finder. Average stream velocity was determined by tracing the speed of the rhodamine-WT dye through the reach. Average depth of the reach was determined by dividing the average streamflow by the product of average velocity and average stream width.

The accuracy of upstream and downstream streamflow measurements for the Terre Haute and Lafayette reaches were rated good on the basis of the number of measurement points (22 to 26 at each cross section), the nearly uniform cross sections, and steady flow through the cross section. A "good" measurement is typically within ±5 percent of the actual streamflow, although this is a subjective rating.

Wind velocity was measured by a Weathertronics model 2131 Indicating Wind System. Wind velocities were measured at each end of the reaches during passage of the tracers.

Collection of Water-Chemistry Samples

Water samples for determination of 5-day biochemical oxygen demand and concentrations of dissolved solids, methylene-blue-active substances (an indicator of detergents), oil and grease and suspended sediment were collected at each end of the reaches during passage of the tracers. Analyses were done by either the Indiana State Board of Health or the U.S. Geological Survey. Methods of analysis included those of the American Public Health Association and others (1980) for 5-day biochemical oxygen demand; Skougstad and others (1979) for dissolved solids; Goerlitz and Brown (1972) for methylene-blue-active substances and oil and grease; and the methods of Guy (1969) for suspended sediment.

STUDY AREA

The locations of the study area and the reaches selected for study are shown in figure 1. Tracer measurements were done on one reach near Terre Haute, Ind., and one near Lafayette, Ind. The reach near Terre Haute was 13.5 mi long and extended from Terre Haute to Darwin (fig. 3). The reach near Lafayette was 18.4 mi long and extended from Lafayette to Attica (fig. 4). Average hydraulic characteristics of each reach during the experiments are presented in table 1.

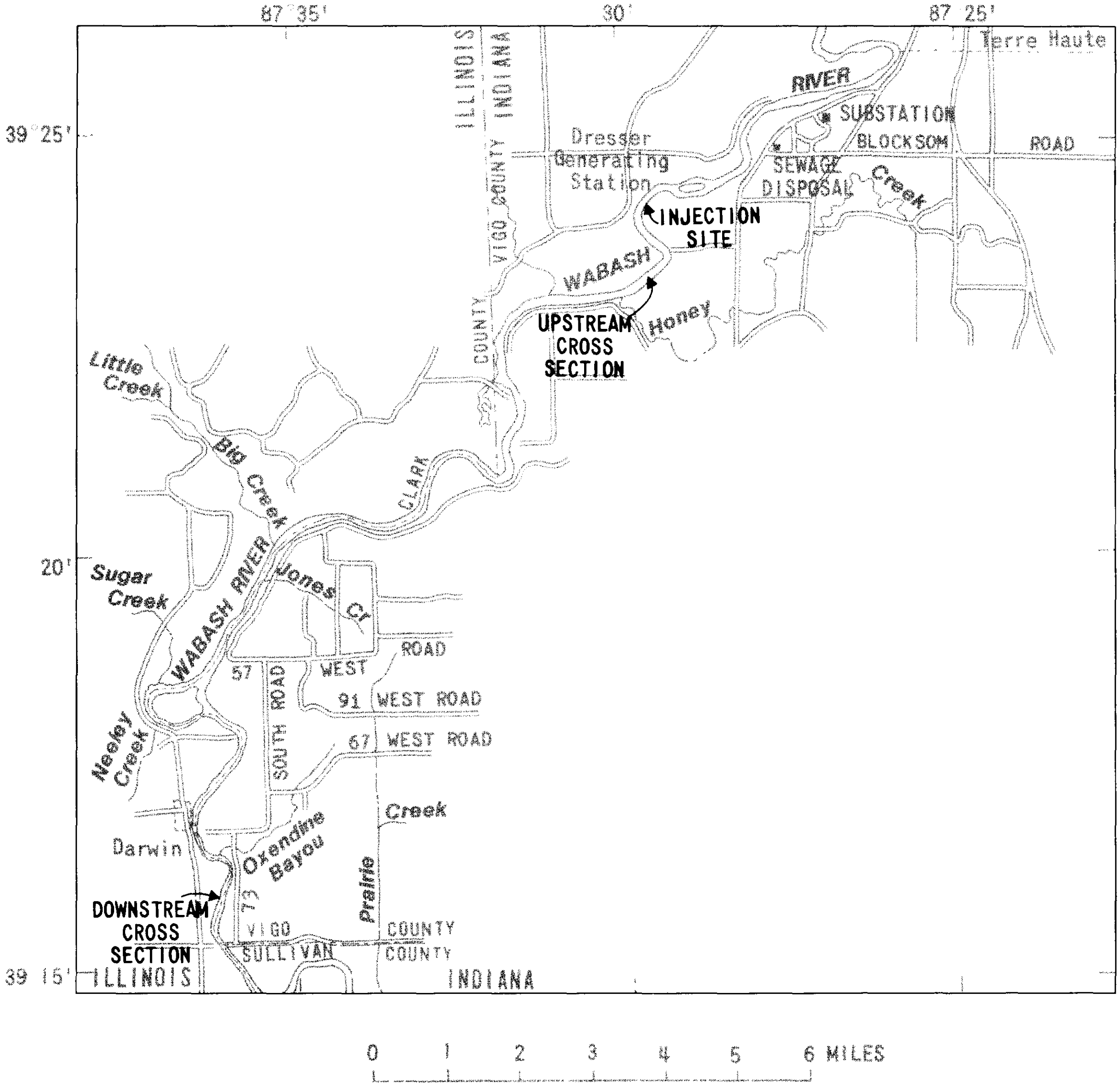


Figure 3.-- Locations of the injection site and upstream and downstream cross sections of the Wabash River near Terre Haute.

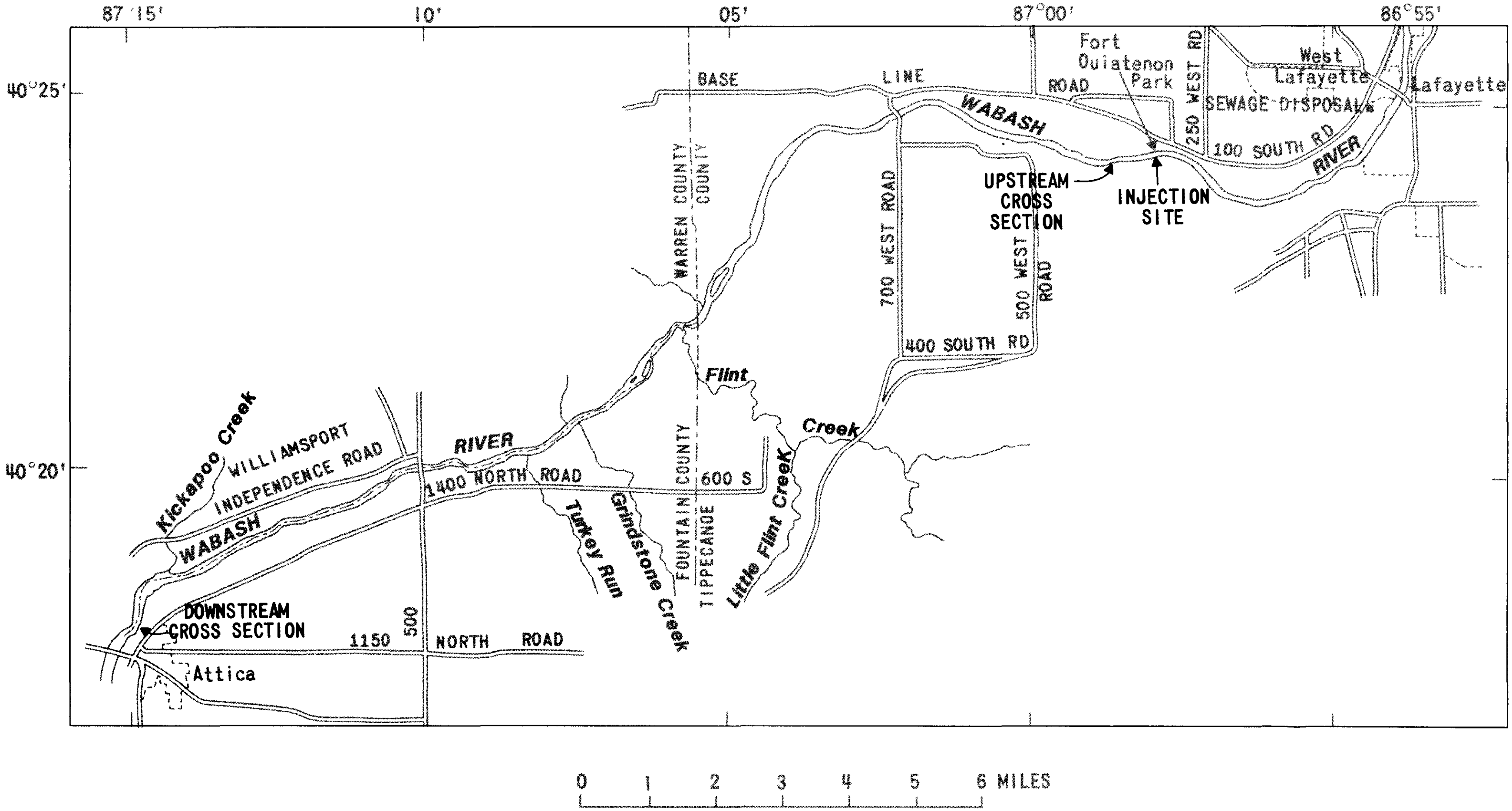


Figure 4.-- Locations of the injection site and upstream and downstream cross sections of the Wabash River near Lafayette.

Table 1.--Average hydraulic characteristics of reaches of the Wabash River near Terre Haute and Lafayette during the reaeration measurements

Reach	Date of field test	Average streamflow (ft^3/s)	Percent of time average streamflow is equaled or exceeded[1]	Average depth (ft)	Average velocity (ft/s)	Slope (ft/ft)
Terre Haute	10/20-21/81	7,400	43	7.4	2.1	0.000114
	8/25-26/82	3,360	71	5.4	1.4	.000114
Lafayette	11/18-19/81	3,420	53	4.4	1.9	.000133
	7/26-27/82	2,310	70	3.4	1.6	.000133

[1] Percentage of time average streamflow is equaled or exceeded is based on flow-duration data from U.S. Geological Survey gaging stations at Terre Haute and Riverton, for the reach near Terre Haute, and Lafayette and Covington, for the reach near Lafayette. These data were used to estimate a weighted-average flow duration for the reaches.

RESULTS

A summary of data collected from the reaches is presented in table 2. A discussion of the results follows. The dye and ethylene data are given in tables 3-18 (at end of report).

Table 2.--Summary of data collected during measurements of reaeration in the Wabash River

[All analyses and measurements by U.S. Geological Survey]

Reach	Date of field test	Time, start of injection	Time, end of injection	Average plateau ethylene concentration upstream cross section, E_U (μg/L)	Peak ethylene concentration downstream cross section, E_D (μg/L)	Average plateau dye concentration upstream cross section, D_U (μg/L)	Peak dye concentration downstream cross section, D_D (μg/L)
Near Terre Haute	10/20-21/81	1640	1840	28.8	15.9	43.7	27.8
	8/25-26/82	1130	1330	25.2	6.3	33.5	14.9
Near Lafayette	11/18-19/81	1210	1410	13.8	5.4	47.9	25.6
	7/26-27/82	1430	1630	18.4	3.2	47.3	18.4

Reach	Date of field test	Average time of travel between upstream dye plateau and downstream dye peaks T_D-T_U (min)	Average temperature (°C)	Streamflow (ft^3/s)		Area of dye time-concentration curve (min-μg/L)	
				At upstream cross section, Q_U	At downstream cross section, Q_D	At upstream cross section, A_U	At downstream cross section, A_D
Near Terre Haute	10/20-21/81	555	14	7270	7520	6,040	4,820
	8/25-26/82	820	23.5	3230	3480	4,350	3,410
Near Lafayette	11/18-19/81	850	9	3470	3360	5,640	5,550
	7/26-27/82	985	28	2290	2320	5,830	5,550

Terre Haute Reach

October 1981 Dye Tracer

The dye time-concentration (T-C) curve at the upstream cross section of the reach near Terre Haute during the October 1981 experiment (fig. 5) is well defined even though erratic operation of one dye pump caused it to be oddly shaped between 70 and 180 minutes after the injection was begun. Dye concentrations observed at multiple points in the cross section of the river (table 3) indicated reasonably uniform lateral mixing at the upstream cross section. The injection period and time of travel to the upstream cross section are short compared to the time required for dispersal of the dye cloud. As a result, the dye T-C curve at the upstream cross section typically approximates a square wave as illustrated by data presented by Rathbun and Grant (1978) for two small streams in Wisconsin (fig. 6). Characteristics of these dye T-C curves are a rapid increase in the dye concentration, a relatively constant concentration on the plateau of the curve, and a rather rapid decrease after the plateau. The time of travel to the downstream cross section is long compared to the injection time. Consequently, at the downstream cross section, the dye cloud has dispersed to resemble a dye T-C curve associated with an instantaneous injection (fig. 7). An average plateau dye concentration and confidence limit can be estimated for the October 1981 measurement if the dye T-C curve at the upstream cross section of the reach near Terre Haute is assumed to have approximated a square wave and the dye pump is assumed to have operated properly. This average is 43.7 ± 2.2 μg/L (±5.0 percent) at the 95-percent confidence limit for the 11 samples collected between 70 and 180 minutes after the injection began.

The theoretical, average concentration of dye on the plateau for the cross section can be determined from the continuity equation for the constant rate injection method of measuring streamflow by dye dilution techniques (Rantz and others, 1982, p. 213):

$$D_{UT} = \frac{DIR \times D_I}{Q_U \times 1697.4} \qquad (5)$$

where

D_{UT} is the theoretical plateau concentration of dye at the upstream cross section, in micrograms per liter;

DIR the dye injection rate, in milliliters per minute;

D_I the concentration of dye in the injection solution, in micrograms per milliliter;

Q_U water discharge at the upstream cross section, in cubic feet per second; and,

1697.4 is a conversion factor.

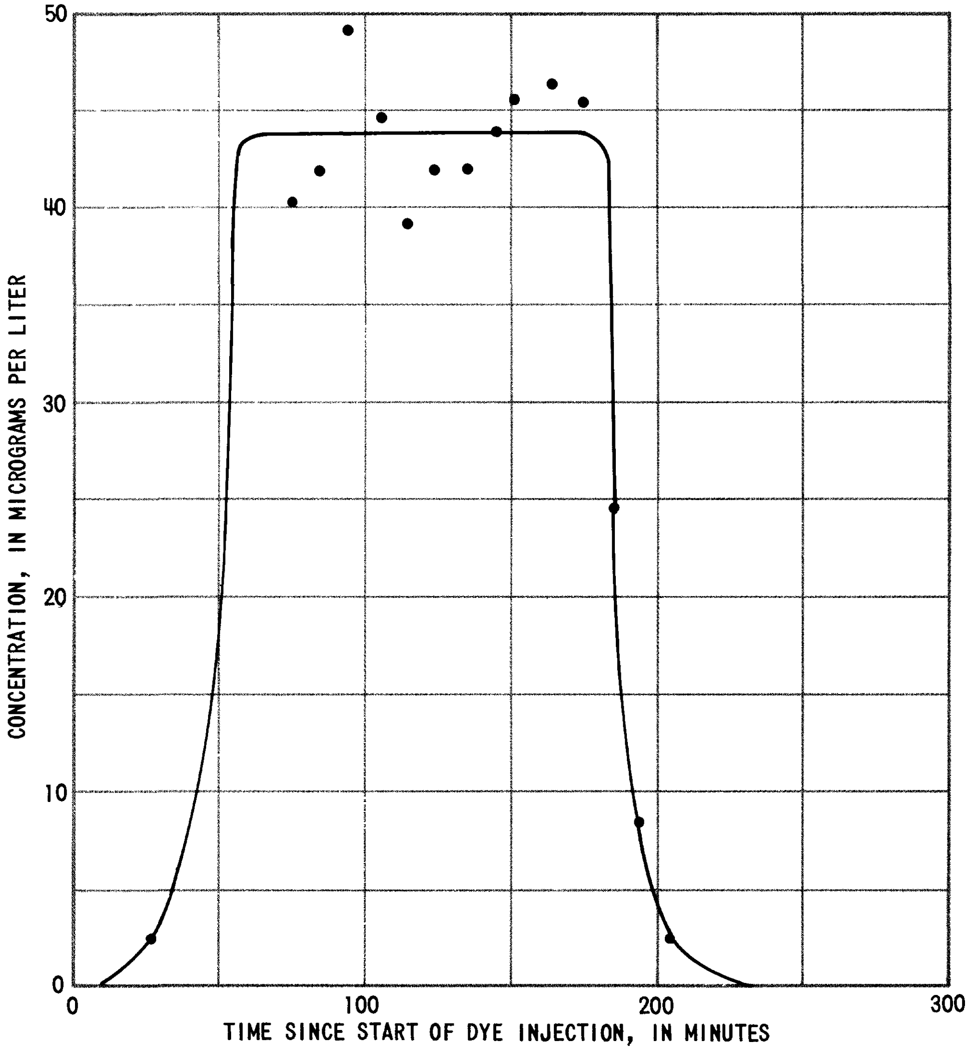


Figure 5.-- Dye time-concentration curve observed in the Wabash River near Terre Haute, upstream cross section, October 20, 1981.

The 20-percent solution of rhodamine-WT dye had a concentration of 2.38 x 10^5 µg/mL rhodamine WT and was injected at a rate of 2,200 mL/min. Water discharge at the upstream cross section was 7,270 ft^3/s. The theoretical average concentration of dye on the plateau was, therefore, 42.4 µg/L. This concentration is within 3 percent of the value calculated from field data.

The area under the upstream dye time-concentration curve is 6,040 minutes-ug/L. The area of the curve calculated for the upper and lower 95-percent confidence limits of the average concentration of dye on the plateau is within ±5 percent of the area based on the average value. For purposes of determining time of travel through the reach, the time at the mid-point of the upstream plateau was used. This time was 135 minutes after the start of the injection.

Scatter in the data makes a determination of the actual time impossible. This time, however, would be near the middle of the plateau, and so the error in this assumption is probably less than ±20 minutes--twice the sampling interval.

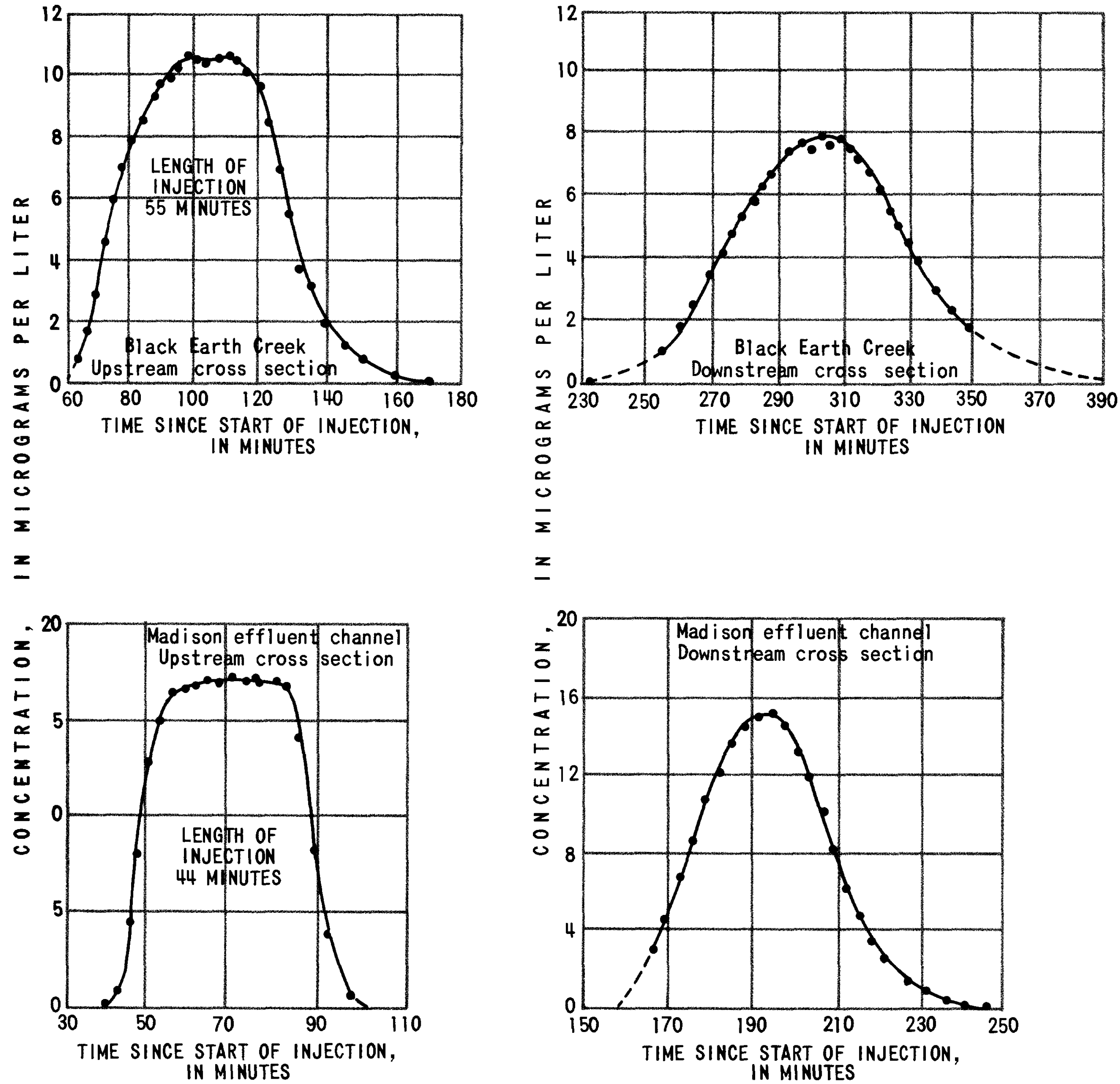


Figure 6.-- Dye time-concentration curves observed in two small streams in Wisconsin (From R. E. Rathbun and R. S. Grant, 1978, figs. 15, 16, 21, and 22).

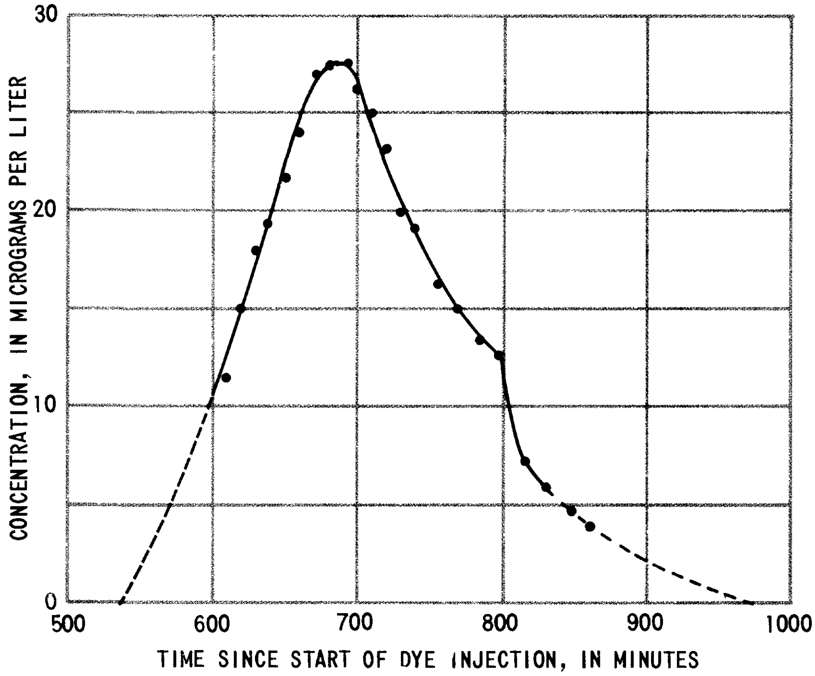


Figure 7.-- Dye time-concentration curve observed in the Wabash River near Terre Haute, downstream cross section. October 21, 1981.

The effect of the erratic injection on the dye T-C curve for the downstream cross section is not evident, because of dispersion (fig. 7). The curve is smooth and is reasonably well defined; however, the rising and falling limbs of the curve were not completely sampled and were estimated. The area of the downstream dye T-C curve is 4,820 minute-μg/L. The area under the rising and falling limbs (fig. 7) constitutes about 13 percent of the total area under the curve. An error of 50 percent in estimating the area in the tails would result in a difference of only 6 percent in the total area of the dye T-C curve. Therefore, because of the insensitivity of the dye T-C curve area to the area in the estimated tails, the overall error in the downstream curve is probably less than ±5 percent. Also, because the peak concentration of dye (27.8 μg/L) is well defined at the cross section, it should be within the ±2 percent analytical error. The peak concentration of dye at the downstream cross section was observed 690 minutes after the injection was begun. Samples for determination of dye concentrations were collected every 10 minutes at the downstream cross section, so that the error in the time of the downstream dye curve is probably less than ±10 minutes.

The relation of ethylene concentration to time in the upstream and downstream cross sections of the Terre Haute reach for the October 1981 experiment is shown in figure 8. The average concentration of 10 samples collected between 70 and 170 minutes after the injection began was 28.8 ±1.9 µg/L (±6.7 percent) at the 95-percent confidence level. Samples taken at multiple points in the stream cross section indicated that the gas concentrations were reasonably uniform across the cross section.

The peak ethylene concentration at the downstream cross section, 15.9 ±0.3 µg/L (±1.9 percent) at the 95-percent confidence level, was estimated by fitting a surface response function to the measured concentrations.

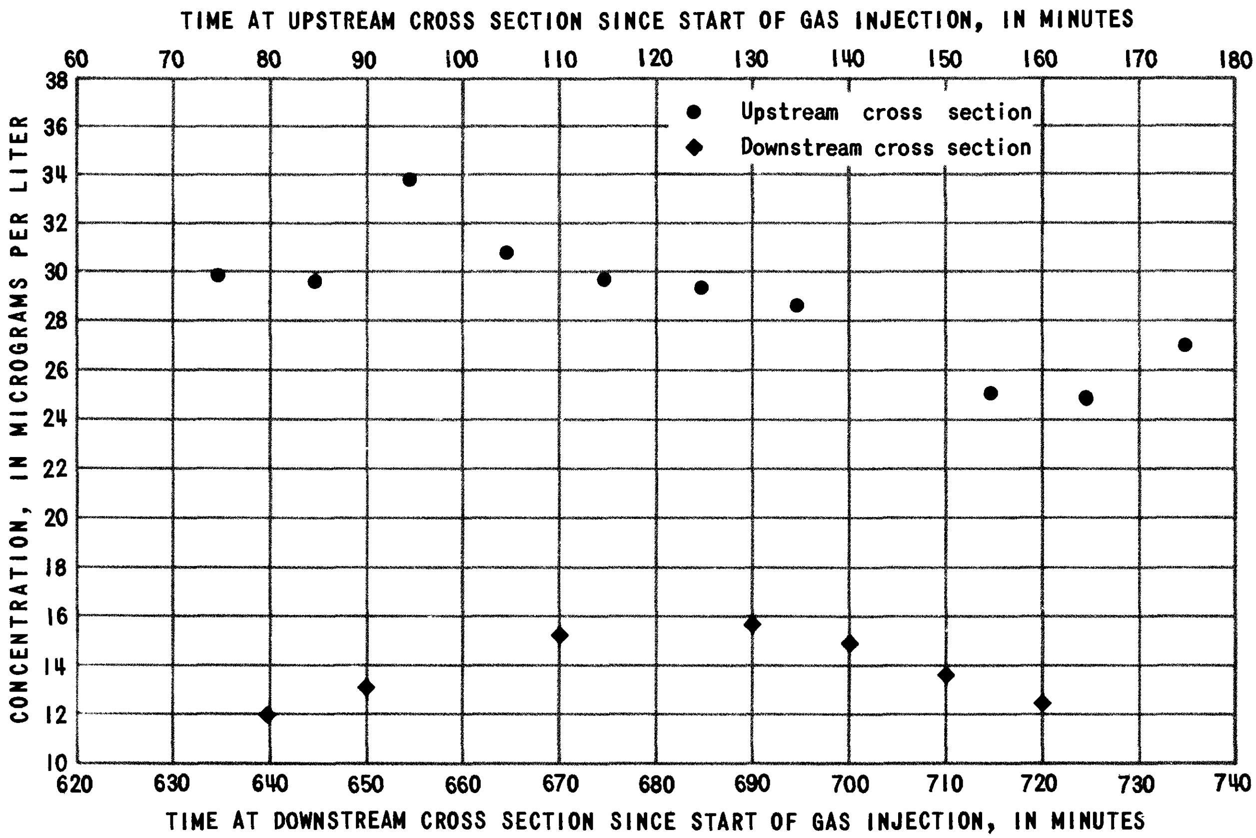


Figure 8.-- Concentration of ethylene as a function of time in the Wabash River near Terre Haute, upstream and downstream cross sections, October 20-21, 1981.

The dye T-C curve for the upstream cross section of the reach near Terre Haute during the August 1982 experiment shows scattered data about the plateau (fig. 9). The average concentration of dye on the plateau is 33.5 ± 1.0 μg/L (±3.0 percent) at the 95-percent confidence limit for the 24 samples collected between 110 and 225 minutes after the injection began. The theoretical, average concentration of dye on the plateau was 32.2 μg/L. This value is within 4 percent of the measured value. Dye concentrations of samples collected at multiple points in the cross section of the river were reasonably uniform laterally at the upstream cross section.

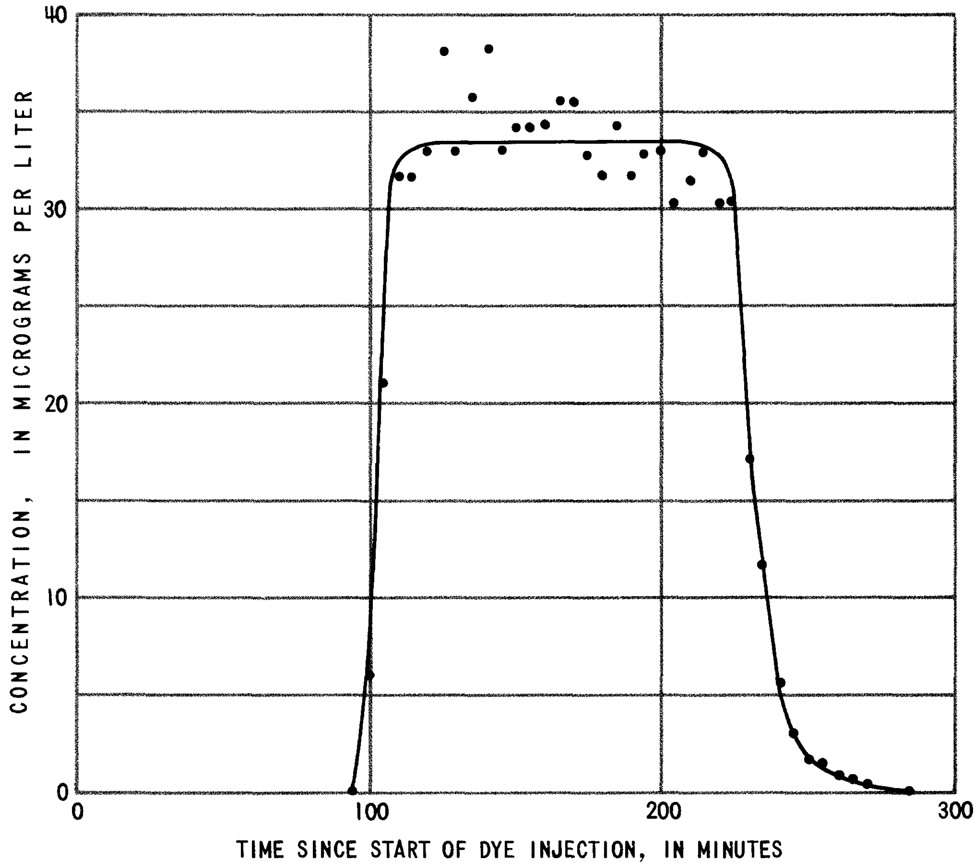


Figure 9.-- Dye time-concentration curve observed in the Wabash River near Terre Haute, upstream cross section, August 25, 1982.

The area of the upstream dye T-C curve drawn through the average concentration of dye on the plateau is 4,350 minutes-μg/L. The areas of the upstream dye T-C curve calculated for the upper and the lower 95-percent confidence limits of the average concentration of dye on the plateau is within 2.5 percent of the area based on the average value. The average time of the plateau at the upstream cross section was assumed to be the time at the middle of the theoretical square wave (170 minutes after the injection was begun). Error in the peak time is probably less than ±10 minutes, twice the sampling interval.

The dye T-C curve for the downstream cross section is smooth and reasonably well defined (fig. 10). The peak dye concentration at the downstream cross section was 14.9 μg/L and was observed at 990 minutes after the injection was started. Error in the peak concentration at this cross section is probably less than the ±2 percent analytical error because the peak is smooth and well defined. The area of the downstream dye T-C curve is 3,410 minutes-μg/L. The error in calculating the area should also be less than the ±2 percent analytical error in determining the dye concentrations. Samples were collected at 10 minute intervals at the downstream cross section, so that the error in the time of the peak dye concentration is probably less than ±10 minutes.

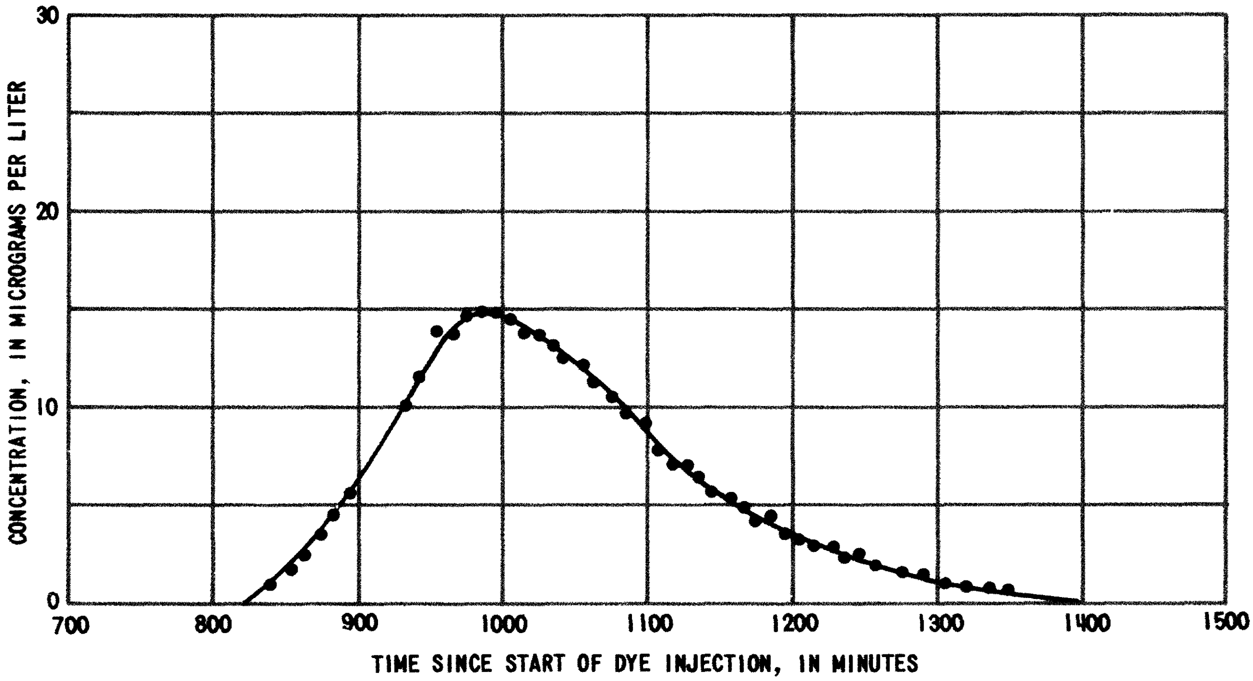


Figure 10.-- Dye time-concentration curve observed in the Wabash River near Terre Haute, downstream cross section, August 26, 1982.

The relation of ethylene concentration to time in the upstream and downstream cross sections of the Terre Haute reach in the August 1982 experiment is shown in figure 11. The plateau ethylene concentration at the upstream cross section was 25.2 ±2.3 μg/L (±9.1 percent) at the 95-percent confidence limit. This concentration is the average of 10 samples collected between 120 and 225 minutes after the injection was started. Samples collected at multiple points in the stream cross section indicated that gas concentrations were reasonably uniform across the cross section.

The peak ethylene concentration for the downstream cross section was 6.3 ±0.1 μg/L (±1.6 percent) at the 95-percent confidence limit. This concentration was estimated by fitting a surface-response function to the measured concentrations as previously discussed.

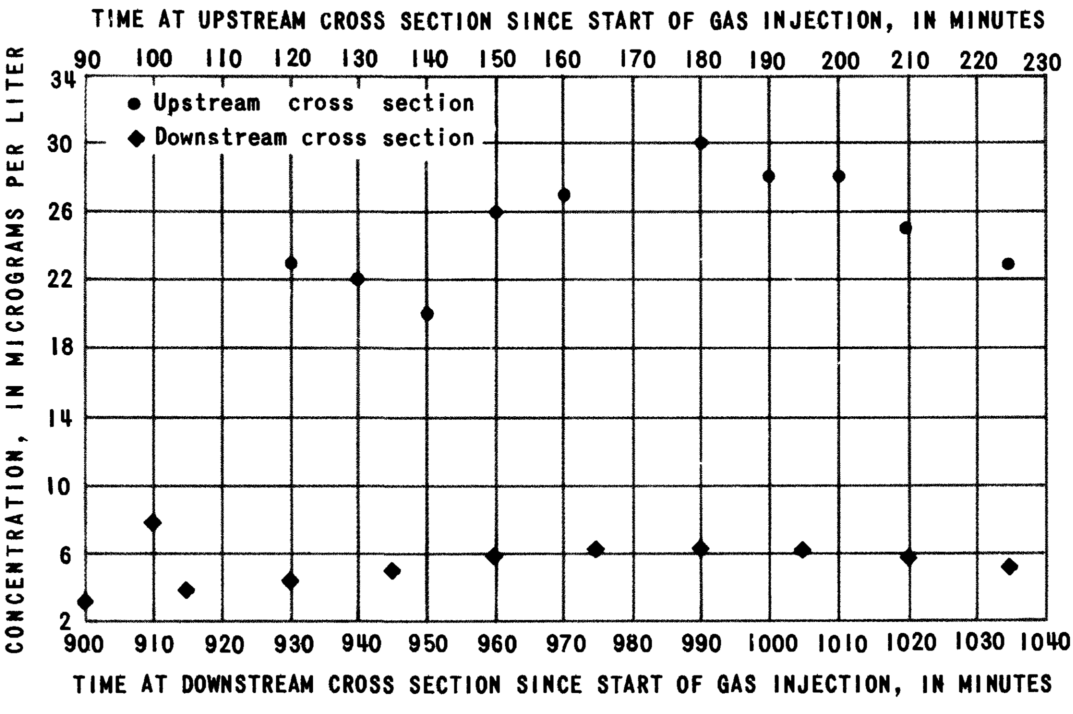


Figure 11.-- Concentration of ethylene as a function of time in the Wabash River near Terre Haute, upstream and downstream cross sections, August 25-26 1982.

Lafayette Reach

November 1981 Dye Tracer

The average concentrations of dye from the upstream cross section of the reach near Lafayette during the November 1981 (fig. 12) experiment show considerable scatter. Water samples collected at multiple points in the cross section indicated that the dye concentrations were not uniform across the upstream cross section. Flow-weighted average concentrations of dye for the cross section were estimated by the following procedure: average dye concentrations at the three sites sampled between 120 and 170 minutes after the dye injection began were assumed to be the average concentrations for sections extending from half the distance to the next sampling point or the bank on either side of the sampling point. The average dye concentration for each of the three sections was multiplied by the streamflow in that section. The three products were summed and divided by the total streamflow to yield the flow-weighted average concentration of dye.

The flow-weighted average concentration of dye for November 18, 1981, is

$$[(142.2\ \mu g/L)(555\ ft^3/s) + (64.3\ \mu g/L)(1{,}319\ ft^3/s) + (2.4\ \mu g/L)(1{,}596\ ft^3/s)] \div 3{,}470\ ft^3/s = 48.3\ \mu g/L.$$

The relation between depth and cumulative streamflow to width, and the location of sampling points used to determine flow-weighted average concentrations of dye are illustrated in figure 13.

The ratio of the flow-weighted average concentration of dye and the average dye concentration in the center section (48.3 µg/L ÷ 64.3 µg/L = 0.75) was used to convert the concentration of samples collected at the center section to a flow-weighted average concentration.

The average flow-weighted concentration of dye on the plateau at the upstream cross section, 47.9 ± 2.8 µg/L(±5.8 percent) at the 95-percent confidence level, is based on all data (22 samples) collected on the plateau (between 65 and 170 minutes after the dye injection began). The theoretical average concentration of dye for the plateau for this cross section is 50.5 µg/L; within about 5 percent of that calculated from field data. The area of the upstream dye T-C curve is 5,640 minutes-µg/L. The areas of the upstream dye T-C curve calculated with the upper and lower 95-percent confidence limits of the average flow-weighted concentration of dye is within ±5 percent of the area determined from the average plateau concentration.

The average time of the upstream plateau concentration of dye was assumed to be 120 minutes after the start of the injection (the center of the theoretical square wave). Error in the time is assumed to be less than ±20 minutes.

The dye T-C curve for the Lafayette reach downstream cross section was less scattered than that at the upstream cross section (fig. 14). This lesser degree of scatter is a result of longitudinal dispersion and good mixing as the dye cloud traveled through the reach. The downstream peak concentration of dye was

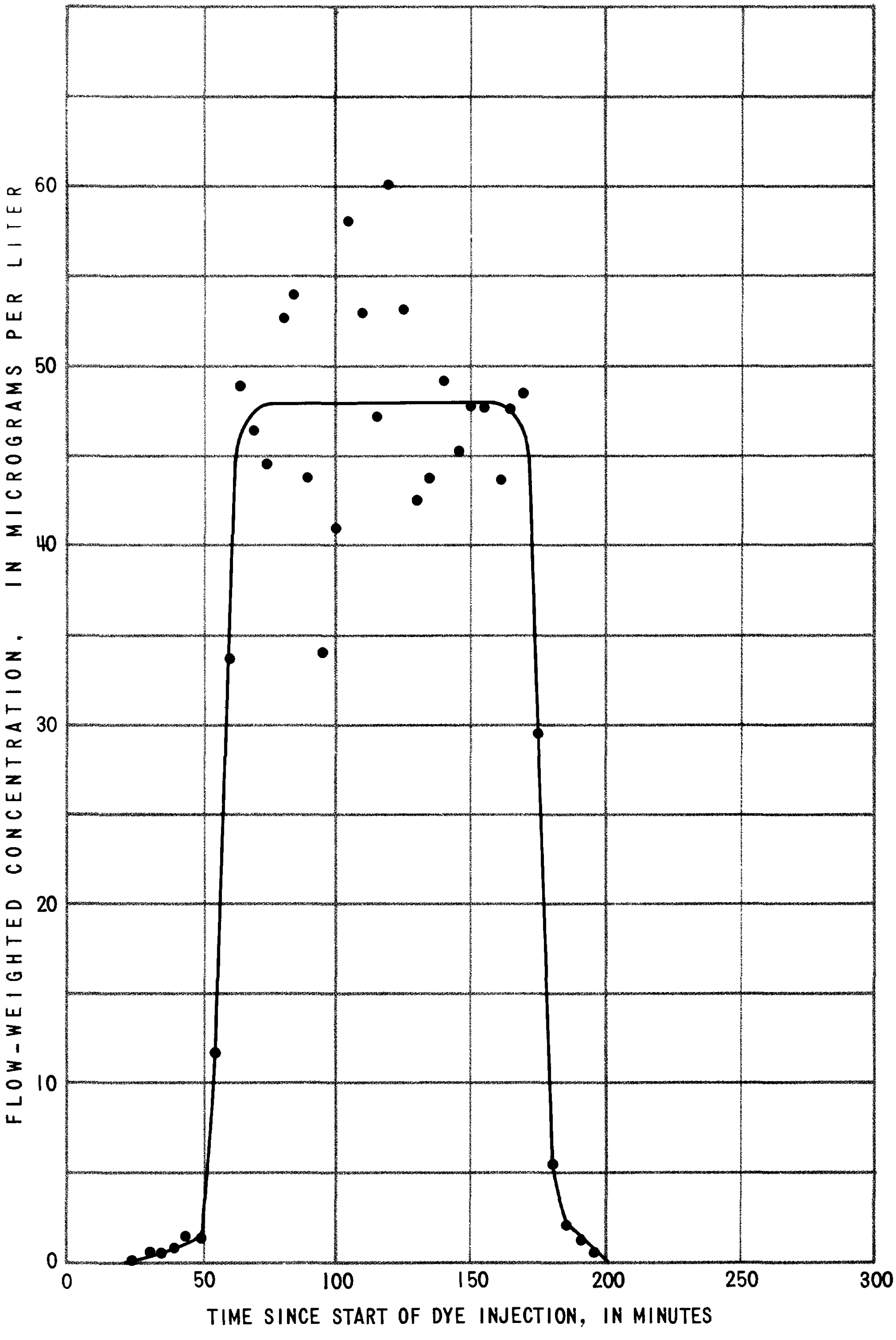


Figure 12.-- Flow-weighted dye time-concentration curve for the Wabash River near Lafayette, upstream cross section, November 18, 1981.

25.6 µg/L and occurred 970 minutes after the start of the injection. The area of the downstream dye T-C curve is 5,550 minutes-µg/L. Error in calculating the dye T-C curve area and the peak dye concentration is probably less than ±2 percent--the measurement error in determining the dye concentrations. The error in the time of the peak at the downstream cross section (970 minutes after the injection was started) is probably less than ±10 minutes.

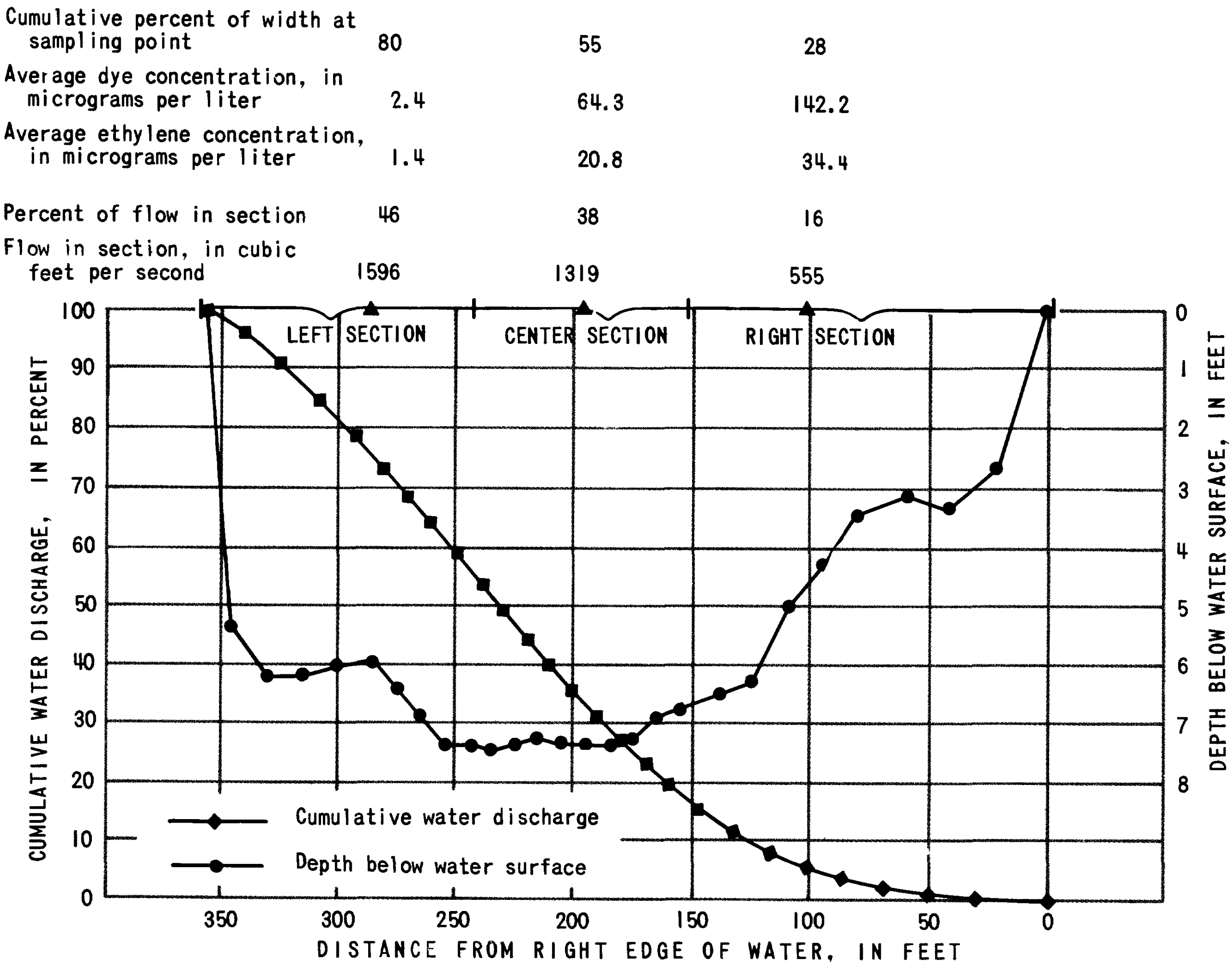


Figure 13.-- Depth and cumulative discharge to width curves used to determine flow-weighted average concentration of dye for the Wabash River near Lafayette, upstream cross section, November 18, 1981.

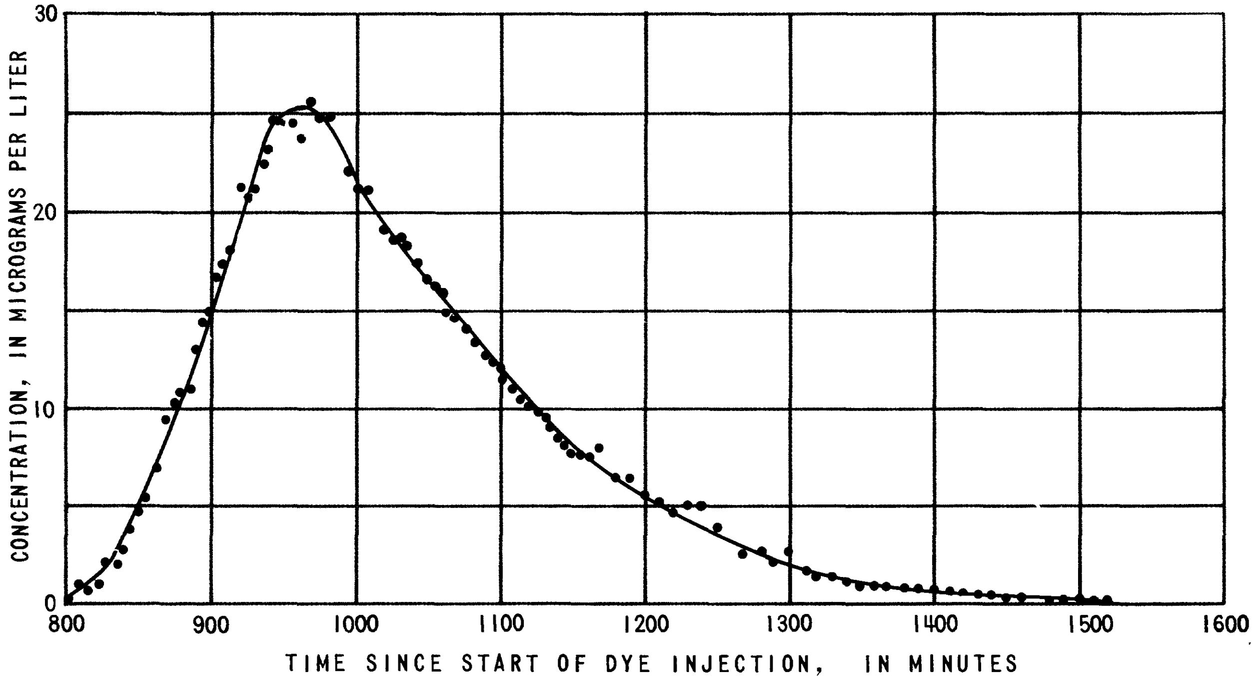


Figure 14.-- Dye time-concentration curve observed in the Wabash River near Lafayette, downstream cross section, November 19, 1981.

November 1981 Ethylene-Gas Tracer

The relation of ethylene concentration to time in the upstream and downstream cross sections of the Lafayette reach in the November 1981 experiment is shown in figure 15. The concentrations of ethylene in the plateau at the upstream cross section showed much less scatter than the corresponding dye concentrations. However, gas concentrations were not uniform across the cross section. Flow-weighted ethylene concentrations were calculated by the same procedure used for the dye. The ratio of the average flow-weighted ethylene concentration and the average ethylene concentration at the center section was 0.68. This ratio was used to estimate the flow-weighted ethylene concentrations from samples collected at the center section. The flow-weighted average plateau concentration of ethylene at the upstream cross section of the Lafayette reach, 13.8 ±1.4 μg/L (±10.1 percent) at the 95-percent confidence limit, was based on 10 samples collected between 60 and 160 minutes after the injection began.

The peak ethylene concentration at the downstream cross section was 5.4 ±0.1 μg/L (±1.9 percent). This concentration was obtained by fitting a surface response function to the measured concentrations. The ethylene concentrations of samples collected along the cross section were not uniform at this site.

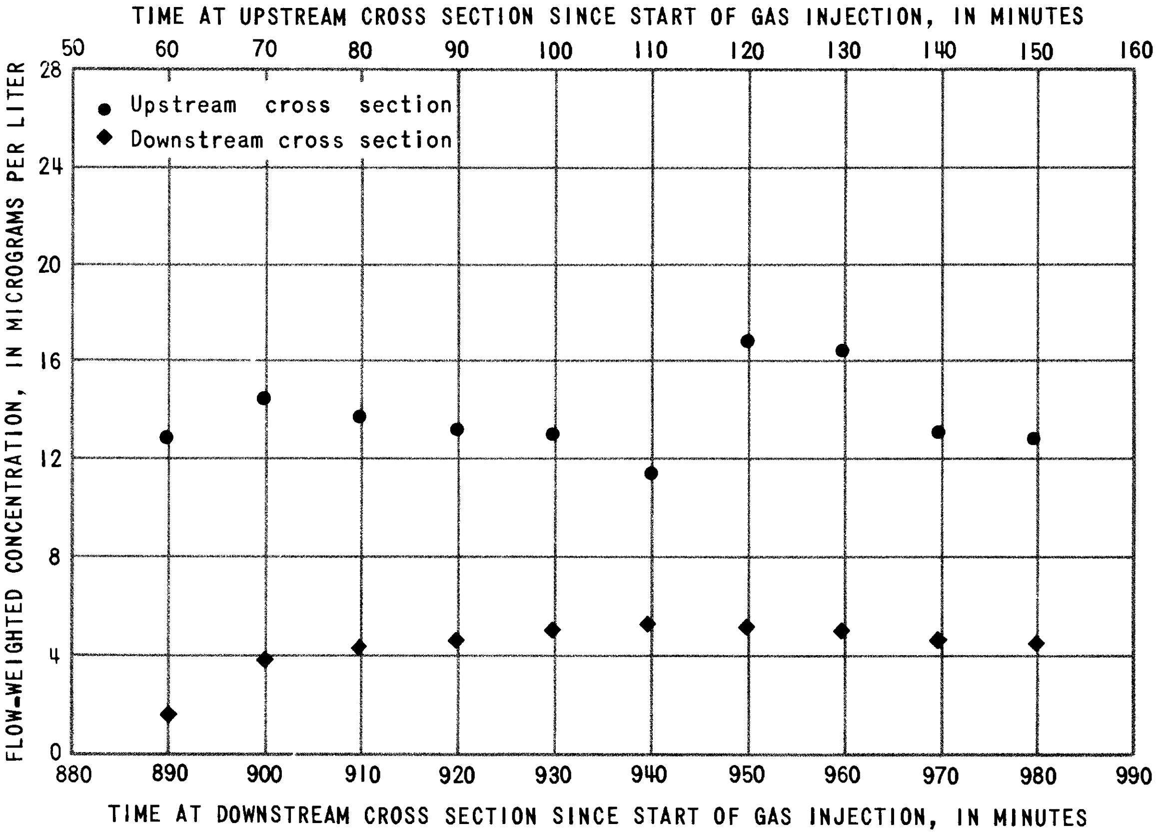


Figure 15.-- Flow-weighted concentration of ethylene as a function of time in the Wabash River near Lafayette, upstream and downstream cross sections, November 18-19, 1981.

The ratio of the flow-weighted average concentration and the average concentration at the center section was 1.0. Consequently, no correction was needed to adjust gas concentrations at the center section to the flow-weighted average concentrations.

July 1982 Dye Tracer

The average concentrations of dye from the upstream cross section in the reach near Lafayette during the July 1982 experiment also showed considerable scatter (fig. 16). Samples collected at multiple points in the channel during this experiment indicated that dye concentrations were not uniform across the cross section. Flow-weighted average concentrations of dye for this experiment were calculated by the procedure described for the November 1981 Lafayette reach experiment. The ratio of the flow-weighted average concentrations of dye and the average dye concentration of the center section (1.14) was calculated from data collected between 80 and 180 minutes after the injection was begun.

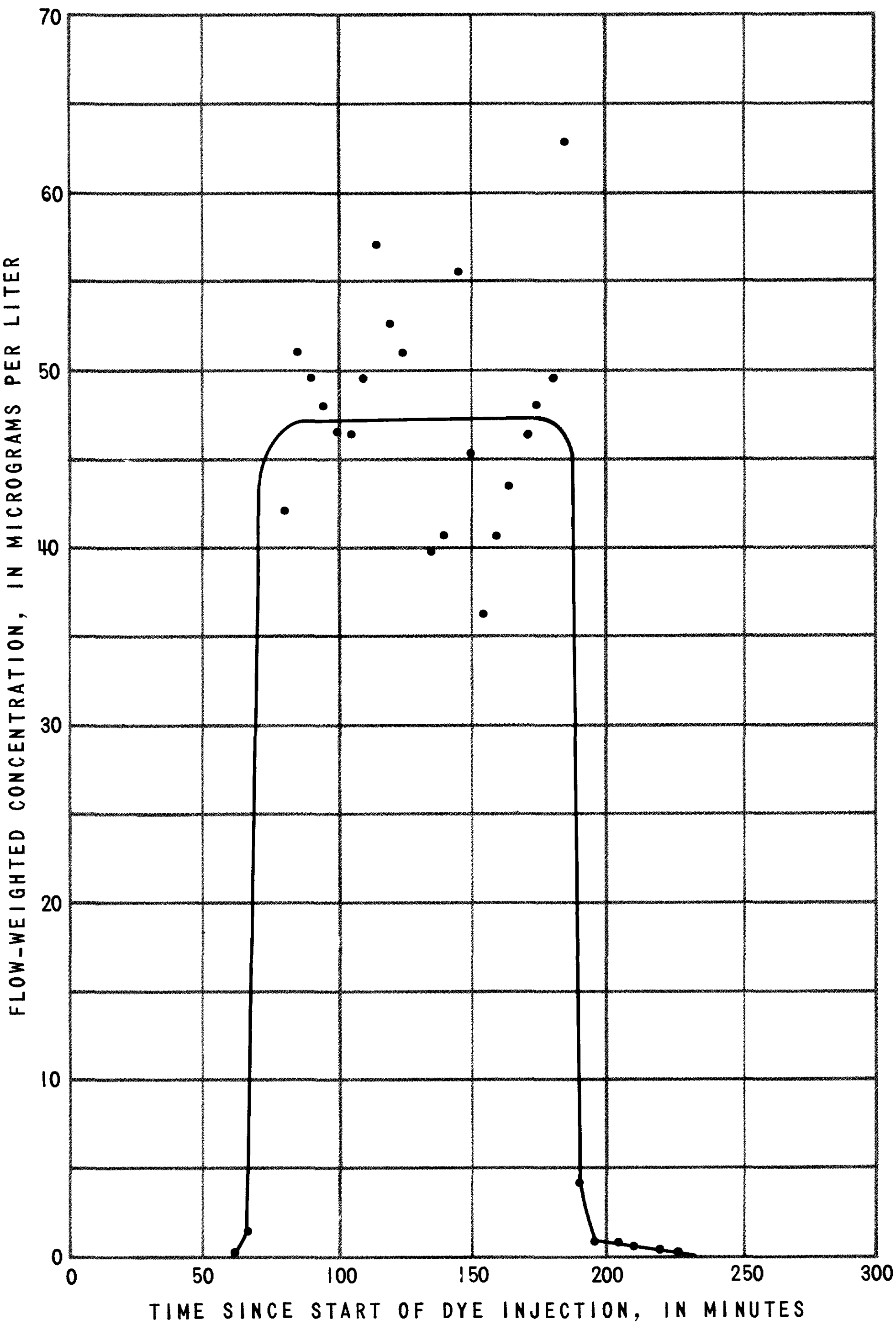


Figure 16.-- Flow-weighted dye time-concentration curve for the Wabash River near Lafayette, upstream cross section, July 26, 1982.

The average flow-weighted concentration of dye on the plateau at the upstream cross section was 47.3 ± 2.9 µg/L (±6.1 percent). This number was calculated from 22 samples collected between 70 and 185 minutes after the injection started. The theoretical average concentration of dye on the plateau at the upstream cross section is 48.3 µg/L. This value is within 3 percent of the value calculated from field data. The area of the dye time-concentration curve drawn through the average plateau concentration was 5,830 minutes-µg/L. The area of the upstream dye time-concentration curve drawn through the upper and lower 95-percent confidence limits is within ±6 percent of the area determined with the average plateau concentration.

The average time of the plateau dye concentration at the upstream cross section was assumed to be at the center of the theoretical square wave (130 minutes after the injection was started). The error in this time should be less than ±10 minutes, twice the sampling interval.

The dye T-C curve at the downstream cross section from the July 1982 measurement was well defined with minor scatter of the data (fig. 17). The peak dye concentration was 18.4 ±0.3 µg/L (±1.6 percent) at the 95 percent confidence limit and occured 1,115 minutes after the injection was started. Because of the scatter, this concentration and its confidence limits were estimated from a surface-response function fit to all data points collected between 1,050 and 1,145 minutes after the injection was started. The area of the dye T-C curve was 5,550 minute-µg/L. Error in the calculation of the curve area is probably

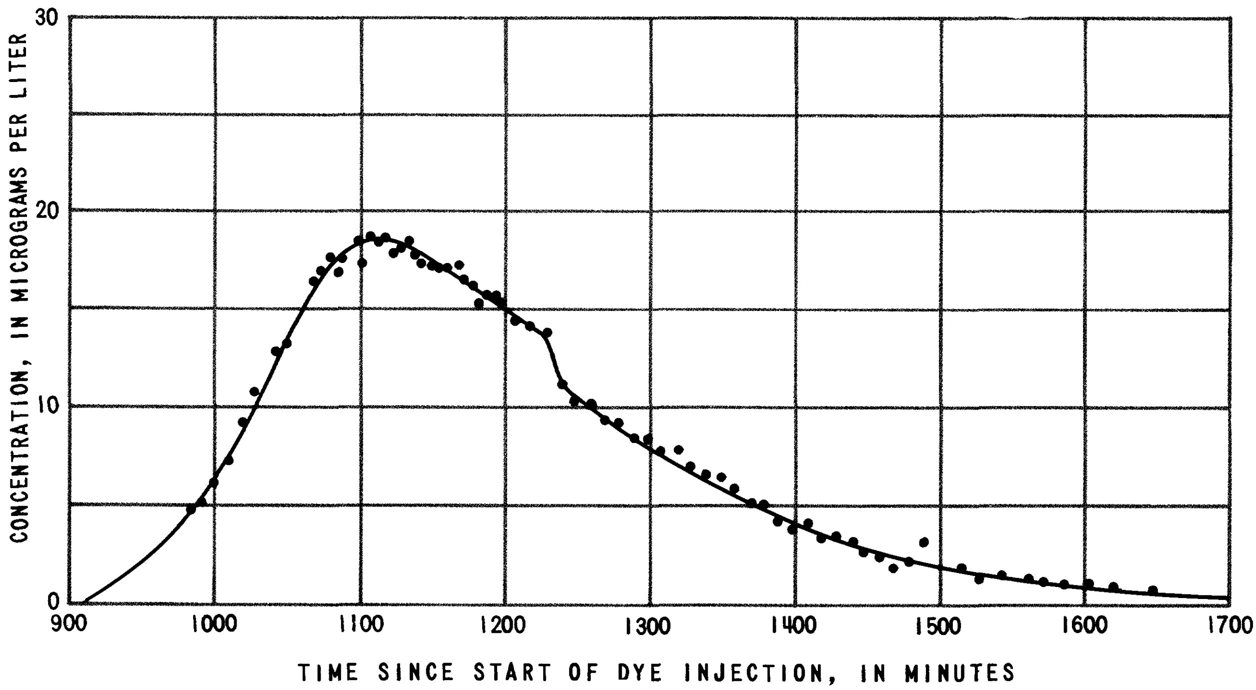


Figure 17.-- Dye time-concentration curve observed in the Wabash River near Lafayette, downstream cross section, July 27, 1982.

less than ±2 percent, the measurement error in determining the dye concentrations. Samples were collected at 5 minute intervals; thus the error in the time of the peak is probably less than ±5 minutes.

July 1982 Ethylene-Gas Tracer

The relation of the ethylene concentrations to time in the upstream and downstream cross sections of the Lafayette reach in the July 1982 experiment is shown in figure 18. The upstream plateau concentrations of ethylene also show scatter. Ethylene concentrations were also not uniform across this cross section. Flow-weighted average concentrations of ethylene were calculated as described previously. The ratio used to estimate flow-weighted concentrations from ethylene concentrations at the center section was 1.07. The flow-weighted average plateau concentration of ethylene at the Lafayette reach upstream cross section was 18.4 ±2.4 μg/L (±13 percent) at the 95-percent confidence limit. The concentration was calculated from 10 samples collected between 68 and 168 minutes after the injection was started.

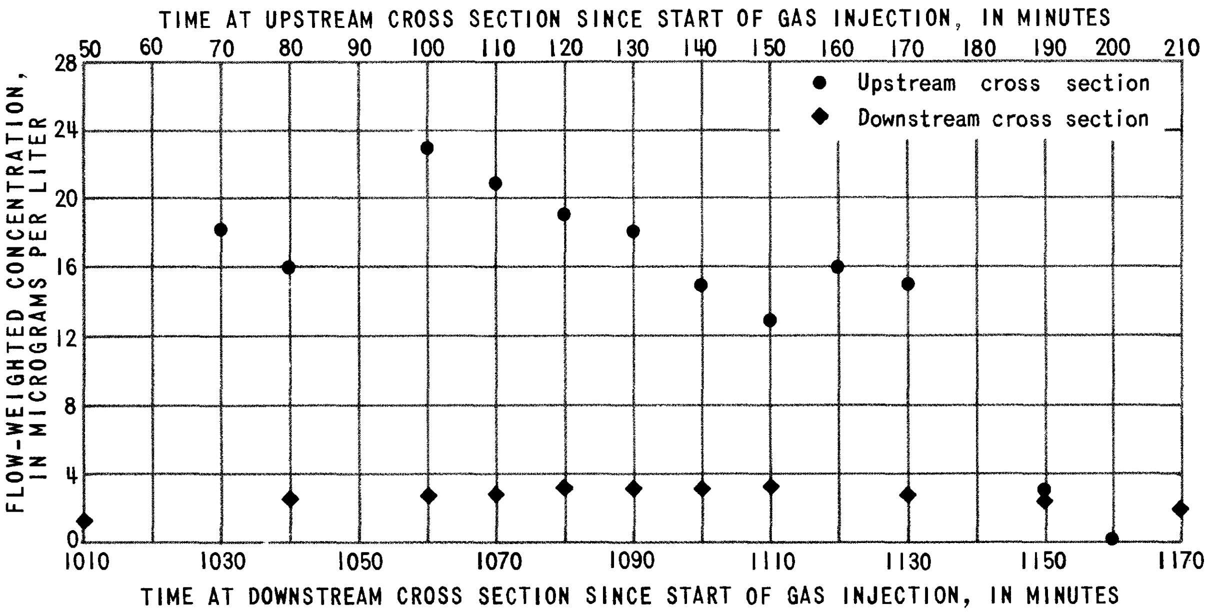


Figure 18.-- Flow-weighted concentration of ethylene as a function of time in the Wabash River near Lafayette, upstream and downstream cross sections, July 26-27, 1982.

The ethylene peak at the downstream cross section was not as well defined as that observed during the other measurements. A peak concentration of 3.2 μg/L ±0.2 (±6 percent) at the 95 percent confidence limit was obtained by fitting a surface-response function to the measured concentrations.

Samples taken at multiple points in the cross section show that ethylene concentrations were not uniform across the downstream cross section. However, the ratio of the flow-weighted ethylene concentrations to the ethylene concentration at the center of width was 1.0.

DYE-LOSS CORRECTION FACTORS

Sensitivity analyses of measurement errors in streamflow and the area of the dye time-concentration curves on the computed dye-loss correction factors (DCF) for the Terre Haute and Lafayette reaches are presented in tables 19-22.

The best estimates of the DCF for the Terre Haute reach are 1.21 and 1.18 for October 1981 and August 1982 respectively. This means that 83 to 85 percent of the rhodamine WT measured at the upstream cross section was also measured at the downstream cross section. The reason for the loss of dye between the sampling cross sections in the reach near Terre Haute is not known. The best estimates of the DCF for the Lafayette reach for the November 1981 and July 1982 measurements are 1.02 and 1.04 (96 to 98 percent recovery). The DCF's could deviate by about ±6 percent if any one of the variables in equation 3 deviated by its maximum probable error. The DCF's could deviate by 10 to 20 percent if errors in the measurements combined to form a maximum or minimum extreme case. Neither the minimum nor the maximum extreme case is likely because of the improbability that all errors would deviate in the direction and the magnitude required for the extreme case. The DCF's were estimated by equation 3. Error estimates of the DCF's were calculated by substituting all possible combinations of the minimum and maximum confidence limits for the individual variables in equation 3.

Table 19.--Effect of errors in measurement of streamflow and the area of the dye time-concentration curve on the computed dye-correction factor, Wabash River near Terre Haute, October 20-21, 1981

[Q_U, streamflow at upstream cross section; Q_D, streamflow at downstream cross section; A_U, area of upstream dye T-C curve; A_D, area of downstream dye curve; DCF, dye T-C correction factor]

Change from best estimate of variables	Q_U (ft^3/s)	Q_D (ft^3/s)	A_U (minutes-μg/L)	A_D (minutes-μg/L)	DCF	Change (percent)
None	7,270	7,520	6,040	4,820	1.21	----
A_U + 5 percent	7,270	7,520	6,340	4,820	1.27	5.0
A_U - 5 percent	7,270	7,520	5,740	4,820	1.15	-4.9
A_D + 5 percent	7,270	7,520	6,040	5,060	1.15	-4.7
A_D - 5 percent	7,270	7,520	6,040	4,580	1.28	5.3
Q_U + 5 percent	7,634	7,520	6,040	4,820	1.27	5.0
Q_U - 5 percent	6,907	7,520	6,040	4,820	1.15	-5.0
Q_D + 5 percent	7,270	7,896	6,040	4,820	1.15	-4.7
Q_D - 5 percent	7,270	7,144	6,040	4,820	1.28	5.3
Maximum extreme case	7,634	7,144	6,340	4,580	1.48	22.1
Minimum extreme case	6,907	7,896	5,740	5,060	[1].97	-18.1

[1]A factor less than 1.0 is not theoretically possible because it indicates a larger mass of dye downstream than upstream. If the dye was uniformly mixed at both cross sections, the minimum extreme case could never be less than 1.0.

Table 20.--Effect of errors in measurement of streamflow and the area of the dye time-concentration curve on the computed-dye correction factor, Wabash River near Terre Haute, August 25-26, 1982

[Q_U, streamflow at upstream cross section; Q_D, streamflow at downstream cross section; A_U, area of upstream dye T-C curve; A_D, area of downstream dye T-C curve; DCF, Dye correction factor]

Change from best estimate of variables	Q_U (ft^3/s)	Q_D (ft^3/s)	A_U (minutes-μg/L)	A_D (minutes-μg/L)	DCF	Change (percent)
None	3,230	3,480	4,350	3,410	1.18	----
A_U + 2.5 percent	3,230	3,480	4,459	3,410	1.21	2.5
A_U - 2.5 percent	3,230	3,480	4,241	3,410	1.15	-2.5
A_D + 2 percent	3,230	3,480	4,350	3,481	1.16	-1.7
A_D - 2 percent	3,230	3,480	4,350	3,344	1.21	2.5
Q_U + 5 percent	3,392	3,480	4,350	3,410	1.24	5.1
Q_U - 5 percent	3,069	3,480	4,350	3,410	1.13	-4.2
Q_D + 5 percent	3,230	3,654	4,350	3,410	1.13	-4.2
Q_D - 5 percent	3,230	3,306	4,350	3,410	1.25	5.9
Maximum extreme case	3,392	3,306	4,459	3,344	1.37	16.1
Minimum extreme case	3,069	3,654	4,241	3,481	1.02	-13.6

Table 21.--Effect of errors in measurement of streamflow and the area of the dye time-concentration curve on the computed dye-correction factor, Wabash River near Lafayette, November 18-19, 1981

[Q_U, streamflow at upstream cross section; Q_D, streamflow at downstream cross section; A_U, area of upstream dye T-C curve; A_D, area of downstream dye T-C curve; DCF, dye correction factor]

Change from best estimate of variables	Q_U (ft^3/s)	Q_D (ft^3/s)	A_U (minutes-µg/L)	A_D (minutes-µg/L)	DCF	Change (percent)
None	([1])	([1])	5,640	5,550	1.02	----
A_U + 5 percent	([1])	([1])	5,922	5,550	1.07	5.0
A_U - 5 percent	([1])	([1])	5,358	5,550	[2]0.97	-5.0
A_D + 2 percent	([1])	([1])	5,640	5,661	[2]1.00	-2.0
A_D - 2 percent	([1])	([1])	5,640	5,439	1.04	2.0
Q_U - 5 percent	3,297	3,360	5,640	5,550	[2]1.00	-1.9
Q_D + 5 percent	3,470	3,528	5,640	5,550	1.00	-1.6
Maximum extreme case	([1])	([1])	5,922	5,439	1.09	7.2
Minimum extreme case	,297	3,528	5,358	5,661	[2]0.89	-12.9

[1]Discharge ratio is not appropriate when the river is losing water. Dye mixed with water will be removed at a rate proportional to that of the water loss. In this case, the DCF is simply A_U/A_D.

[2]A factor less than 1.0 is not theoretically possible because it indicates a larger mass of dye downstream than upstream. If the dye was uniformly mixed at both cross sections, the minimum extreme case could never be less than 1.0.

Table 22.--Effect of errors in measurement of streamflow and the area of the dye time-concentration curve on the computed dye-correction factor, Wabash River near Lafayette, July 26-27, 1982

[Q_U, streamflow at upstream cross section; Q_D, streamflow at downstream cross section; A_U, area of upstream dye T-C curve; A_D, area of downstream dye T-C curve; DCF, dye correction factor]

Change from best estimate of variables	Q_U (ft³/s)	Q_D (ft³/s)	A_U (minutes-µg/L)	A_D (minutes-µg/L)	DCF	Change (percent)
None	2,290	2,320	5,830	5,550	1.04	----
A_U + 6 percent	2,290	2,320	6,170	5,550	1.10	5.8
A_U - 6 percent	2,290	2,320	5,495	5,550	[1]0.98	-5.8
A_D + 2 percent	2,290	2,320	5,830	5,662	1.02	-1.9
A_D - 2 percent	2,290	2,320	5,830	5,440	1.06	1.9
Q_U + 5 percent	2,405	2,320	5,830	5,550	1.09	4.8
Q_U - 5 percent	2,175	2,320	5,830	5,550	[1]0.98	-5.8
Q_D + 5 percent	2,290	2,436	5,830	5,550	[1]0.99	-4.8
Q_D - 5 percent	2,290	2,204	5,830	5,550	1.09	4.8
Maximum extreme case	2,405	2,204	6,170	5,440	1.24	19.2
Minimum extreme case	2,175	2,436	5,495	5,662	[1]0.87	-16.3

[1]A factor less than 1.0 is not theoretically possible because it indicates a larger mass of dye downstream than upstream. If the dye was uniformly mixed at both cross sections, the minimum extreme case could never be less than 1.0.

ETHYLENE-GAS-TRANSFER COEFFICIENTS

The effects of measurement errors in the rhodamine-WT dye and ethylene concentrations, the dye-loss correction factor, and the time of travel on the ethylene gas-transfer coefficient computed for the Terre Haute and Lafayette reaches are presented in tables 23-26. The number of significant figures retained for the coefficients in the tables does not reflect the accuracy of the calculation. Rather, they are retained to minimize round-off error in converting the ethylene gas-transfer coefficient to the oxygen gas-transfer coefficient.

If any one of the variables used in equation 1 deviates by its maximum probable error, the ethylene gas-transfer coefficients differ by ±5 to 20 percent. If errors in the measurements combine to form an extreme case, the ethylene gas-transfer coefficient could differ from the best estimate by ±40 to 100 percent in the Terre Haute reach and ±50 to 75 percent in the Lafayette reach. However, as with the dye-correction factor, neither a maximum nor a minimum extreme case is likely.

Table 23.--Effect of errors in measurement of the dye and ethylene concentrations, the dye-correction factor and the time of travel on the computed ethylene-gas transfer coefficient (K_E) for the Wabash River near Terre Haute, October 20-21, 1981

[E_U, plateau ethylene concentration at the upstream cross section; D_U, plateau dye concentration at the upstream cross section; E_D, peak ethylene concentration at the downstream cross section; D_D, peak dye concentration at the downstream cross section; DCF; dye-correction factor; T_U, time of the upstream dye peak; T_D, time of the downstream dye peak; T_D-T_U, average time of travel through reach; K_E, ethylene gas transfer coefficient]

Change from best estimate of variables	E_U (µg/L)	D_U (µg/L)	E_D (µg/L)	D_D (µg/L)	DCF	(T_D-T_U) (min)	K_E ($x10^{-4}$/min)	Change (percent)
None	28.8	43.7	15.9	27.8	1.21	555	5.989	-----
E_U + 7 percent[1]	30.7	43.7	15.9	27.8	1.21	555	7.140	19.2
E_U - 7 percent[2]	26.9	43.7	15.9	27.8	1.21	555	4.759	-20.5
D_U + 5 percent	28.8	45.9	15.9	27.8	1.21	555	5.104	-14.8
D_U - 5 percent	28.8	41.5	15.9	27.8	1.21	555	6.919	15.5
E_D - 2 percent	28.8	43.7	16.2	27.8	1.21	555	5.652	-5.6
E_D - 2 percent	28.8	43.7	15.6	27.8	1.21	555	6.332	5.7
D_D + 2 percent	28.8	43.7	15.9	28.4	1.21	555	6.373	6.4
D_D - 2 percent	28.8	43.7	15.9	27.2	1.21	555	5.595	-6.6
DCF + 5 percent	28.8	43.7	15.9	27.8	1.27	555	6.889	15.0
DCF - 5 percent	28.8	43.7	15.9	27.8	1.15	555	5.072	-15.3
Maximum extreme DCF	28.8	43.7	15.9	27.8	1.48	555	9.618	60.6
Minimum extreme DCF	28.8	43.7	15.9	27.8	1.00	555	2.554	-57.4
T_U-20 min T_D+10 min	28.8	43.7	15.9	27.8	1.21	585	5.681	-5.1
T_U+20 min T_D-10 min	28.8	43.7	15.9	27.8	1.21	525	6.331	5.7
Maximum extreme condition	30.7	41.5	15.6	28.4	1.48	525	13.138	119
Minimum extreme condition	26.9	45.9	16.2	27.2	1.00	585	[3]-.0258	-100

[1]Used in maximum probable condition calculation.
[2]Used in minimum probable condition calculation.
[3]A negative value of the ethylene gas transfer rate is not realistically possible, therefore the lower limit is zero.

Table 24.--Effect of errors in measurement of the dye and ethylene concentration, the dye-correction factor and the time of travel on the computed ethylene-gas transfer coefficient (K_E) for the Wabash River near Terre Haute, August 25-26, 1982

[E_U, plateau ethylene concentration at the upstream cross section; D_U, plateau dye concentration at the upstream cross section; E_D, peak ethylene concentration at the downstream cross section; D_D, peak dye concentration at the downstream cross section; DCF; dye-correction factor; T_U, time of the upstream dye peak; T_D, time of the downstream dye peak; T_D-T_U, average time of travel through reach; K_E, ethylene gas transfer coefficient]

Change from best estimate of variables	E_U (μg/L)	D_U (μg/L)	E_D (μg/L)	D_D (μg/L)	DCF	(T_D-T_U) (min)	K_E ($\times 10^{-4}$/min)	Change (percent)
None	25.2	33.5	6.3	14.9	1.18	820	9.044	-----
E_U + 9.1 percent[1]	27.5	33.5	6.3	14.9	1.18	820	10.109	11.8
E_U - 9.1 percent[2]	22.9	33.5	6.3	14.9	1.18	820	7.877	-12.9
D_U + 3 percent	25.2	34.5	6.3	14.9	1.18	820	8.685	-4.0
D_U - 3 percent	25.2	32.5	6.3	14.9	1.18	820	9.414	4.1
E_D - 2 percent	25.2	33.5	6.4	14.9	1.18	820	8.852	-2.1
E_D - 2 percent	25.2	33.5	6.2	14.9	1.18	820	9.239	2.2
D_D + 2 percent	25.2	33.5	6.3	15.2	1.18	820	9.287	2.7
D_D - 2 percent	25.2	33.5	6.3	14.6	1.18	820	8.796	-2.7
DCF + 6 percent	25.2	33.5	6.3	14.9	1.25	820	9.747	7.8
DCF - 4 percent	25.2	33.5	6.3	14.9	1.13	820	8.516	-5.8
Maximum extreme DCF	25.2	33.5	6.3	14.9	1.37	820	10.865	20.1
Minimum extreme DCF	25.2	33.5	6.3	14.9	1.02	820	7.267	-19.7
T_U-20 min T_D+10 min	25.2	33.5	6.3	14.9	1.18	840	8.829	-2.4
T_U+20 min T_D-10 min	25.2	33.5	6.3	14.9	1.18	800	9.270	2.5
Maximum extreme condition	27.5	32.5	6.3	15.2	1.37	800	12.856	42.1
Minimum extreme condition	22.9	34.5	6.4	14.6	1.02	840	5.175	-42.8

[1]Used in maximum probable condition calculation.
[2]Used in minimum probable condition calculation.

Table 25.--Effect of errors in measurement of the dye and ethylene concentrations, the dye-correction factor, and the time of travel on the computed ethylene-gas transfer coefficient (K_E) for the Wabash River near Lafayette, November 18-19, 1981

[E_U, plateau ethylene concentration at the upstream cross section; D_U, plateau dye concentration at the upstream cross section; E_D, peak ethylene concentration at the downstream cross section; D_D, peak dye concentration at the downstream cross section; DCF; dye- correction factor; T_U, time of the upstream dye peak; T_D, time of the downstream dye peak; T_D-T_U, average time of travel through reach; K_E, ethylene gas transfer coefficient]

Change from best estimate of variables	E_U (µg/L)	D_U (µg/L)	E_D (µg/L)	D_D (µg/L)	DCF	(T_D-T_U) (min)	K_E ($\times 10^{-4}$/min)	Change (percent)
None	13.8	47.9	5.4	25.6	1.02	850	3.901	-----
E_U + 10 percent[1]	15.2	47.9	5.4	25.6	1.02	850	5.037	29.1
E_U - 10 percent[2]	12.4	47.9	5.4	25.6	1.02	850	2.642	-32.3
D_U + 6 percent	13.8	50.7	5.4	25.6	1.02	850	3.232	-17.2
D_U - 6 percent	13.8	45.1	5.4	25.6	1.02	850	4.609	18.2
E_D + 2 percent	13.8	47.9	5.5	25.6	1.02	850	3.685	-5.5
E_D - 2 percent	13.8	47.9	5.3	25.6	1.02	850	4.120	5.6
D_D + 2 percent	13.8	47.9	5.4	26.1	1.02	850	4.128	5.8
D_D - 2 percent	13.8	47.9	5.4	25.1	1.02	850	3.669	-5.9
DCF + 5 percent	13.8	47.9	5.4	25.6	1.07	850	4.464	14.4
Maximum extreme DCF	13.8	47.9	5.4	25.6	1.09	850	4.681	20.0
Minimum extreme DCF	13.8	47.9	5.4	25.6	1.00	850	3.668	-4.8
T_U-20 min T_D+10 min	13.8	47.9	5.4	25.6	1.02	880	3.768	-3.4
T_U+20 min T_D-10 min	13.8	47.9	5.4	25.6	1.02	820	4.043	3.6
Maximum extreme condition	15.2	46.9	5.3	26.1	1.09	820	6.752	73.1
Minimum extreme condition	12.4	50.8	5.5	25.1	1.00	880	1.226	-68.6

[1]Used in maximum probable condition calculation.
[2]Used in minimum probable condition calculation.

Table 26.--Effect of errors in measurement of the dye and ethylene concentrations, the dye-correction factor, and the time of travel on the computed ethylene-gas transfer coefficient (K_E) for the Wabash River near Lafayette, July 26-27, 1982

[E_U, plateau ethylene concentration at the upstream cross section; D_U, plateau dye concentration at the upstream cross section; E_D, peak ethylene concentration at the downstream cross section; D_D, peak dye concentration at the downstream cross section; DCF; dye-correction factor; T_U, time of the upstream dye peak; T_D, time of the downstream dye peak; T_D-T_U, average time of travel through reach; K_E, ethylene gas transfer coefficient]

Change from best estimate of variables	E_U (μg/L)	D_U (μg/L)	E_D (μg/L)	D_D (μg/L)	DCF	(T_D-T_U) (min)	K_E ($\times 10^{-4}$/min)	Change (percent)
None	18.4	47.3	3.2	18.4	1.04	985	8.571	-----
E_U + 13 percent[1]	20.8	47.3	3.2	18.4	1.04	985	9.816	14.5
E_U - 13 percent[2]	16.0	47.3	3.2	18.4	1.04	985	7.152	-16.6
D_U + 6.1 percent	18.4	50.2	3.2	18.4	1.04	985	7.967	-7.0
D_U - 6.1 percent	18.4	44.4	3.2	18.4	1.04	985	9.214	7.5
E_D + 6.3 percent	18.4	47.3	3.4	18.4	1.04	985	7.956	-7.2
E_D - 6.3 percent	18.4	47.3	3.0	18.4	1.04	985	9.226	7.6
D_D + 2 percent	18.4	47.3	3.2	18.7	1.04	985	8.735	1.9
D_D - 2 percent	18.4	47.3	3.2	18.1	1.04	985	8.404	-1.9
DCF + 6 percent	18.4	47.3	3.2	18.4	1.10	985	9.141	6.6
DCF - 4 percent	18.4	47.3	3.2	18.4	1.00	985	8.173	-4.6
Maximum extreme DCF	18.4	47.3	3.2	18.4	1.24	985	10.357	20.8
Minimum extreme DCF	18.4	47.3	3.2	18.4	1.00	985	8.173	-4.6
T_U-10 min T_D+5 min	18.4	47.3	3.2	18.4	1.04	1000	8.443	-1.5
T_U+10 min T_D-5 min	18.4	47.3	3.2	18.4	1.04	970	8.704	1.5
Maximum extreme condition	20.8	44.4	3.0	18.7	1.24	970	13.265	54.8
Minimum extreme condition	16.0	50.2	3.4	18.1	1.00	1000	5.287	-38.3

[1]Used maximum probable condition calculation.
[2]Used minimum probable condition calculation.

REAERATION-RATE COEFFICIENTS

The reaeration-rate (oxygen gas-transfer) coefficients for the Terre Haute and Lafayette reaches are presented in table 27. The ethylene gas-transfer coefficients were converted to the oxygen gas-transfer coefficient by multiplying them by the coefficient ratio for oxygen and ethylene. This ratio, 1.15 ±0.0226 (±2.0 percent) at the 95-percent confidence limit, was experimentally determined by Rathbun and others (1978). For comparison between coefficients determined at different stream temperatures, the reaeration-rate coefficients were adjusted to a common temperature (20° C). The temperature adjustment was done by the following equation (Elmore and West, 1961):

$$Ka_{20} = Ka_T \quad (1.0241)^{20-T}, \tag{6}$$

where

Ka_{20} is the reaeration-rate coefficient at 20° C, in day^{-1},

Ka_T the reaeration-rate coefficient at T° C, in day^{-1},

T the stream temperature, in degrees Celsius; and,

1.0241 is the temperature-conversion factor.

Elmore and West did not publish a confidence limit for the conversion factor (1.0241). However, using their published data, the author calculated a value 1.0241 ±0.0010 at the 95-percent confidence limit.

Because a reaeration-rate coefficient was determined only once for each flow condition in each reach, statistical confidence limits cannot be calculated. Two subjective confidence ranges for the estimate of the reaeration-rate coefficient are included in table 27. Errors in the variables used to compute the ethylene gas-transfer coefficient do not necessarily result in cumulative errors in the transfer coefficient. Two errors can cancel the effect of one another. For example, an error in the plateau ethylene concentration at the upstream cross section could be offset by errors in the plateau dye concentration at the upstream cross section, the peak dye concentration at the downstream cross section, the peak ethylene concentration at the downstream cross section, or the dye-correction factor. The maximum/minimum probable condition is based on the largest single change in the computed ethylene-gas transfer coefficient where only one variable differs by its maximum error. This range assumes that errors in other variables are negligible or cancel one another. The maximum/minimum extreme condition is based on the largest change in the computed ethylene gas-transfer coefficient where all variables differ by the maximum amount in a way that all errors are additive. The maximum/minimum extreme condition represents the possible range in which the reaeration-rate coefficient could fall. The combinations of the variables used to calculate the maximum/minimum probable and extreme conditions are given in tables 23 to 26.

Table 27.--Experimentally determined reaeration-rate coefficients for reaches of the Wabash River near Terre Haute and Lafayette.

[Maximum and minimum conditions include possible errors in the coefficient ratio for oxygen and ethylene and the temperature conversion factor as well as errors listed in tables 23 to 26]

			Oxygen gas-transfer coefficient (day^{-1} at 20° C)			
Reach	Date of field test	Best estimate	Maximum probable condition	Minimum probable condition	Maximum extreme condition	Minimum extreme condition
Terre Haute	10/20-21/81	1.1	1.4	0.9	2.6	<0.1
	8/25-26/82	1.4	1.6	1.2	2.0	.8
Lafayette	11/18-19/81	.8	1.1	.5	1.5	.3
	7/26-27/82	1.2	1.3	1.0	1.9	.7

The reader should be aware that determination of reaeration-rate coefficients on large rivers is quite sensitive to measurement errors in the tracers because reaeration-rate coefficients are small (Nobuhiru Yotsukura, written commun., 1982). This sensitivity condition can be illustrated by considering the general form of the exponential decay equation used to estimate K_E in the modified tracer technique:

$$C_T = C_O \exp(-KT), \qquad (7)$$

where

C_T is the concentration at time T,
C_O is the concentration at time zero,
K is the decay-rate coefficient; and
T is the time.

(Equation 1 can be derived from this general form by substituting E_U/D_U for C_O and $E_D/(D_D \times DCF)$ for C_T and solving for K.)

Differentiating C with respect to K yields

$$\frac{dC}{dK} = -CT. \qquad (8)$$

If the right hand side of equation 8 is rearranged and multiplied by K/K the following relation can be developed:

$$\frac{dC}{C} = KT \frac{dK}{K}. \qquad (9)$$

The measurement error of concentration, dC/C, is shown to be related to the estimate of error of the decay coefficient, dK/K, by the nondimensional number, KT (assuming that equation 7 is the correct model).

Where KT is less than 1, concentration measurement errors result in larger errors in the estimate of K. The nondimensional K_E $(T_D - T_U)$ for the Wabash River data is 0.33 to 0.39 for the high-flow measurements and 0.80 to 0.82 for the low-flow measurements. Thus, cumulative measurement errors in E_U, E_D, D_U, D_D, and DCF result in estimates of errors in K_E that are 1.22 to 3 times the cumulative measurement errors. [The range in measurement errors is equal to the inverse of the range for the term K_E $(T_D - T_U)$; 1/0.82 to 1/0.33.] This is the principal reason that the maximum/minimum extreme condition for the estimated reaeration coefficients are so much larger than the individual measurements errors.

COMPARISON OF RESULTS WITH PREDICTIVE EQUATIONS

The reaeration-rate coefficients determined for the two reaches of the Wabash River were compared to various conceptual, empirical, and semi-empirical predictive equations taken from the literature. A discussion of reaeration and the various predictive equations can be found in Bennett and Rathbun (1972) and Rathbun (1977).

The conceptual equation used in the comparison was developed by O'Connor and Dobbins (1958):

$$K=12.27\ U^{0.5}/H^{1.5},$$

where U is the average reach velocity, in ft/s,
H the average reach depth, in ft,
and K the reaeration-rate coefficient, in day^{-2} at 20° C.

The empirical equations used were:

$K=11.57\ U^{0.969}/H^{1.673}$,	Churchill, Elmore, and Buckingham (1962)	(11)
$K=21.73\ U^{0.67}/H^{1.85}$,	Owens, Edwards, and Gibbs (1964)	(12)
$K=7.61\ U/H^{1.33}$,	Langbein and Durum (1967)	(13)
$K=8.61\ U/H^{1.5}$,	Isaacs and Gaudy (1968)	(14)
and		
$K=20.18\ U^{0.607}/H^{1.689}$.	Bennett and Rathbun (1972)	(15)

The semiempirical equations used were:

$K=0.03452\ U^{2.695}/H^{3.085}S^{0.823}$,	Churchill, Elmore, and Buckingham (1962)	(16)
$K=336.6\ (US)^{0.5}/H$,	Cadwallader and McDonnell (1969)	(17)
$K=106.1\ U^{0.413}S^{0.273}/H^{1.408}$,	Bennett and Rathbun (1972)	(18)
and		
$K=4133\ S\ U$,	Tsivoglou and Wallace (1972)	(19)

where
S is the slope of the energy gradient in feet/foot.

A comparison of the determined and predicted reaeration-rate coefficients for the reaches of the Wabash River near Terre Haute and Lafayette is presented in table 28. The range and average absolute value of the prediction errors are presented in table 29. The prediction error (PE) is defined as:

$$PE = \frac{Kp-Km}{Km} \times 100, \qquad (20)$$

where Kp is the predicted reaeration coefficient, and
Km the best estimate of the measured reaeration coefficient.

Error in the prediction of individual determinations ranged from -43 to 288 percent. The average of absolute-prediction errors for the equations ranged from 22 to 154 percent.

The equations used in the comparison given in table 28 as a group did much better predicting reaeration in the Terre Haute reach than in the Lafayette reach. Individual prediction errors for Terre Haute reach ranged from -29 to 0 percent. Although all the equations tended to predict reaeration-rate coefficients less than those determined for this reach, predicted reaeration coefficients were within the confidence limits of the determined reaeration-rate coefficients.

Individual prediction errors for the Lafayette reach ranged from -25 to 288 percent. All but two of the 10 equations predict values of reaeration-rate coefficients that were outside the confidence limits of the determined coefficients. The two exceptions were the semiempirical equations proposed by Cadwallader and McDonnell (1969) and Tsivoglou and Wallace (1972).

One explanation for the poor performance of predictive equations in the Lafayette reach is that the reaeration coefficients determined for this reach are inaccurate owing to the lack of mixing that necessitated the estimation of the plateau tracer concentrations. The theoretical plateau dye concentrations and the flow-weighted plateau dye concentrations were shown to differ by less than 6 percent. This small difference cannot account for the discrepancy between the predicted and observed reaeration coefficients.

An analysis comparing theoretical and observed concentrations cannot be done for the gas tracer because the efficiency of the injection apparatus is not known. However, inferences can be drawn by comparing the Terre Haute and Lafayette reach injections. The ratio of the calculated and maximum theoretical plateau concentrations of ethylene for the upstream cross section for all four measurements are given in table 30. This ratio is a measure of the efficiency of ethylene absorption in the water. It is a function of stream temperature and

Table 28.--Reaeration-rate coefficients obtained by measurement and by conceptual, empirical and semi-empirical predictive equations, for reaches of the Wabash River near Terre Haute and Lafayette

[Reaeration coefficients (day^{-1} at 20° C, base e)]

Reach	Date of field test	Measured	Conceptual equations	Empirical equations				
			O'Connor and Dobbins (1958)	Churchill, Elmore and Buckingham (1962)	Owens, Edwards and Gibbs (1964)	Langbein and Durum (1967)	Isaacs and Gaudy (1969)	Bennett and Rathbun (1972)
Terre Haute	10/20-21/81	1.1	.9	.8	.9	1.1	.9	1.1
	8/25-26/82	1.4	1.2	1.0	1.2	1.1	1.0	1.4
Lafayette	11/18-19/81	0.8	1.8	1.8	2.2	2.0	1.8	2.4
	7/26-27/82	1.2	2.5	3.6	3.1	2.4	2.2	3.4
Average absolute prediction error (percent).			66	95	91	68	64	96

Reach	Date of field test	Measured	Semiempirical equations				Average absolute prediction error for all equations (percent)
			Churchill, Elmore and Buckingham (1962)	Cadwallader and McDonnell (1969)	Bennett and Rathbun (1972)	Tsivoglou and Wallace (1972)	
Terre Haute	10/20-21/81	1.1	.9	.7	.7	1.0	18
	8/25-26/82	1.4	.8	.8	1.0	1.0	25
Lafayette	11/18-19/81	0.8	3.1	1.2	1.5	1.0	135
	7/26-27/82	1.2	4.4	1.4	2.0	.9	121
Average absolute prediction error (percent).			154	37	55	22	

depth. The maximum theoretical plateau concentration of ethylene was determined by assuming 100 percent of the gas was absorbed in the water at the injection site. This value was calculated by dividing the rate of gas injection by the streamflow and adjusting for loss of gas to the atmosphere between the injection point and the upstream cross section. The rate of gas loss was assumed to be the same as that measured between the sampling cross sections. For example, the maximum theoretical concentration of ethylene in the plateau for the November 1981 measurement in the Lafayette reach was 61.5 μg/L or (0.80 lb/min)(453.5 g/lb)(10^6 μg/g)/(5,892,060 min-1).

The ratios of the calculated and the maximum plateau concentrations of ethylene are much higher for the Terre Haute reach than for the Lafayette reach. Because of the much greater depths at the Terre Haute reach injection site than at the Lafayette reach injection site it is not surprising that the estimated injection efficiencies were much higher in the Terre Haute reach.

Table 29.--Prediction error in reaeration-rate coefficients estimated by conceptual, empirical, and semi-empirical predictive equations for reaches of the Wabash River near Terre Haute and Lafayette

Equation	Range in prediction error (percent)	Average absolute prediction error (percent)
O'Connor and Dobbins (1958)	-18.2 to 125.0	66.5
Churchill, Elmore and Buckingham (1962)	-28.6 to 200.0	95.2
Owens, Edwards and Gibbs (1964)	-18.2 to 175.0	91.5
Langbein and Durum (1967)	-21.4 to 150.0	67.9
Isaacs and Gaudy (1968)	-28.6 to 125.0	63.8
Bennett and Rathbun (1972)	0.0 to 200.0	95.9
Churchill, Elmore and Buckingham (1962)	-42.9 to 287.5	153.8
Cadwallader and McDonnell (1969)	-42.9 to 50.0	36.5
Bennett and Rathbun (1972)	-36.4 to 87.5	54.8
Tsivoglou and Wallace (1972)	-28.6 to 25.0	21.9

Table 30.--Estimates of efficiencies of ethylene injection for reaeration measurements in the Wabash River

Reach	Date of field test	Rate of ethylene injection (lb/min)	Maximum theoretical concentration of ethylene in the plateau (ug/L)	Concentration of ethylene in the plateau calculated from field data (ug/L)	Water temperature (°C)	Depth of gas diffusers below water surface (feet)	Estimate of efficiency of ethylene injection (Ratio of calculated and maximum theoretical concentration of ethylene in the plateau)
Terre Haute	10/20-21/81	1.28	44.9	28.8	14.0	11.0	0.64
	8/25-26/82	0.80	59.9	25.2	23.5	7.0	.42
Lafayette	11/18-19/81	0.80	60.1	13.8	9.0	4.0	.23
	7/26-27/82	1.08	118.7	18.4	28.0	2.5	.16

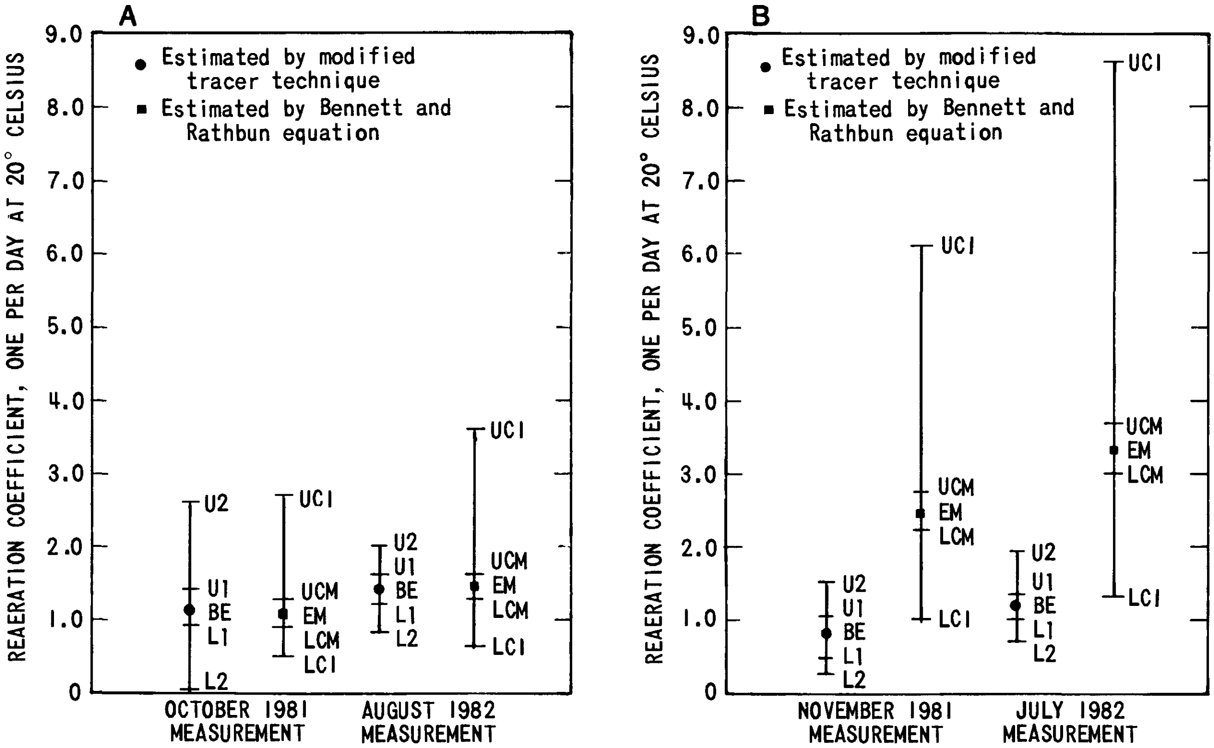
The average predicted reaeration-rate coefficients of the Lafayette reach experiments (table 28) in November 1981 and July 1982 were 1.9 and 2.6 day^{-1} respectively. The upstream plateau ethylene concentrations necessary to match these values are 21.1 and 51.4 µg/L (compared to 13.8 and 18.4 µg/L observed during the field tests). The ratios of the maximum theoretical concentration of ethylene and of these concentrations are 0.34 and 0.55. Because of the shallow depths at the Lafayette reach injection site, it is probable that the gas absorption was too low to result in ratios this high.

A more feasible explanation is that current theory is inadequate for accurate prediction of reaeration for a wide variety of hydrologic conditions. Similarily, Wilson and MacLeod (1974) concluded that the available predictive models were incomplete in terms of some unknown variable that would be necessary to make the predictive equations a consistently accurate modeling tool.

The lack of close agreement of the determined reaeration-rate coefficient, and those calculated from predictive equations for the Lafayette data is not surprising. Most of the predictive reaeration equations found in the literature were developed by linear regression analysis. The most commonly used of these equations contain only the terms velocity and depth. A reaeration coefficient obtained for a stated width and depth from one of these equations actually represents an estimate of the average reaeration coefficient that would be expected if reaeration were measured for a large number of streams of similar widths and depths. In a statistical sense it is the expected mean of the sampling distribution and does not necessarily represent the expected mean reaeration for the stated hydrologic conditions in a specific stream. Confidence limits for the expected mean value and the range in discrete values expected are quite large if there is considerable measurement error or scatter in the data used to develop the regression equation.

This fact can be illustrated by examining one of the common predictive reaeration equations. Bennett and Rathbun (1972) used data reported by O'Connor and Dobbins (1958), Churchill and others (1962), Owens and others (1964) and Tsivoglou (1967) to develop a predictive equation. Since this equation was based on the combined data of these investigators it encompasses a much wider range in hydrologic conditions than any of the equations proposed by the individual investigators. Reaeration-rate coefficients predicted by the Bennett and Rathbun equation for the Terre Haute and Lafayette reaches and 95 percent confidence limits for the expected mean value and the range in discrete values are shown in figure 19. The confidence limits for the coefficients predicted by the Bennett and Rathbun equation are quite large and overlap with the confidence limits estimated for the experimentally determined values. The confidence limits for predicted values in the reach near Lafayette are larger than those for the Terre Haute reach because few data collected by the previous investigators were from rivers hydrologically similar to the Wabash River near Lafayette. The use of a regression equation to extrapolate beyond the range of observed data typically results in very large confidence limits. The reader is referred to Walpole and Meyers (1978, p. 329-331) for a discussion of the confidence limits for linear regression equations.

The best equation in terms of the average, absolute-prediction error was the Tsivoglou-Wallace equation. This equation had an average, absolute-prediction error of 27.3 percent. However, the equation predicted decreasing reaeration with decreasing streamflow. The opposite trend was observed in the measured data.



EXPLANATION

UCI Upper 95-percent confidence limit for the range of expected reaeration coefficient
UCM Upper 95-percent confidence limit for the expected mean reaeration coefficient
EM Expected mean reaeration coefficient
LCM Lower 95-percent confidence limit for the expected mean reaeration coefficient
LCI Lower 95-percent confidence limit for the range of expected reaeration coefficient
U2 Maximum possible condition
U1 Maximum probable condition
BE Best estimate of the reaeration coefficient
L1 Minimum probable condition
L2 Minimum possible condition

Figure 19.-- Reaeration coefficients and their confidence limits estimated by the modified tracer technique and the Bennett and Rathbun equation for reaches of the Wabash River near Terre Haute (A) and near Lafayette (B).

COMPARISON OF REAERATION-RATE COEFFICIENTS IN THE TERRE HAUTE AND LAFAYETTE REACHES

Reaeration-rate coefficients in the Lafayette reach are surprisingly less than those in the Terre Haute reach. The Terre Haute reach was considerably deeper than the Lafayette reach during the experiments. The commonly accepted model of gas transfer in streams originally proposed by Streeter and Phelps (1925) and expanded by O'Connor and Dobbins (1958) assumes gas transfer and stream depth are negatively correlated. This relationship has been supported by the data reported by O'Connor and Dobbins (1958), Churchill, Elmore, and Buckingham (1962), and Owens, Edwards, and Gibbs (1964), although there is considerable scatter in the data.

The question then remains as to why reaeration in the Lafayette reach is less than that in the Terre Haute reach. One possible explanation is differences in water quality. Detergents or surfactants and sewage have been shown by several investigators to reduce the liquid-film gas-transfer coefficient, and in turn, the reaeration-rate coefficient. The reader is referred to Bennett and Rathbun (1972) and Tsivoglou and Wallace (1972) for a discussion of these effects. Alonso, McHenry, and Hong (1975) have demonstrated that high suspended sediment concentrations also tend to reduce reaeration. Tsivoglou and Wallace (1972) demonstrated that oil in the water tends to increase reaeration. The results of analyses for several water quality constituents shown to have an effect on stream reaeration are presented in table 31. Methylene-blue-active substances were used as an indicator of detergents in this study. Water samples analyzed were collected during passage of the tracers through the cross section. None of the values in table 31 are high enough to affect the reaeration capacity of the Wabash River significantly. More importantly, however, the differences between the two reaches are relatively small and cannot account for the low value of reaeration measured in the Lafayette reach of the Wabash River.

The effect of wind on all four reaeration experiments should also have been negligable. Wind velocities measured at the sampling cross sections during passage of the tracers ranged from 0 to 10 mph (mile per hour) at the Lafayette reach and 0 to 6 mph at the Terre Haute reach. Average wind velocities measured during all four experiments were less than 4 mph and were not substantially different from each other.

Table 31.--Concentrations of selected water-quality constituents in samples collected from the Wabash River during the reaeration measurements

[Dash indicates no data.]

Reach	Date of field test	Sampling location	Biochemical oxygen demand, 5-day at 20° C (mg/L)	Dissolved solids, residue at 180° C (mg/L)	Methylene blue active substances (mg/L)	Oil-grease total (mg/L)	Suspended-sediment Concentration (mg/L)
Terre Haute	10/20-21/81	Upstream cross section	[1]1.6	[1]430	[1]<0.1	[1]5.6	[1]80
		Downstream cross section	---	[1]420	[1]<0.1	[1]7.0	[1]52
	8/25-26/82	Upstream cross section	[2]11.0	[2]380	[2]<0.1	[2]1.0	[2]152
		Downstream cross section	[2]9.0	---	---	---	[2]73
Lafayette	11/18-19/81	Upstream cross section	[1]2.1	---	[1]<0.1	[1]2.8	[1]16
		Downstream cross section	[1]1.6	---	[1]<0.1	---	--
	7/26-27/82	Upstream cross section	[2]12.3	[1]340	[1]<0.1	[1]2.4	[2]66
		Downstream cross section	[2]12.0	[1]320	[1]<0.1	[1]2.5	[2]82

[1]Analysis by Indiana State Board of Health.
[2]Analysis by U.S. Geological Survey.

SUMMARY

The modified tracer technique was used to measure reaeration coefficients in reaches of the Wabash River near Lafayette and Terre Haute, Ind., at streamflows ranging from 2,310 to 7,400 ft^3/s. The study was done in cooperation with the Indiana State Board of Health as part of a series of studies to determine the waste-assimilative capacity of the middle Wabash River basin.

Chemically pure (CP grade) ethylene was used as the tracer gas, and rhodamine-WT dye was used as the dispersion-dilution tracer. Ethylene was bubbled into the water at rates of 0.80 to 1.28 lb/min through a series of 20 to 32 porous flat-plate diffusers. Each diffuser was 41 in. long and 3 in. wide with an average pore size of 1.5 to 2.0 micrometers. The gas was released in the diffusers from high pressure cylinders through two-stage regulating valves. The rhodamine-WT was injected into the river by either one or two pumps operated by 12-volt batteries at rates ranging from 17 to 74 oz/min.

Reaeration coefficients measured in a 13.5-mi reach near Terre Haute were 1.4 and 1.1 day^{-1} at 20° C, at streamflows of 3,360 and 7,400 ft^3/s (71 and 43 percent flow duration), respectively. Reaeration coefficients measured in a 18.4-mi reach near Lafayette were 1.2 and 0.8 day^{-1} at 20° C, at streamflows of 2,310 and 3,420 ft^3/s (70 and 53 percent flow duration), respectively.

None of the common equations found in the literature predicted reaeration-rate coefficients similar to those measured for the Terre Haute and Lafayette reaches of the Wabash River. The average absolute prediction error for 10 commonly used reaeration equations ranged from 22 to 154 percent. The equations used in the comparison as a group did much better predicting reaeration-rate coefficients in the reach near Terre Haute than in the reach near Lafayette. The overall average of the absolute prediction errors for all 10 equations was 22 percent for the reach near Terre Haute. Although all of the equations in the reach near Terre Haute tended to predict reaeration-rate coefficients less than the best estimate of those determined in the study, predicted values were within the confidence limits of the determined reaeration-rate coefficients. The overall average of the absolute prediction errors for all 10 equations was 128 percent for the reach near Lafayette. All but 2 of the 10 equations predicted reaeration-rate coefficients that were outside of the confidence limits for the coefficients determined in this study.

Reaeration-rate coefficients determined for the reach near Lafayette were less than coefficients determined for the reach near Terre Haute, even though the average depth of the reach near Terre Haute was considerably more (2 to 3 ft) than the Lafayette reach under similar hydrologic conditions. The reason for this difference is unknown, but cannot be attributed to variations in water quality or wind-induced reaeration.

REFERENCES

Alonso, C. V., McHenry, J. R., and Hong, J. C. S., 1975, The influence of suspended sediment on the reaeration of uniform streams: Water Research, v. 9, p. 695-700.

American Public Health Association and others, 1980, Standard Methods for the Examination of Water and Wastewater, 15th ed.: New York, American Public Health Association and others, 1181 p.

Bennett, J. P., and Rathbun, R. E., 1972, Reaeration in open channel flow: U.S. Geological Survey Professional Paper 737, 75p.

Cadwallader, T. E., and McDonnell, A. J., 1969, A multivariate analysis of reaeration date: Water Research, v. 3, p. 731-742.

Churchill, M. A., Elmore, H. L., and Buckingham, R. A., 1962, The prediction of stream reaeration rates: American Society of Civil Engineers, Proceedings, Journal of the Sanitary Engineering Division, v. 88, no. SA-4, p. 1-46.

Elmore, W. L., and West, W. F., 1961, Effect of water temperature on stream reaeration: American Society of Civil Engineers, Proceedings, Journal of the Sanitary Engineering Division, v. 87, no. SA-6, p. 59-71.

Goerlitz, D. F., and Brown, Eugene, 1972, Methods for Analysis of Organic Substances in Water: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 5, Chapter A3, 40 p.

Guy, H. P., 1969, Laboratory theory and methods for sediment analysis: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 5, Chapter C1, 58 p.

Guy, H. P., Norman, V. W., 1970, Field methods for measurement of fluvial sediment: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chapter C2, 59 p.

Isaacs, W. P., and Gaudy, A. F., 1968, Atmospheric oxygenation in a simulated stream: American Society of Civil Engineers, Proceedings, Journal of the Sanitary Engineering Division, v. 94, no. SA-2, p. 319-344.

Langbein, W. B., and Durum, W. N., 1967, The aeration capacity of streams: U.S. Geological Survey Circular no. 542, 6 p.

O'Connor, D. J., and Dobbins, W. E., 1958, Mechanism of reaeration in natural streams: American Society of Civil Engineers Transactions, v. 123, p. 641-684

Owens, M., Edwards, R. W., and Gibbs, J. W., 1964, Some reaeration studies in streams: International Journal of Air and Water Pollution, v. 8, no. 819, p. 469-486.

Rantz, S.E., and others, 1982, Measurement and computation of streamflow--measurement of stage and discharge: U.S. Geological Survey Water-Supply Paper 2175, v. 1, 284p.

Rathbun, R. E., 1977, Reaeration coefficients of streams--state of the art: American Society of Civil Engineers, Proceedings, Journal of the Hydraulics Division, v. 103, no. HY-4, p. 409-424.

1979, Estimating the gas and dye quantities for modified tracer technique measurements of stream reaeration coefficients: U.S. Geological Survey Water-Resources Investigations 79-27, 42 p.

Rathbun, R. E., and Grant, R. S., 1978, Comparison of the radioactive and modified techniques for measurement of stream reaeration coefficients: U.S. Geological Survey Water-Resources Investigations 78-68, 57 p.

Rathbun, R. E., Shultz, D. J., and Stephens, D. W., 1975, Preliminary experiments with a modified tracer technique for measuring stream reaeration coefficients: U.S. Geological Survey Open-File Report 75-256, 36 p.

Rathbun, R. E., Stephens, D. W., Shultz, D. J., and Tai, D. Y., 1978, Laboratory studies of gas tracers for reaeration: American Society of Civil Engineers, Proceedings, Journal of the Environmental Engineering Division, v. 104, no. EE1, p. 215-229.

Shultz, D. J., Pankow, J. F., Tai, D. Y., Stephens, D. W., and Rathbun, R. E., 1976, Determination, storage, and preservation of low molecular weight hydrocarbon gases in aqueous solution: U.S. Geological Survey Journal of Research, v. 4, no. 2, p. 247-251.

Skougstad, M. W., Fishman, M. J., Friedman, L. C., Erdmann, D. E., and Duncan, S. S., eds., 1979, Methods for determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey Techniques of Water Resources Investigations, Book 5, Chapter A1, 626 p.

Stewart, J. A., 1983, Low-flow characteristics of Indiana streams: U.S. Geological Survey Open-File Report 82-1007, 277 p.

Streeter, H. W., and Phelps, E. B., 1925, A study of pollution and natural purification of the Ohio River: Washington, U.S. Public Health Service, Public Health Bulletin 146, 75 p.

Tsivoglou, E. C., 1967, Tracer measurement of stream reaeration: Federal Water Pollution Control Adm. Rept., 86 p.

Tsivoglou, E. C., and Wallace, J. R., 1972, Characterization of stream reaeration capacity: U. S. Environmental Protection Agency Report no. EPA-R3-72-012, 317 p.

Walpole, R. E., and Meyers, R. N., 1978, Probability and Statistics for Engineers and Scientists, 2d edition: New York, MacMillan and Co., 580 p.

Wilson, G. T., and MacLeod, N., 1974, A critical appraisal of empirical equations and models for the prediction of the coefficient of reaeration of deoxygenated water: Water Research, U.S., no. 6, p. 341-366.

Wilson, J. F., 1968, Fluorometric procedures for dye tracing: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chapter A12, 31 p.

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Tables 3-18

Table 3.--Dye concentrations observed in the Wabash River near Terre Haute, upstream cross section, October 20, 1981

[Analyses by U.S. Geological Survey. Total width of cross section is 515 ft. Zero percent of width is at right bank. Dash indicates no data.]

Time	Dye concentration (µg/L)				
	At 10 percent of width	At 25 percent of width	At 50 percent of width	At 75 percent of width	At 90 percent of width
1707	----	----	2.5	----	----
1755	----	----	40.2	----	----
1805	39.3	----	42.0	----	----
1810	----	41.1	----	----	----
1815	----	----	49.3	----	----
1822	----	----	----	56.6	----
1825	----	----	44.7	----	----
1832	----	----	----	----	28.3
1835	----	----	39.3	----	----
1840	42.9	----	----	----	----
1845	----	----	42.0	----	----
1850	----	43.8	----	----	----
1855	----	----	42.0	----	----
1900	----	----	----	42.0	----
1905	----	----	43.8	----	----
1910	----	----	----	----	28.3
1915	----	----	45.6	----	----
1925	----	----	46.5	----	----
1930	41.1	----	----	----	----
1935	----	----	45.6	----	----
1945	----	----	24.7	----	----
1950	----	4.7	----	----	----
1955	----	----	8.4	----	----
2005	----	----	2.5	----	----

Table 4.--Dye concentrations observed in the Wabash River near Terre Haute, downstream cross section, October 21, 1981

[Analyses by U.S. Geological Survey. Total width of cross section is 495 ft. Zero percent of width is at right bank. Dash indicates no data.]

	Dye Concentrations (μg/L)				
Time	At 10 percent of width	At 25 percent of width	At 50 percent of width	At 75 percent of width	At 90 percent of width
0250	----	----	11.4	----	----
0300	----	----	15.3	----	----
0310	----	----	18.1	----	----
0320	----	----	19.5	----	----
0330	----	----	21.7	----	----
0340	----	----	23.9	----	----
0350	----	----	27.0	----	----
0400	----	----	27.5	----	----
0410	----	----	27.8	----	----
0420	----	----	26.2	----	----
0430	----	----	25.3	----	----
0440	25.0	----	----	----	----
0443	----	23.9	----	----	----
0446	----	----	----	----	23.1
0450	----	----	20.0	----	26.2
0500	----	----	19.2	----	----
0510	19.2	----	----	----	----
0513	----	17.8	----	----	----
0515	----	----	16.4	----	----
0516	----	----	----	20.0	----
0519	----	----	----	----	20.8
0530	----	----	15.0	----	----
0540	13.6	----	----	----	----
0543	----	12.3	----	----	----
0545	----	----	13.6	----	----
0546	----	----	----	11.4	----
0549	----	----	----	----	12.3
0600	----	----	12.8	----	----
0615	----	----	7.3	----	----
0630	----	----	6.1	----	----
0645	----	----	4.7	----	----
0700	----	----	3.9	----	----

Table 5.--Ethylene concentrations observed in the Wabash River near Terre Haute, upstream cross section, October 20, 1981

[Analyses by U.S. Geological Survey. Total width of cross section is 515 ft. Zero percent of width is at right bank. Dash indicates no data.]

Time	Ethylene gas concentration ($\mu g/L$)				
	At 10 percent of width	At 25 percent of width	At 50 percent of width	At 75 percent of width	At 90 percent of width
1755	----	----	29.9	----	----
1805	----	----	29.6	----	----
1815	----	----	33.8	----	----
1825	----	----	30.7	----	----
1835	----	----	29.7	----	----
1840	32.9	----	----	----	----
1845	----	----	29.4	----	----
1850	----	27.3	----	----	----
1855	----	----	28.5	----	----
1900	----	----	----	28.1	----
1915	----	----	25.0	----	----
1925	----	----	24.7	----	----
1935	----	----	27.0	----	----

Table 6.--Ethylene concentrations observed in the Wabash River near Terre Haute, downstream cross section, October 21, 1981

[Analyses by U.S. Geological Survey. Total width of cross section is 495 ft. Zero percent of width is at right bank. Dash indicates no data.]

Time	Ethylene gas concentration (µg/L)				
	At 10 percent of width	At 25 percent of width	At 50 percent of width	At 75 percent of width	At 90 percent of width
0320	----	----	12.0	----	----
0330	----	----	13.3	----	----
0350	----	----	15.3	----	----
0410	----	----	15.7	----	----
0420	----	----	14.9	----	----
0430	----	----	13.7	----	----
0440	12.7	----	12.3	----	----
0446	----	13.4	----	----	----
0448	----	----	----	11.6	----
0450	----	----	----	----	12.2

Table 7.--Dye concentrations observed in the Wabash River near Terre Haute, upstream cross section, August 25, 1982

[Analyses by U.S. Geological Survey. Total width of cross section is 520 ft. Zero percent of width is at right bank. Dash indicates no data.]

	Dye concentration (μg/L)						
Time	At 30 percent of width	At 50 percent of width	At 70 percent of width	Time	At 30 percent of width	At 50 percent of width	At 70 percent or width
1250	----	0.2	0.3	1425	----	31.7	----
1255	----	6.0	----	1430	----	33.0	34.9
1300	5.0	21.2	----	1435	----	33.0	----
1305	----	31.7	----	1440	38.3	30.4	----
1310	----	31.7	34.3	1445	----	31.7	----
1315	----	33.0	----	1450	----	33.0	33.0
1320	35.7	38.3	----	1455	----	30.4	----
1325	----	33.0	----	1500	36.9	30.4	----
1330	----	35.6	34.3	1505	----	17.3	----
1335	----	38.3	----	1510	----	11.7	25.7
1340	40.9	33.0	----	1515	----	5.7	----
1345	----	34.3	----	1520	7.1	3.3	----
1350	----	34.3	38.3	1525	----	1.8	----
1355	----	34.3	----	1530	----	1.6	1.7
1400	42.2	35.6	----	1535	----	.9	----
1405	----	35.6	----	1540	1.5	.8	----
1410	----	33.0	39.6	1545	----	.6	----
1415	----	31.7	----	1550	----	.6	.7
1420	36.9	36.9	----	1555	----	.3	----

Table 8.--Dye concentrations observed in the Wabash River near Terre Haute, downstream cross section, August 26, 1982

[Analyses by U.S. Geological Survey. Total width of cross section is 500 ft. Zero percent of width is at right bank. Dash incidates no data.]

Dye concentration (µg/L)					
Time	At 50 percent of width	Time	At 50 percent of width	Time	At 50 percent of width
0115	1.0	0410	13.7	0700	4.8
0130	1.8	0420	13.7	0710	3.6
0140	2.6	0430	13.3	0720	3.4
0150	3.5	0440	12.5	0730	3.0
0200	4.6	0450	12.1	0740	2.8
0210	5.6	0500	11.3	0750	2.4
0220	10.7	0510	10.5	0800	2.5
0230	----	0520	9.7	0810	2.0
0240	----	0530	9.3	0820	----
0250	10.3	0540	7.7	0830	1.6
0300	11.7	0550	7.3	0845	1.5
0310	13.7	0600	7.3	0900	1.1
0320	13.7	0610	6.5	0915	.9
0330	14.5	0620	5.8	0930	.8
0340	14.9	0630	5.4	0945	.7
0350	14.9	0640	4.8		
0400	14.5	0650	4.3		

Table 9.--Ethylene concentrations observed in the Wabash River near Terre Haute, upstream cross section, August 25, 1982

[Analyses by U.S. Geological Survey. Total width of cross section is 520 ft. Zero percent of width is at right bank]

Time	Ethylene concentration (μg/L)		
	At 30 percent of width	At 50 percent of width	At 70 percent of width
1255	--	7.9	--
1315	--	23.0	--
1320	25.0	----	--
1325	--	22.0	--
1330	--	----	20.0
1335	--	20.0	--
1345	--	26.0	--
1355	--	27.0	--
1415	--	30.0	--
1420	30.0	----	--
1425	--	28.0	--
1430	--	----	26.0
1435	--	28.0	--
1445	--	25.0	--
1500	--	23.0	--

Table 10.--Ethylene concentrations observed in the Wabash River near Terre Haute, downstream cross section, August 26, 1982

[Analyses by U.S. Geological Survey. Total width of cross section is 500 ft. Zero percent of width is at right bank. Dash indicates no data.]

Time	Ethylene concentration (μg/L)		
	At 30 percent of width	At 50 percent of width	At 65 percent of width
0215	---	3.1	---
0230	---	3.9	---
0240	4.2	---	---
0245	---	4.3	---
0300	---	5.0	5.2
0315	---	5.8	---
0320	5.9	---	---
0330	---	6.3	---
0340	---	---	6.4
0345	---	6.3	---
0400	---	6.3	---
0415	---	5.8	---
0430	---	5.2	---

Table 11.--Dye concentrations observed in the Wabash River near Lafayette, upstream cross section, November 18, 1981

[Analyses by U.S. Geological Survey. Total width of cross section is 355 ft. Zero percent of width is at right bank. Column labeled at 70 percent of width located at 80 percent of width after 1410. Dash indicates no data.]

	Dye concentration (µg/L)								
Time	At 28 percent of width	At 55 percent of width	At 70 percent of width	Flow-weighted average	Time	At 28 percent of width	At 55 percent of width	At 70 percent of width	Flow-weight average
1235	-----	0.2	----	0.2	1410	-----	80.2	----	60.2
1236	0.2	----	----	----	1415	-----	71.1	----	53.3
1237	-----	----	0.2	----	1417	153.1	----	----	----
1240	-----	.8	----	.6	1420	-----	56.6	----	42.5
1245	-----	.8	----	.6	1425	-----	58.4	----	43.8
1250	-----	1.2	----	.9	1427	134.9	----	----	----
1254	1.9	----	----	----	1430	-----	65.7	----	49.2
1255	-----	2.0	----	1.5	1435	-----	60.2	2.4	45.2
1300	-----	1.9	9.3	1.4	1440	-----	63.8	----	47.9
1305	-----	15.6	----	11.7	1445	-----	63.8	----	47.9
1310	-----	48.4	----	36.3	1446	-----	----	2.4	----
1314	-----	----	18.6	----	1450	136.8	58.4	----	43.8
1315	-----	65.7	----	49.2	1455	145.9	63.8	----	47.9
1317	93.1	----	----	----	1500	140.4	64.7	----	48.5
1320	-----	62.0	----	46.5	1505	147.6	39.3	----	29.5
1325	-----	52.9	----	39.7	1510	116.7	7.4	----	5.5
1330	-----	72.9	----	54.7	1515	-----	2.8	----	2.1
1335	-----	75.7	----	56.7	1520	-----	1.6	----	1.2
1340	-----	58.4	----	43.8	1525	-----	.7	----	.5
1341	129.5	----	----	----	1530	-----	.6	----	.5
1345	-----	45.6	----	34.2	1535	-----	.5	----	.4
1348	-----	----	8.1	----	1540	-----	.6	----	.5
1350	-----	54.7	----	41.0	1545	-----	.5	----	.4
1355	-----	77.5	----	58.1	1550	-----	.5	----	.4
1400	-----	71.1	8.6	53.3	1555	-----	.4	----	.3
1405	-----	62.9	----	47.2	1600	-----	.4	----	.3

Table 12.--Dye concentrations observed in the Wabash River near Lafayette, downstream cross section, November 19, 1981

[Analyses by U.S. Geological Survey. Total width of cross section is 270 ft. Zero percent of width is at right bank. Dash indicates no data.]

Rhodamine-WT dye (µg/L)									
Time	At 50 percent of width	Time	At 50 percent of width	Time	At 50 percent of width	Time	At 50 percent of width	Time	At 50 percent of width
0129	0.2	0321	17.5	0520	18.9	0710	8.6	1020	1.5
0140	1.2	0325	18.1	0525	18.4	0715	8.4	1030	1.3
0149	.6	0331	21.4	0534	17.5	0720	7.8	1040	1.2
0155	1.0	0336	20.9	0540	16.7	0725	7.9	1050	1.2
0200	2.1	0340	21.4	0545	16.4	0730	7.6	1100	1.0
0205	2.1	0345	22.3	0550	16.1	0740	8.1	1110	1.1
0210	2.7	0350	23.1	0556	15.0	0750	6.5	1120	1.0
0215	3.9	0355	24.7	0601	14.8	0800	6.6	1130	.7
0221	4.7	0401	24.7	0606	14.2	0810	5.6	1140	.7
0225	5.4	0405	24.7	0612	13.4	0820	5.3	1150	.6
0230	14.2	0413	23.8	0621	12.8	0830	4.6	1200	.5
0235	7.0	0420	25.6	0625	12.5	0840	5.1	1220	.4
0240	9.5	0425	24.7	0630	12.3	0850	5.2	1230	.4
0245	10.3	0431	24.7	0635	12.0	0900	4.0	1250	.4
0250	10.6	0438	24.7	0640	11.1	0920	2.8	1300	.3
0255	11.1	0447	22.0	0645	10.6	0930	2.8	1310	.3
0300	13.1	0455	21.1	0650	10.3	0940	2.3	1320	.4
0305	14.5	0503	21.1	0655	10.0	0950	2.8	1330	.3
0310	15.0	0510	19.2	0700	9.8	1000	1.9		
0315	16.7	0515	18.6	0705	9.2	1010	1.6		

Table 13.--Ethylene concentrations observed in the Wabash River near Lafayette, upstream cross section, November 18, 1981

[Analyses by U.S. Geological Survey. Total width of cross section is 355 ft. Zero percent of width is at right bank. Data collected for column labeled at 70 percent of width located at 80 percent of width after 1410. Dash indicates no data.]

Time	Ethylene concentration (μg/L)			
	At 28 percent of width	At 55 percent of width	At 70 percent of width	Flow-weighted average
1310	----	18.9	----	12.9
1314	----	----	12.3	----
1320	----	21.3	----	14.5
1324	37.2	----	----	----
1330	----	20.1	----	13.7
1340	38.1	----	----	----
1346	----	----	4.2	----
1350	----	19.6	----	13.3
1400	----	19.3	4.9	13.1
1410	----	16.8	----	11.4
1416	36.1	----	----	----
1420	----	24.8	----	16.9
1427	34.9	----	----	----
1430	----	24.2	----	16.5
1434	----	----	1.6	----
1440	----	19.2	----	13.1
1446	----	----	1.3	----
1450	32.2	18.8	----	12.8

Table 14.--Ethylene concentrations observed in the Wabash River near Lafayette, downstream cross section, November 19, 1981

[Analyses by U.S. Geological Survey. Total width of cross section is 270 ft. Zero percent of width is at right bank. Dash indicates no data.]

Time	Ethylene concentration (μg/L)		
	At 25 percent of width	At 50 percent of width	At 75 percent of width
0300	---	1.7	---
0310	---	3.9	---
0318	1.1	---	---
0320	---	4.2	---
0322	---	---	3.4
0330	---	4.6	---
0338	5.7	---	---
0340	---	5.0	---
0342	---	---	4.4
0350	---	5.4	---
0358	5.7	---	---
0400	---	5.3	---
0402	---	---	4.3
0410	---	5.1	---
0420	---	4.9	---
0430	---	4.9	---

Table 15.--Dye concentrations observed in the Wabash River near Lafayette, upstream cross section, July 26, 1982

[Analyses by U.S. Geological Survey. Total width of cross section is 290 ft. Zero percent of width is at right bank. Dash indicates no data.]

	Dye concentration (µg/L)								
Time	At 30 percent of width	At 50 percent of width	At 70 percent of width	Flow-weighted average	Time	AT 30 percent of width	At 50 percent of width	At 70 percent of width	Flow-weight average
1520	-----	----	0.2	----	1655	-----	48.8	----	55.6
1530	0.2	0.2	----	0.2	1700	-----	39.6	81.6	45.1
1535	-----	1.5	----	1.7	1705	-----	31.7	----	36.1
1540	-----	33.0	38.3	37.6	1710	6.1	35.6	----	40.6
1550	7.0	36.9	----	42.1	1715	-----	38.3	----	43.7
1555	-----	44.8	----	51.1	1720	-----	40.9	84.2	46.6
1600	-----	43.5	77.7	49.6	1725	-----	42.2	----	48.1
1605	-----	42.2	----	48.1	1730	7.7	43.5	----	49.6
1610	5.3	40.9	----	46.6	1735	-----	55.3	----	63.0
1615	-----	40.9	----	46.6	1740	-----	3.7	56.6	4.2
1620	-----	43.5	80.3	49.6	1745		0.9	----	1.0
1625	-----	50.1	----	57.1	1750	0.3	----	----	----
1630	8.9	46.1	----	52.6	1755	-----	.7	----	0.8
1635	-----	44.8	----	51.1	1800	-----	.6	2.1	.7
1640	-----	----	81.6	----	1810	.3	.4	----	.5
1645	-----	34.3	----	39.1	1815	-----	.3	----	.3
1650	5.6	35.6	----	40.6					

Table 16.--Dye concentrations observed in the Wabash River near Lafayette, downstream cross section, July 27, 1982

[Analyses by U.S. Geological Survey. Total width of cross section is 470 ft. Zero percent of width is at right bank. Dash indicates no data.]

Dye concentration (µg/L)							
Time	At 50 percent of width	Time	At 50 percent of width	Time	At 50 percent of width	Time	At 50 percent of width
0655	4.8	0910	18.5	1110	11.1	1430	3.3
0700	5.2	0915	17.7	1120	10.4	1440	2.7
0710	6.1	0920	18.1	1130	10.2	1450	2.5
0720	7.3	0925	18.5	1140	9.4	1500	2.4
0730	9.3	0930	17.7	1150	9.3	1510	2.2
0740	10.9	0935	17.3	1200	8.5	1520	3.3
0750	12.9	0940	17.3	1210	8.5	1545	1.9
0800	13.3	0945	17.3	1220	7.9	1600	1.5
0810	14.9	0950	17.3	1230	7.8	1615	1.5
0815	15.3	0955	16.9	1240	7.0	1630	1.4
0820	16.5	1000	17.3	1250	6.6	1645	1.2
0825	16.9	1005	16.5	1300	6.5	1700	1.1
0830	17.7	1010	16.1	1310	5.8	1715	1.1
0835	16.9	1015	15.3	1320	5.2	1730	.9
0840	17.7	1020	15.7	1330	5.0	1745	1.0
0845	17.7	1025	15.7	1340	4.2	1800	.7
0850	18.5	1030	15.3	1350	3.9		
0855	17.3	1040	14.5	1400	4.3		
0900	18.9	1050	14.1	1410	3.5		
0905	18.1	1100	13.7	1420	3.6		

Table 17.--Ethylene concentrations observed in the Wabash River near Lafayette, upstream cross section, July 26, 1982.

[Analyses by U.S. Geological Survey. Total width of cross section is 290 ft. Zero percent of width is at right bank. Dash indicates no data.]

Time	Ethylene concentration (μg/L)			
	At 30 percent of width	At 50 percent of width	At 70 percent of width	Flow-weighted average
1540	----	17.0	-----	18.2
1550	----	15.0	-----	16.1
1610	----	23.0	-----	24.6
1620	----	21.0	33.0	22.5
1630	3.3	19.0	-----	20.3
1640	----	18.0	-----	19.3
1650	2.7	15.0	-----	16.1
1700	----	13.0	28.0	13.9
1710	----	16.0	-----	17.1
1720	----	15.0	-----	16.1
1740	----	2.8	-----	3.0
1750	----	.2	-----	.2

Table 18.--Ethylene concentrations observed in the Wabash River near Lafayette, downstream cross section, July 27, 1982

[Analyses by U.S. Geological Survey. Total width of cross section is 470 ft. Zero percent of width is at right bank. Dash indicates no data.]

Time	Ethylene (µg/L)		
	At 30 percent of width	At 50 percent of width	At 70 percent of width
0720	----	1.3	----
0750	----	2.6	----
0810	----	2.8	----
0820	1.8	3.1	----
0830	----	3.2	3.5
0840	----	3.1	----
0850	----	3.1	3.5
0900	2.4	3.3	----
0920	----	3.0	----
0940	----	2.4	----
1000	----	2.1	----

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