UNITED STATES
DEPARTMENT OF THE INTERIOR
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RATHBUN, et. al.

PRELIMINARY EXPERIMENTS WITH A MODIFIED TRACER TECHNIQUE FOR MEASURING STREAM REAERATION COEFFICIENTS

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By R.E. Rathbun, D.J. Shultz, and D.W. Stephens

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CONVERSION TABLE

Metric	Multiply by	English
Millimetres (mm)	0.03937	Inches (in)
Metres (m)	3.281	Feet (ft)
Metres per second (m/s)	3.281	Feet per second (ft/s)
Cubic metres per second (m^3/s)	35.31	Cubic feet per second (ft^3/s)
Kilograms (kg)	2.205	Pounds (lb)
Millilitres (ml)	.0339	Fluid ounces (fl oz)

SYMBOLS

Symbol	Definition
a, b	Empirical constants in the relation between mean depth of flow and water discharge.
c, d	Empirical constants in the relation between mean velocity and water discharge.
C_{G_U}, C_{G_D}	Concentration of tracer gas at the upstream and downstream ends of the reach, respectively, in micrograms per litre.
C_{L_U}, C_{L_D}	Concentration of dispersion and dilution tracer at the upstream and downstream ends of the reach, respectively, in micrograms per litre.
H	Mean depth of flow, in metres.
K	Desorption coefficient for the tracer gas, natural logarithm base, in reciprocal days.
K_2	Reaeration coefficient, natural logarithm base, in reciprocal days.
K_{2_T}, $K_{2_{20}}$	Reaeration coefficient, natural logarithm base, at T^o Celsius and 20^o Celsius, respectively, in reciprocal days.
Log_e	Natural logarithm.
Q	Water discharge, in cubic metres per second.
R	Ratio of the desorption coefficient for the tracer gas to the reaeration coefficient.
T	Water temperature, in degrees Celsius.
Δt	Time of travel of the water from the upstream end to the downstream end of the measurement reach, in days.
V	Mean water velocity, in metres per second.
θ	Temperature correction factor for reaeration coefficients, equal to 1.0241.

PRELIMINARY EXPERIMENTS WITH A MODIFIED TRACER TECHNIQUE FOR REAERATION COEFFICIENT MEASUREMENTS

By

R.E. Rathbun, D.J. Shultz, and D.W. Stephens

ABSTRACT

A modified tracer technique was used to measure reaeration coefficients for a reach of West Hobolochitto Creek near Millard, Miss. Ethylene was used as the tracer gas and Rhodamine-WT dye as the dispersion and dilution tracer. Concentrations of ethylene in the water samples were determined using a gas chromatographic technique. Measured reaeration coefficients were within the range of coefficients predicted with equations from the literature. Results of these preliminary experiments suggest that the modified tracer technique is a potentially useful procedure for reaeration coefficient measurements. Additional evaluation and testing of the technique is in progress.

INTRODUCTION

With the current emphasis on improving the water quality of our streams and rivers, it is essential to be able to measure or predict the reaeration coefficient. It is this coefficient which quantifies the process of reaeration by which a stream replaces the dissolved oxygen consumed in the oxidation of organic wastes.

Procedures for measuring the reaeration coefficient of open-channel flows were evaluated by Bennett and Rathbun (1972). It was concluded that the radioactive tracer technique of Tsivoglou and others (1965, 1968) is far superior to other techniques. Extremely small quantities of tracer can be measured when using radioactive tracers; therefore, they may be the only type of tracer that can be used under certain circumstances. However, because of the hazardous nature of radiation, there are strict controls on the use of radioactive tracers in the natural environment.

Swinnerton and Linnenbom (1967) developed a gas chromatographic procedure for measuring extremely small quantities of low molecular weight hydrocarbon gases in water samples; this suggested the possibility of using one of these gases as the gaseous tracer. Two preliminary experiments in which the tracer technique was used with ethylene as the tracer gas are described.

BASIS OF THE TECHNIQUE

The fundamentals of the tracer technique and its application were described in detail by Tsivoglou and co-workers (Tsivoglou and others, 1965; Tsivoglou, 1967; Tsivoglou and others, 1968; Tsivoglou and Wallace, 1970, 1972; Tsivoglou and others, 1972). Hence, only a brief summary of the technique and a discussion of the modifications used in the present study are presented here.

The tracer technique is based on the observation that the ratio of the rate coefficient for a tracer gas desorbing from water in a stirred tank to the rate coefficient for oxygen being absorbed by the same water is a constant, within experimental error, regardless of the mixing conditions within the stirred tank. The basic procedure, therefore, consists of injecting a quantity of the tracer gas into a stream, determining a desorption coefficient for the gas from measurements of the gas concentration at various points downstream, and converting the desorption coefficient for the tracer gas to a reaeration coefficient for oxygen by means of the constant determined in the laboratory. Because tracers in streams are subject to dispersion, and dilution as a result of flow accrual, it is necessary to adjust the tracer gas concentrations for the effects of dispersion and dilution by injecting a conservative tracer concurrently with the gas tracer and sampling both tracers.

The desorption coefficient, K, of the tracer gas is computed from

$$K = \frac{1}{\Delta t} \log_e \frac{\left(\frac{C_G}{C_L}\right)_U}{\left(\frac{C_G}{C_L}\right)_D} \tag{1}$$

where C_G is the concentration of tracer gas, C_L is the concentration of the conservative dispersion and dilution tracer, the U and D subscripts refer to the upstream and downstream ends, respectively, of the measurement reach, and Δt is time of travel through the reach. The desorption coefficient of the tracer gas is converted to a reaeration coefficient with the relation

$$K_2 = K/R \tag{2}$$

where R is the ratio of the desorption coefficient for the tracer gas to the absorption coefficient for oxygen determined in the laboratory stirred-tank calibration studies.

The three assumptions fundamental to the tracer technique were presented by Tsivoglou (1967). These are as follows: First, it is assumed that the ratio R is independent of mixing conditions, temperature, and the presence of pollutants for the range of conditions occurring in natural streams; second, it is assumed that the dispersion and dilution tracer is conservative; and finally, it is assumed that the tracer gas undergoes the same dispersion and dilution as the conservative tracer and is lost to the atmosphere only by desorption through the water surface.

Basic modification to the technique consists of using ethylene as the tracer gas, Rhodamine-WT dye as the conservative tracer, and continuous injection of the tracer materials.

Ethylene was used as the tracer gas for several reasons. First, it is a hydrocarbon, and, therefore, measurable in microgram-per-litre quantities in water samples by a gas chromatograph with a flame ionization detector. Second, it is one of the more water-soluble of the low molecular weight hydrocarbon gases. Solubility is an important consideration in getting the required amount of tracer gas into the water for the experiments. Third, ethylene has a molecular diffusion coefficient in water about 0.9 that of oxygen in water (Duda and Vrentas, 1968) and, therefore, according to the arguments of Tsivoglou and others (1965), it has mass transfer characteristics desirable in a tracer gas. Finally, ethylene is inexpensive, non-toxic, and its lower flammable limit is considerably above any concentrations occurring in a tracer experiment.

Ethylene is not completely inert biologically, and significant production or degradation of ethylene by the bacterial community of the stream system would affect a measurement of the reaeration coefficient using ethylene as the tracer gas. The role of ethylene in plant biology was reviewed by Abeles (1973). He pointed out that some bacteria and fungi produce small amounts of ethylene, as do higher plants during fruit development. Natural concentrations of ethylene were found in ocean water and considered to be biological in origin (Swinnerton and Lamontagne, 1974). However, concentrations in ocean water were at least two orders of magnitude smaller than concentrations used in the reaeration tracer experiments. Background samples from the stream used for the tracer experiments did not at any time have detectable concentrations of ethylene at the concentration levels used in the experiments.

The assimilation of hydrocarbons by microorganisms was reviewed by Zobell (1950). He stated that almost all kinds of hydrocarbons are susceptible to attack by microorganisms, but that the susceptibility depends greatly on the size and type of the hydrocarbon molecule. For example, methane is attacked by only a few specialized species of bacteria and only with difficulty. However, as the chain length of the paraffin hydrocarbons increases, the number of species and the ease of utilization appear to increase. Olefinic hydrocarbons appear to be more susceptible than their paraffinic homologs. Zobell (1950) and Kabler (1967) discussed the process of acclimatization or adaptation. Zobell observed that many bacteria, which normally lacked the ability to attack hydrocarbons, developed the ability after prolonged exposure to these hydrocarbons. Because ethylene is a volatile gas, and, therefore, only transient in a stream system, it would seem that aquatic bacteria with a particular affinity for ethylene would not normally be abundant. It is clear, however that ethylene cannot be considered completely inert biologically.

Rhodamine-WT dye was used as the conservative tracer concurrently with the tracer gas to permit adjusting the gas tracer concentrations for dispersion and dilution, as well as to indicate when to sample for the tracer gas. In contrast, Tsivoglou and others (1968) used tritium as the conservative tracer and used the dye only to indicate when to sample for the radioactive tracers. Some fluorescent dyes are subject to adsorption losses on suspended sediment, bottom materials, and vegetation. However, Rhodamine-WT dye has the lowest potential for loss of any dye currently available, and is the dye tracer most frequently used by the U.S. Geological Survey for dispersion studies and dye-dilution discharge measurements (Cobb and Bailey, 1965; Kilpatrick, Martens, and Wilson, 1970). For the purpose of this study, it was assumed that Rhodamine-WT dye is a conservative tracer. This assumption can be checked by measuring the dye concentration-versus-time curves for the upstream and downstream ends of the reach, the water discharges at these points, and comparing the areas under the curves after adjusting for flow accrual or loss. This was done for one of the experiments and results will be described later.

The final modification of the tracer technique was the use of a continuous injection as compared with the slug injection used by Tsivoglou and others (1968). The primary reason for this change is that a slug injection requires a quantity of tracer solution too large to handle easily. The limiting factor is the solubility of ethylene in water, 131 mg/ℓ (milligrams per litre) at 25°C.

EXPERIMENTAL PROCEDURE

Two experiments were conducted on a reach of West Hobolochitto Creek near Millard, Miss. The measurement reach was 4,190 m (13,800 ft) long. Low flow conditions existed at the time of the studies. For run 1, the discharge was 1.21 m^3/s (42.6 ft^3/s), and for run 2 the discharge was 0.94 m^3/s (33.3 ft^3/s). Under these conditions, West Hobolochitto Creek was a pool-and-riffle stream with a large variety of hydraulic features. The bottom was predominantly sand, although some clay areas existed in the riffle sections. The stream meandered throughout the measurement reach and contained numerous trees, logs, and other debris.

The experimental procedure consisted of three steps: Injecting the tracers into the stream, sampling the tracers at downstream points, and analyzing the samples for concentrations of the tracers. Each of these steps is described in the following sections.

Injection of the Tracers

The ethylene tracer gas was injected into the stream by bubbling the gas through a porous tube diffuser like those used for aeration in sewage treatment plants. The diffuser was 0.61 m (2.0 ft) long, 64 mm (2.5 in) in outside diameter, and 9.53 mm (0.375 in) thick. The average pore size was 60 micrometres. The tube was mounted in a frame and placed on the bottom of the stream, generally at the deepest point or the area of largest flow. Ethylene was fed directly from a high-pressure cylinder through a two-stage regulating valve and a rotameter for monitoring the flow to the diffuser tube. Technical grade ethylene was used.

The ethylene flow rate and the length of the injection period were adjusted to give a peak ethylene concentration at the downstream end of the measurement reach of at least 1 μg/ℓ (microgram per litre). This concentration was approximately the lower limit of the range of concentrations which could be measured with good precision by the gas chromatographic analysis procedure. The quantity of ethylene required to give this concentration is a function of the combination of a number of variables. Among these are the water discharge, reaeration coefficient, dispersion coefficient, time of travel, flow accrual, and the efficiency of the absorption process which in turn depends on the flow rate of the ethylene through the diffuser, the depth of water over the diffuser, and, to some extent the flow velocity at the injection point. The water temperature also affects the absorption process through its effect on the solubility. Because the parameter being measured is among these variables, and also because little is known about the absorption efficiency of the diffuser tube for gases other than air or oxygen, it was possible at this stage of developing the technique only to estimate the flow rate and injection time needed.

For run 1, a total of 1.2 kg (2.6 lb) of ethylene was injected over a 90-minute period. For run 2, a total of 1.9 kg (4.2 lb) of ethylene was injected over a 100-minute period. At the time of the experiments (August, 1974) technical grade ethylene cost $1.25 per pound, hence, the cost of the tracer gas was insignificant. In essence, the injection process was not a true continuous injection process because plateau concentrations generally were not achieved at downstream measurement sections. The injection was continued only long enough to obtain the desired concentration of ethylene in the stream.

A Rhodamine-WT dye and water solution was injected at the same injection point and for the same injection period as was used for the ethylene in each run. A pressure-type injection tank was used to obtain the continuous injection. Details of the design and operation of this tank were described by Cobb (1967). Dye injection rates and concentrations appropriate for the water discharges were estimated using equations presented by Cobb and Bailey (1965).

Sampling the Tracers

A dye-detection system consisting of a fluorometer with a flow-through door, a pump, and a portable generator was set up at the first sampling point. This point was 900 m (3,000 ft) and about 1.5 hours time of travel downstream from the injection point, thus the tracers should have had ample time to become uniformly mixed in the vertical and lateral directions of the flow. Upon arrival of the dye, samples of the water were obtained from the stream at approximately the center of the flow. Samples were also collected at the right and left quarter points of the cross section to verify that lateral mixing was complete.

Samples for gas analysis were obtained by allowing the water to flow slowly into a 60-ml (2.0-fl oz) glass bottle with a ground-glass stopper. Because it was necessary to collect a large number of samples in a relatively short time period as the tracer peaks passed, it was not possible to use a displacement-type sampler commonly used in sampling for dissolved gases. The sample bottles were held in the flow such that they filled with a minimum amount of turbulence. Samples were refrigerated until analysis to retard any possible biological degradation. Samples for dye analysis were obtained in 32-ml (1.1-fl oz) polyseal-cap bottles.

Sampling was continued as the dye peak passed the sampling point and until it was estimated that a sufficient number of samples had been obtained to define accurately the peaks of the concentration-versus-time curves for the tracer gas and the dye. The equipment was then moved to the next sampling point. Sampling at intermediate locations and at the downstream end of the reach was limited to one point at the center of the flow.

In run 1, samples were collected at three points in the measurement reach, 780 m (2,550 ft), 2,680 m (8,800 ft), and 4,190 m (13,800 ft) downstream from the injection point. In run 2, samples were collected at five points in the measurement reach, 780 m (2,550 ft), 1,720 m (5,650 ft), 2,680 m (8,800 ft), 3,370 m (11,100 ft), and 4,190 m (13,800 ft) downstream from the injection point. Figure 1 is a sketch of the experimental reach showing the relative locations of the injection point and the sampling points.

In addition to collecting samples for both gas and dye concentration determinations, discharge measurements using a current meter and standard U.S. Geological Survey procedures (Buchanan and Somers, 1969) were made, usually at the upstream and downstream ends of the measurement reach.

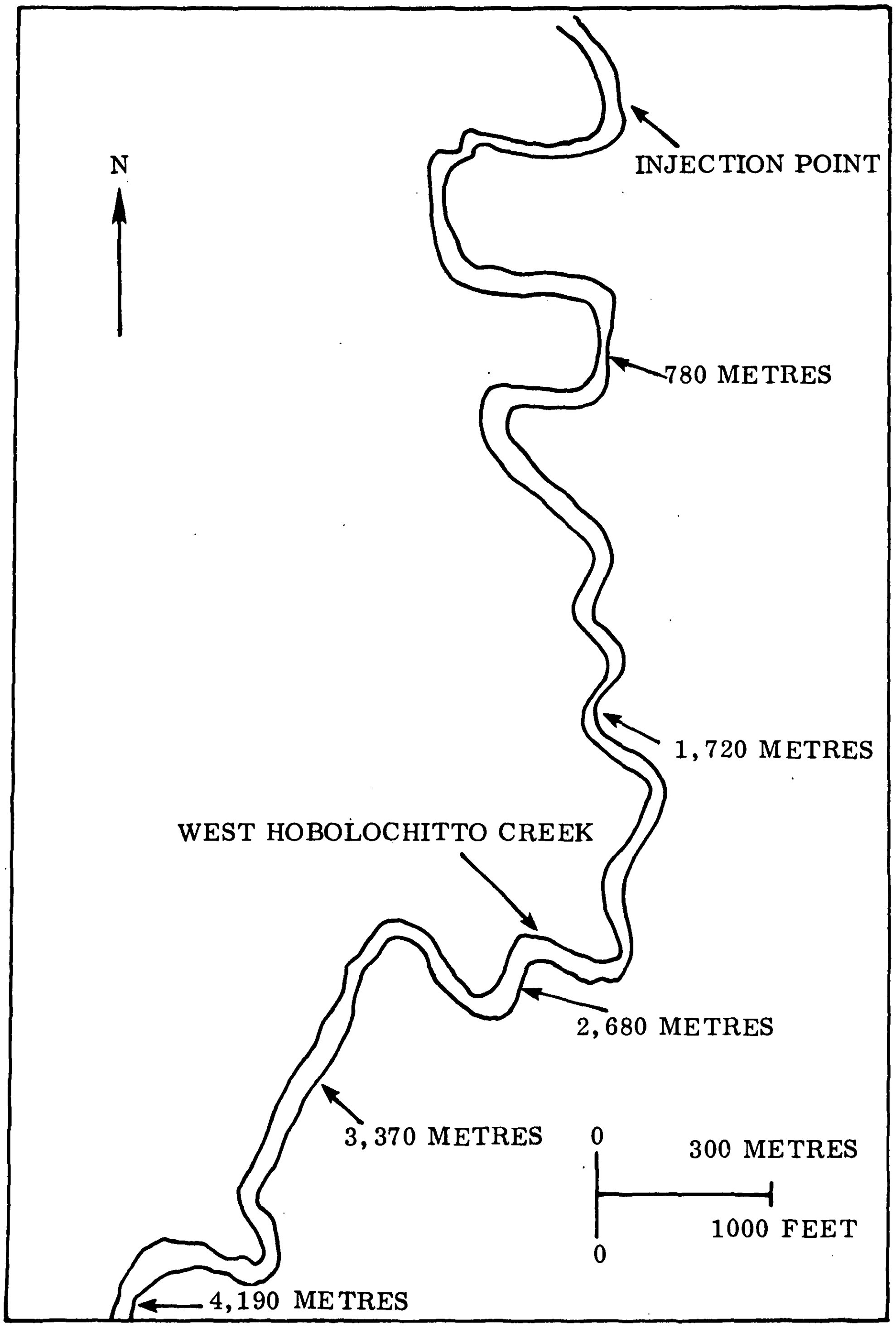

Figure 1.-- Sketch of the experimental reach showing the relative locations of the injection point and sampling points.

Sample Analysis

Ethylene concentrations in the water samples were determined using a modification of the gas chromatographic technique of Swinnerton and Linnenbom (1967). Basically the technique consisted of introducing a known aliquot of the water sample into a stripping column, stripping the ethylene from the water with helium gas, trapping the ethylene in a cold trap, warming the trap once the stripping process was completed, and flushing the ethylene from the cold trap into a gas chromatograph equipped with a flame ionization detector.

Dye samples were analyzed using a fluorometer and standard techniques described by Cobb and Bailey (1965), Wilson (1968), and Kilpatrick, Martens, and Wilson (1970).

PRESENTATION AND DISCUSSION OF RESULTS

Results obtained from the tracer experiments consisted of concentration-versus-time data for ethylene and dye for each of the sampling points. The ethylene and dye concentration data from the three sampling points of run 1 are presented in figures 2 and 3, and the data from the five sampling points of run 2 are presented in figures 4 and 5. The decrease of the peak concentrations with distance downstream is apparent as is the tendency for the curves to become flatter with distance downstream.

From curves such as these, the peak concentration and the time of the peak were determined for the ethylene and dye for each measurement point. These values are presented in table 1. Sampling points are designated by the distance in metres downstream from the injection point for the tracers.

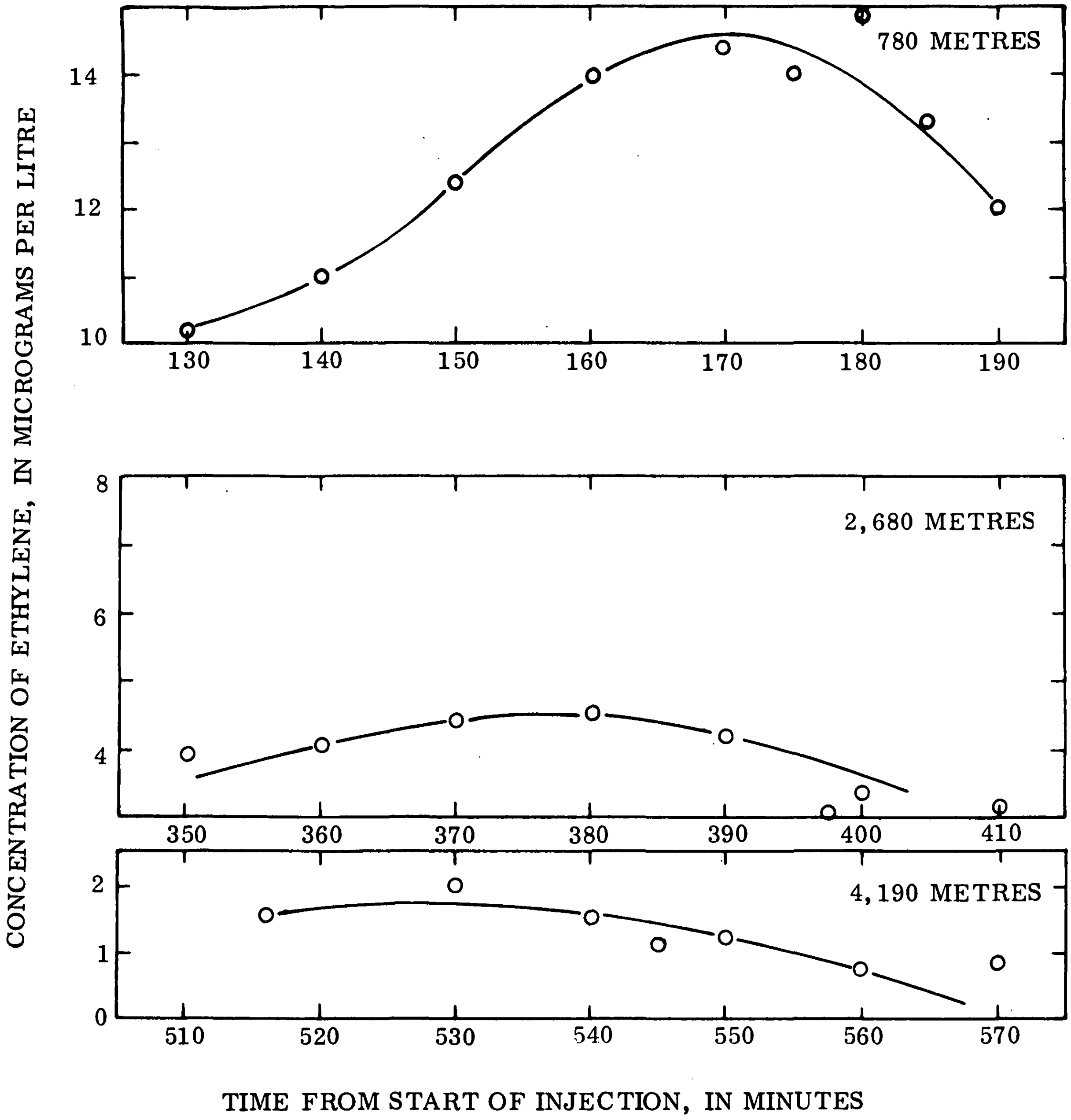

Figure 2. -- Concentration of ethylene versus time for the three sampling points of 780 m (2,550 ft), 2,680 m (8,800 ft), and 4,190 m (13,800 ft) downstream from the injection point for the tracers; run 1.

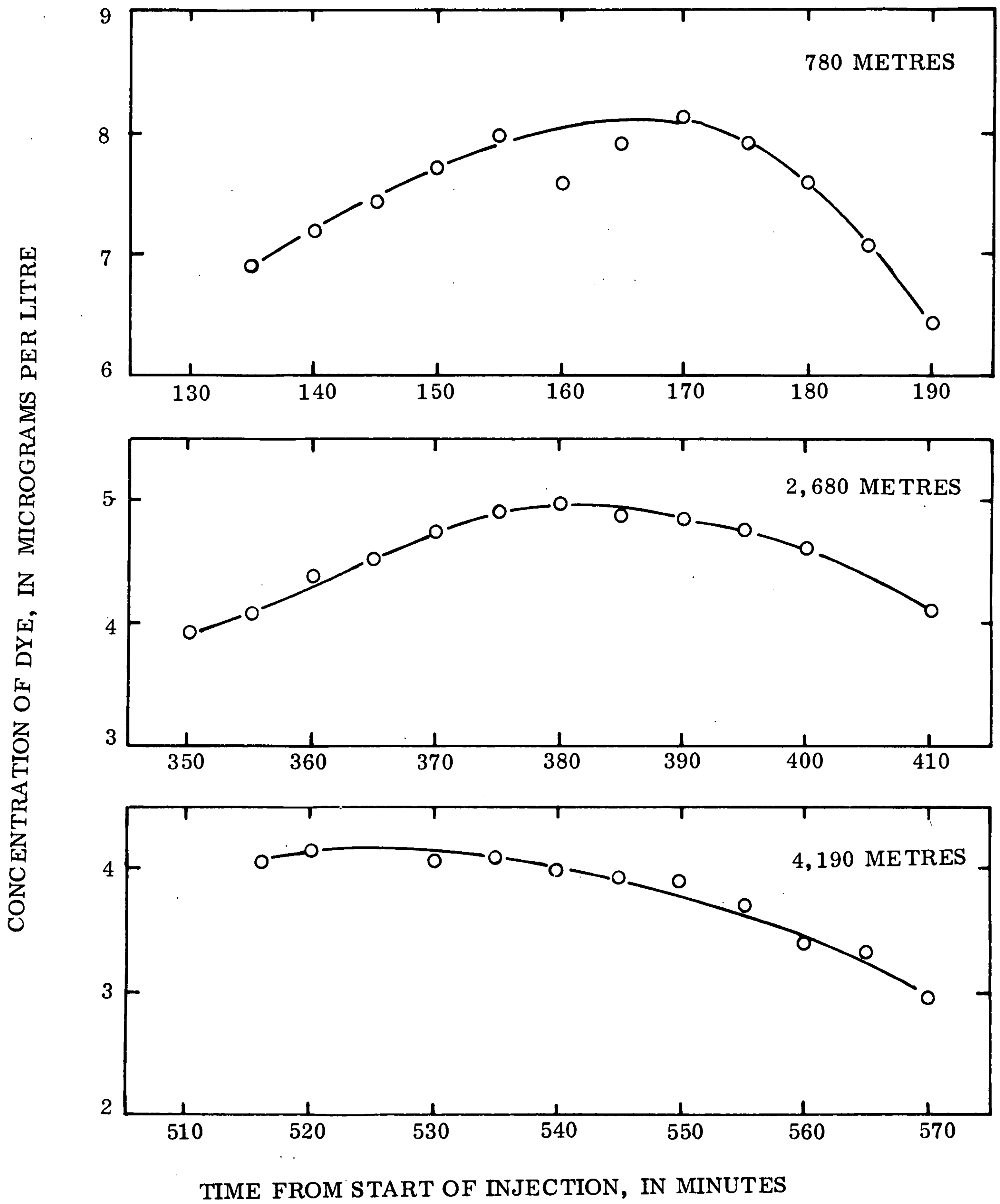

Figure 3. -- Concentration of dye versus time for the three sampling points of 780 m (2,550 ft), 2,680 m (8,800 ft), and 4,190 m (13,800 ft) downstream from the injection point for the tracers; run 1.

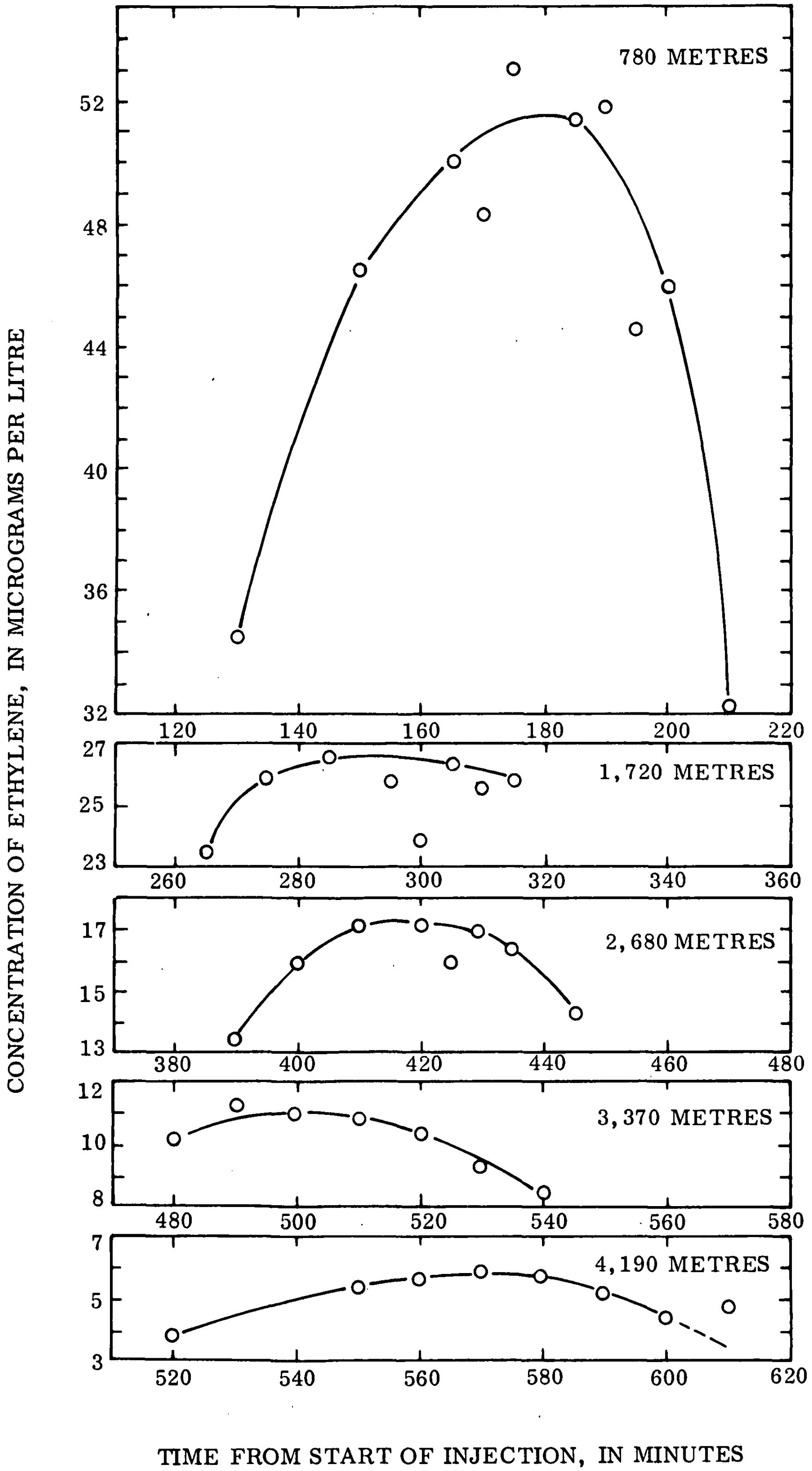

Figure 4. -- Concentration of ethylene versus time for the five sampling points of 780 m (2,550 ft), 1,720 m (5,650 ft), 2,680 m (8,800 ft), 3,370 m (11,100 ft), and 4,190 m (13,800 ft) downstream from the injection point for the tracers; run 2.

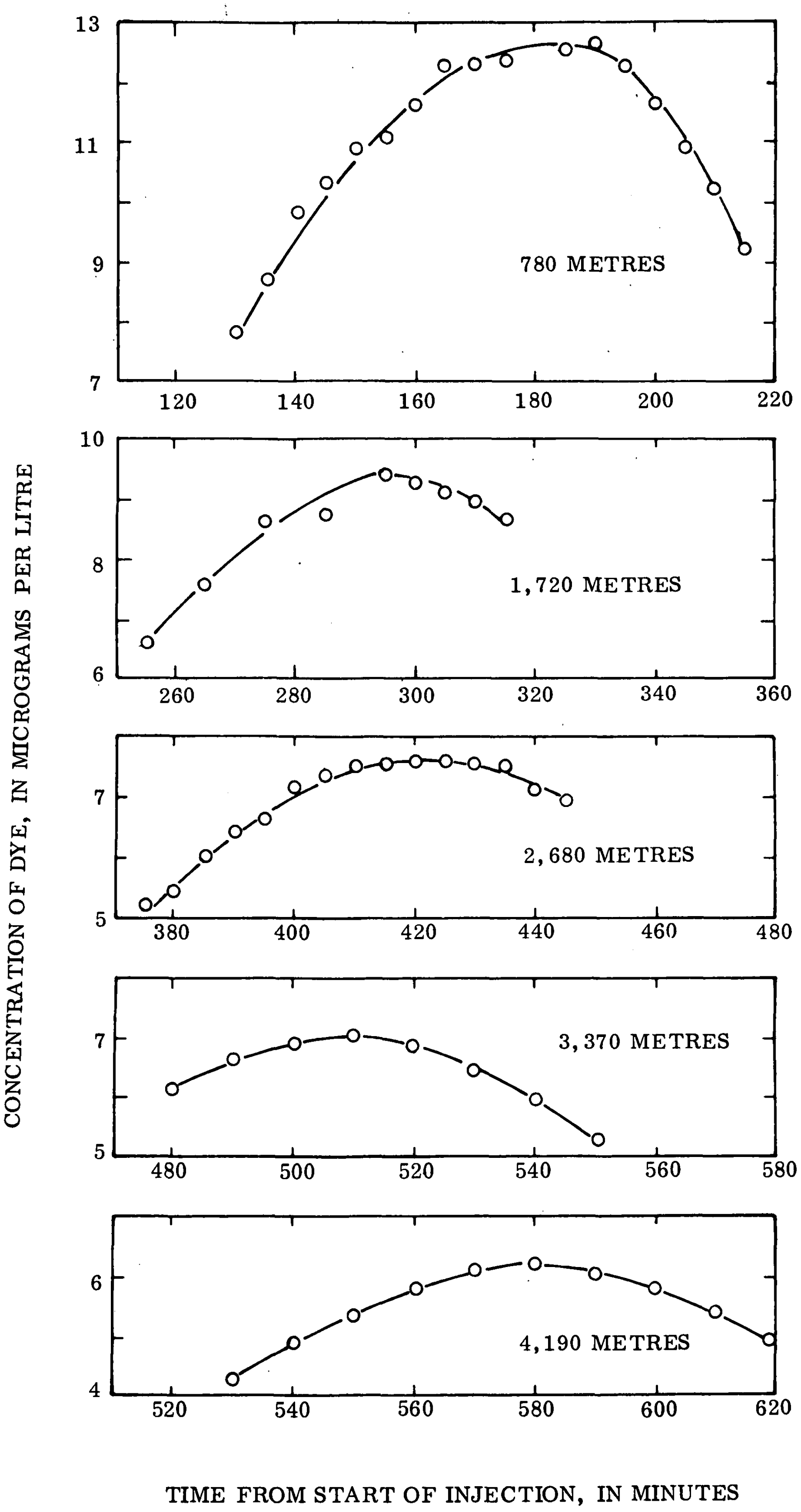

Figure 5. -- Concentration of dye versus time for the five sampling points of 780 m (2,550 ft), 1,720 m (5,650 ft), 2,680 m (8,800 ft), 3,370 m (11,100 ft), and 4,190 m (13,800 ft) downstream from the injection point for the tracers; run 2.

Table 1. -- Peak concentrations and peak times for ethylene and dye.

Run	Sampling point, in metres	Peak concentration, in µg/ℓ Ethylene	Peak concentration, in µg/ℓ Dye	Peak time, in minutes Ethylene	Peak time, in minutes Dye
1	780	14.6	8.10	170	170
	2,680	4.51	4.97	379	380
	4,190	1.75	4.17	526	525
2	780	51.5	12.6	180	186
	1,720	26.7	9.43	293	295
	2,680	17.3	7.62	420	420
	3,370	11.0	7.06	504	510
	4,190	5.99	6.25	580	580

A series of laboratory stirred-tank studies with a variety of mixing conditions, three water temperatures, and with various substances added to the water was completed to determine the value for ethylene of R in equation 2; a mean value of 0.89 was obtained. Using this value of R, the peak concentrations in table 1, and the times of travel determined from the dye peak times, reaeration coefficients were computed for the various subreaches and the overall reach using equations 1 and 2. Results are presented in table 2. Also presented in table 2 are the mean water velocity as determined from the dye measurements, the mean water temperatures at the time of the runs, and the water discharge measured at the downstream end of the reach.

Table 2. --Observed reaeration coefficients, water discharges measured at downstream end of reach, mean water temperatures, and mean velocities determined from dye concentration curves.

Run	Reach, in metres	Discharge, in m^3/s	Mean velocity, in m/s	Mean water temperature, in °C	Reaeration coefficient, K_2, in $days^{-1}$
1	780 to 2,680		0.151		5.29
	2,680 to 4,190		.173		8.60
	Overall 780 to 4,190	1.21	.160	27	6.64
2	780 to 1,720		0.144		5.45
	1,720 to 2,680		.128		2.86
	2,680 to 3,370		.127		6.77
	3,370 to 4,190		.196		11.2
	Overall 780 to 4,190	.94	.144	27	5.96

To compare the experimental reaeration coefficients with coefficients estimated from predictive equations, it was necessary to determine mean velocities and depths of flow for the measurement reach. Therefore, mean hydraulic parameters were determined for two flow conditions. Four days prior to run 1, cross section measurements at 150-m (500-ft) intervals and eight discharge measurements spaced over the measurement reach were obtained. Similarly, 2 days after run 1, and 6 days prior to run 2, cross section measurements at 75-m (250-ft) intervals and eight discharge measurements spaced over the measurement reach were obtained. The water discharge at the downstream end of the measurement reach was 1.78 and 1.09 m^3/s (62.8 and 38.5 ft^3/s) for the first and second sets of cross section measurements, respectively, and the discharge at the time of the tracer runs was 1.21 and 0.94 m^3/s (42.6 and 33.3 ft^3/s) for runs 1 and 2, respectively. Thus, an interpolation and a slight extrapolation were necessary to adjust the mean hydraulic parameters at the times of the cross section measurements to the discharge conditions prevailing at the time of the tracer runs. This interpolation and extrapolation were accomplished assuming equations of the form

$$H = a\,Q^{b} \qquad (3)$$

and

$$V = c\,Q^{d} \qquad (4)$$

where H is the mean depth of flow, V is the mean velocity of flow, Q is the water discharge, and a, b, c, and d are empirical constants. Mean velocities and depths of flow thus determined for the various subreaches and the overall reach are presented in table 3.

Table 3. -- Mean velocities and depths of flow

Run	Reach, in metres	Mean velocity, in m/s	Mean depth of flow, in metres
1	780 to 2,680	0.198	0.500
	2,680 to 4,190	.223	.439
	Overall (780 to 4,190)	.209	.472
2	780 to 1,720	0.191	0.439
	1,720 to 2,680	.168	.491
	2,680 to 3,370	.168	.463
	3,370 to 4,190	.197	.411
	Overall (780 to 4,190)	.181	.454

Comparison of the mean velocities determined from the time of travel of the dye peaks (table 2) with the mean velocities determined from the cross section and discharge measurements (table 3) shows that, with one exception, the dye velocities are lower, averaging about 76 percent of the mean hydraulic velocities. The exception is the 3,370 to 4,190 m (11,100 to 13,800 ft) reach of run 2 for which there was virtually no difference in the velocities. The lower velocities as measured by the dye were apparently the result of several deep pools which significantly affected the time of travel. The exception has the shallowest mean depth of any reach, and, therefore, is affected least by these pools. Because the dye tracers measure the actual mean velocities at the time of the tracer experiments, these velocities are representative of the true conditions more so than the mean hydraulic velocities based on discharge measurements. Hence, the dye velocities are used with the depth of flow data to compute predicted reaeration coefficients.

Reaeration coefficients at 20°C were computed with the equations of Owens, Edwards, and Gibbs (1964), Churchill, Elmore, and Buckingham (1962), Langbein and Durum (1967), Negulescu and Rojanski (1969), O'Connor and Dobbins (1958), and Bennett and Rathbun (1972). The equations of Owens, Edwards, and Gibbs (1964) and Langbein and Durum (1967) gave maximum and minimum predicted reaeration coefficients, respectively, for the hydraulic conditions of the runs. The predicted reaeration coefficients together with the experimental reaeration coefficients corrected to 20°C are presented in table 4.

The temperature correction was made using the equation

$$K_{2_T} = K_{2_{20}} \theta^{(T-20^\circ)} \qquad (5)$$

where a value of 1.0241 was used for θ (Elmore and West, 1961) and T is the temperature in degrees Celsius. The average water temperature for both tracer runs was 27°C.

Table 4. -- Experimental and predicted reaeration coefficients at 20°C.

Run	Reach, in metres	Reaeration coefficients, K_2, in days^{-1}						
		Exp.	Owens and others (1964)	Churchill and others (1962)	Langbein Durum (1967)	O'Connor Dobbins (1958)	Negulescu Rojanski (1969)	Bennett Rathbun (1972)
1	780 to 2,680	4.48	6.33	2.56	1.95	4.33	3.95	5.71
	2,680 to 4,190	7.28	8.79	3.64	2.66	5.63	4.96	7.74
	Overall (780 to 4,190)	5.62	7.29	2.98	2.23	4.85	4.36	6.51
2	780 to 1,720	4.61	7.69	3.05	2.22	5.14	4.25	6.93
	1,720 to 2,680	2.42	5.79	2.25	1.69	4.09	3.48	5.33
	2,680 to 3,370	5.73	6.37	2.46	1.82	4.45	3.64	5.85
	3,370 to 4,190	9.48	10.8	4.56	3.28	6.59	5.81	9.29
	Overall (780 to 4,190)	5.05	7.24	2.88	2.12	4.88	4.13	6.54

Consideration of the results in table 4 shows that all the experimental reaeration coefficients are within the ranges of the values estimated with the predictive equations. The experimental values generally are smaller than the values predicted by the equations of Owens and others (1964) and Bennett and Rathbun (1972) and larger than the values predicted by the other four equations. The mean percentage differences, computed without regard to the algebraic sign of the difference, are 22, 26, 32, 42, 46, and 57 percent for the equations of O'Connor and Dobbins (1958), Negulescu and Rojanski (1969), Bennett and Rathbun (1972), Churchill and others (1962), Owens and others (1964), and Langbein and Durum (1967), respectively.

The various predictive equations considered were developed from data covering a wide range of hydraulic conditions. In selecting an empirical predictive equation, it is generally preferable to use one based on data covering the same range of hydraulic conditions as observed in the experimental runs. Of the equations considered, the range of velocities and depths for the studies of Owens and others (1964) on small English streams was approximately the same as the range of velocities and depths observed in the tracer runs. The other predictive equations were based on data for larger and deeper flows. Therefore, the equation of Owens and others (1964) should be the most suitable equation for predicting reaeration coefficients for West Hobolochitto Creek.

Consideration of the results in table 4 shows, however, that the experimental values average 46 percent less than the values predicted with the equation of Owens and others (1964), and this percentage difference is the second largest observed. Thus, for these limited tests, the equation of Owens and others (1964) either predicted reaeration coefficients that are too large or the experimental reaeration coefficients are too small.

There are several possible ways in which the tracer technique could give reaeration coefficients that are too small. Among these are losses of the dispersion and dilution tracer and sources of the tracer gas within the stream system other than the injected tracer, with the latter not very probable. The tracer technique would also give a measured reaeration coefficient smaller than the coefficient expected for the hydraulic conditions in the stream if a pollutant were present that retards desorption of the tracer gas. In this instance, however, the tracer technique would give the true reaeration coefficient for conditions in Hobolochitto Creek at the time of the measurement, whereas the predictive equation would give a coefficient appropriate for the same hydraulic and water-quality conditions in the English streams where the data were collected for development of the equation.

There is no basis to suggest that the equation of Owens and others (1964) predicts reaeration coefficients that are always too large. Although the mean depths and velocities covered the same range for the two studies, there could be differences in other hydraulic parameters not included in the correlation or in the characteristics of the water that resulted in the differences in the reaeration coefficients.

If dye losses were to occur, then the downstream dye concentrations would be reduced, and the measured reaeration coefficients would be smaller than the true values. In run 1, sufficient dye samples were obtained so that the concentration-versus-time curves could be estimated for both the upstream and downstream ends of the reach. The area under the downstream curve was 18 percent less than the area under the upstream curve, indicating dye loss and (or) flow accrual. Discharge measurements indicated an 8.1 percent flow accrual, resulting in a net 11 percent dye loss. Neglecting this dye loss results in a 6.7 percent error in the measured reaeration coefficient for the overall reach of run 1. This estimate of the dye loss tended to be a maximum for two reasons. First, it was not practical to sample completely the very long tail of the dye distribution at the downstream end of the reach, and hence, the true area may be slightly larger than the measured area if the tail concentrations are under estimated. Second, any deviations from complete lateral mixing at the upstream end of the reach would result in concentrations at the center of the channel that are too large, and hence, the measured area would be larger than the true area for complete lateral mixing. Therefore, the assumption that Rhodamine-WT dye is a conservative tracer was not a large source of error in run 1.

The use of reaeration coefficients predicted by empirical equations as a basis for verifying a measurement procedure can be criticized because of the well-known difficulties associated with predicting reaeration coefficients for streams. The wide range of predicted reaeration coefficients presented in table 4 emphasizes this difficulty. Therefore, the comparison of the results presented in table 4 should be considered as approximate only. It is encouraging, however, that the experimental results are all within the range of values estimated with the various predictive equations.

These comparisons and the general overall results of the preliminary experiments suggest that the modified tracer technique is a potentially useful procedure for reaeration coefficient measurements. The ability to inject ethylene into a stream, to sample, and to analyze water samples containing microgram-per-litre quantities of the gas was demonstrated. A possible difficulty with the modified technique is that ethylene may not be completely inert biologically, although a review of the literature suggests that low molecular weight hydrocarbon gases are least susceptible of any hydrocarbon to microbial degradation.

Summary

A modified tracer technique, in which ethylene was used as the tracer gas and Rhodamine-WT dye was used as the dispersion and dilution tracer, was applied to the measurement of reaeration coefficients for a reach of West Hobolochitto Creek near Millard, Miss. A continuous injection of both tracers was used. Gas concentrations were determined using a gas chromatographic technique and dye concentrations were determined using a fluorometric technique. Discharge and cross section measurements were obtained so that mean velocities and depths of flow could be determined for the measurement reach. The depth of flow values and mean velocities determined from the dye curves were used to estimate reaeration coefficients with several predictive equations from the literature. The experimental reaeration coefficients were within the ranges of values estimated with the predictive equations, with the mean percentage differences ranging from 22 to 57 percent.

Results of these preliminary experiments suggest that the modified tracer technique is a potentially useful procedure for reaeration coefficient measurements. The principal advantage is that radioactive tracers are not necessary. A question remains regarding the biological inertness of the ethylene tracer gas.

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