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Hon. Keith C. Norton, Q.C., *Minister*

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# **FIELD MEASUREMENTS OF STREAM REAERATION COEFFICIENT**



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OF STREAM REAERATION COEFFICIENT**

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## **ABSTRACT**

Studies were carried out during the summer of 1978, to measure the atmospheric reaeration rate coefficients for selected reaches of the Grand and Speed rivers as part of the Grand River Basin Water Management Study.

The measurement technique described in this report - the "modified tracer" technique - was developed by the United States Geological Survey, U.S. Department of the Interior. It utilizes ethylene as a tracer gas and Rhodamine WT dye as a dispersion and dilution tracer.

This report describes theoretical background, experimental procedure and data analysis for the study of reaeration rates in surface waters. The field study section outlines typical manpower and equipment requirements and sampling location considerations. Schematic diagrams show the method of dye injection and dye detection systems. Sample data are then subjected to typical computations, and a comparison is made between experimental and predicted reaeration rates. A listing of the computer program HGREDYET, developed to compute reaeration rate coefficients, and a sample copy of the input and output are presented in the Appendix.

The results of these studies indicate that the modified tracer technique is a useful tool for measuring the atmospheric reaeration rate coefficient.



## ACKNOWLEDGEMENTS

The author is indebted to Mr. L. Van Biesbrouch, who adapted this technique from the USGS method (Rathburn *et al*, June 1975) and carried out initial hardware assembly, testing and experimentation for this Unit.

The author would like to thank Dr. T.P.H. Gowda for providing guidance in the preparation of this report, Messrs. F.C. Fleischer and D.G. Weatherbe and Dr. I. W. Heathcote for reviewing it, and Messrs. D. Draper, P. Basu and J. Penny for their assistance in collecting the field data.

Measurement of the atmospheric reaeration coefficient was carried out as part of the activities of the River Systems Unit, Water Modelling Section, Water Resources Branch, Ontario Ministry of the Environment. The particular examples used in the text were based on field work carried out in the Grand River Basin Water Management Study.

Word processing for this report was carried out by Mrs. N. Pestano.



## 1. INTRODUCTION

The ability of a stream to maintain an adequate supply of dissolved oxygen for the support of aquatic life has been an important concern in water pollution control. In particular, it determines the amount of oxygen-demanding wastes that can be discharged into a stream without severely depleting its dissolved oxygen resources.

The replenishment of dissolved oxygen depends primarily on reaeration through the water surface exposed to the atmosphere. It is generally accepted that the rate of reaeration can be represented by a first order process as follows:

$$dc/dt = k_2 (c_s - c)$$

where  $c$  = concentration of dissolved oxygen in a stream  
 $c_s$  = saturation value of dissolved oxygen  
 $t$  = time  
 $k_2$  = reaeration coefficient

The reaeration coefficient hence indicates the capacity of a stream to assimilate oxygen-demanding wastes. Obviously, a knowledge of this coefficient is of value to those regulatory agencies and municipalities that are concerned with determining appropriate levels of waste water treatment.

Several empirical and semi-empirical formulae are available for estimating the reaeration coefficient for a stream (1). However, the applicability of these formulae may be hindered by the disparity between the stream of interest and the conditions for which these formulae were derived. Consequently, there is a real need for a practical field survey technique that can produce reliable estimates.

This report describes the adaptation of a field technique developed by Rathburn, Schultz and Stephens (2) for determining the reaeration coefficient in open channel flow. Ethylene is used as a tracer gas and Rhodamine WT dye as the dispersion and dilution tracer.

## 2. THEORETICAL BACKGROUND

The modified tracer technique by Rathburn *et al.* (2) is based on the observation that the ratio between the rate coefficient of a tracer gas desorbing from water in a stirred tank and the rate coefficient for oxygen being absorbed by the same water is constant regardless of the mixing conditions (3).

The rate of desorption of a tracer gas is directly proportional to the change in concentration of gas in water, and is expressed mathematically by the relation

$$dc/dt = k (c_{\infty} - c)$$

in which  $c$  = the concentration of the gas in the water at time  $t$ ;  $c_{\infty}$  = the concentration of the gas in the water in equilibrium with the atmosphere at steady state conditions; and  $k$  = the rate coefficient or "desorption coefficient". However, it is assumed that the concentration of ethylene gas in the atmosphere above the water surface is zero, thus the equilibrium concentration in the water will be zero and the equation now becomes

$$dc/dt = -kc$$

Integration of this equation:

$$-\int_{c_1}^{c_2} dc/c = k \int_{t_1}^{t_2} dt$$

where  $c_1$  and  $c_2$  are concentrations of tracer gas at times  $t_1$  and  $t_2$ , respectively, yields

$$\ln c_1/c_2 = k (t_2 - t_1) = k \Delta t$$

and  $k = (1/\Delta t) \ln (c_1/c_2)$  (1)

Since tracers injected into a stream are subject to the dispersion and dilution effects of flow accrual, it is necessary to adjust the tracer gas concentration for these effects by injecting a conservative tracer concurrently with the gas tracer and sampling both tracers simultaneously.

The desorption coefficient,  $k$ , of the tracer gas subject to dispersion and dilution effects, is determined from

$$k = (1/\Delta t) \ln [(c_g / c_i)_u] / [(c_g / c_i)_d] \quad (2)$$

where

$c_g$  = concentration of tracer gas

$c_i$  = concentration of the conservative tracer

$u$  = subscript denoting upstream end of a stream reach

$d$  = subscript denoting downstream end of the reach

$\Delta t$  = time of travel through the reach in days

$k$  = desorption coefficient of gas (to base  $e$ )

The desorption coefficient of the tracer gas is related to the reaeration coefficient by

$$k_2 = k/R \quad (3)$$

where  $R$  is the ratio of the desorption coefficient for tracer gas to the absorption coefficient for oxygen. Low molecular weight hydrocarbon gases such as ethylene, propane, etc. can be used as the tracer gas. For this study, ethylene gas was used for reasons noted in the following section. In laboratory stirred-tank calibration studies using ethylene as the tracer gas, the value of the ratio  $R$  was found to be 0.89 (2). In 1978, Rathburn *et al.* (4) conducted further laboratory studies and found  $R$  to be closer to 0.87. However, for this study,  $R$  was taken as 0.89 based on results reported in Ref. 2.

### 3. PROPERTIES OF TRACER GAS AND DYE

The tracer technique is based on the following assumptions:

- (1) The ratio R is independent of the mixing conditions occurring in natural streams.
- (2) 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.

Because of these assumptions, tracer gas and dye substances must have certain properties. For the modified tracer technique, the preferred materials are ethylene as the non-conservative tracer gas, and Rhodamine WT dye as the conservative tracer.

Reasons for using ethylene as the tracer gas are as follows (2, 5):

- i) It is a hydrocarbon measurable in micrograms per litre in water samples by a gas chromatograph with a flame ionization detector.
- ii) It is one of the most water soluble, low molecular weight hydrocarbon gases. (Solubility of a gas in water is an important factor in getting the required amount of tracer gas into the water for reaeration studies.)
- iii) It has a molecular diffusion coefficient in water close to that of oxygen in water (i.e., it has the mass transfer characteristics required of an ideal tracer gas).
- iv) It is relatively inexpensive, non-toxic at the concentrations encountered in practice and has a lower flammable limit than other hydrocarbon gases.
- v) It is a volatile gas and is only transient in streams. Hence, aquatic bacteria with particular affinity for ethylene are not likely to become abundant in the streams into which ethylene gas is injected.

Rhodamine WT dye is used as the conservative tracer because of the following reasons:

- (1) It is a fluorescent dye that possesses all the characteristics of a good tracer e.g. high detectability, low sorptive tendency, good diffusivity, low acidity and low photo-chemical decay.

Fluorescent dyes possess properties which allow their detection at extremely low concentrations with the naked eye.

Furthermore, they provide the least expensive method of tracing and with the development of modern fluorometric techniques, they can not only be detected but quantitatively measured at levels of less than one part per billion (ppb) (6). Tests conducted by Smart and Smith (7), (quoted by Smart and Laidlaw (8)) on several dyes concluded that Rhodamine WT is generally the most satisfactory dye for water tracing.

- (2) Because of the above-mentioned properties, Rhodamine WT dye permits measurement of dispersion and dilution. Thus, the tracer gas concentrations can be adjusted for these effects. Its presence also helps to indicate when to sample for the tracer gas. One word of caution: Rhodamine WT dye has demonstrated DNA-modifying activity and mutagenic activity (D. Rokosh, MOE Laboratory Services Branch, 1980; personal communication). Protective clothing should be worn to avoid direct contact with the dye.

## 4. FIELD METHODOLOGY

To determine the atmospheric reaeration coefficient for any stream, a quantity of tracer gas is injected into the stream. The desorption coefficient for the gas is then determined from measurements of the gas concentrations at various points downstream and used to compute the reaeration coefficient for oxygen by means of a constant determined in the laboratory. The constant used is the ratio, R, described in Equation 3; the value of R in this study was taken as 0.89. To adjust the tracer gas concentrations for the effects of dispersion and dilution, a conservative tracer is simultaneously injected with the tracer gas and both tracers are sampled downstream. These two major steps of injection and sampling of the tracers are described in the following sections.

### 4.1 Injection of the Tracers

#### 4.1.1 Equipment and Manpower Requirements

Equipment and manpower requirements for an average size stream in southern Ontario\* are listed below. Figures 2 and 3 show the purpose or use of most of the equipment; the rest are self explanatory.

#### Equipment

- a) high pressure turbine type pump with variable rpm and dynamic head of 120 m at a minimum flow of 27 litres per minute. This is essential in order to maintain a constant flow rate of the tracers.
- b) 1 Mariotte tank - a dye container that maintains a constant flow rate of dye solution.
- c) 30 m of 6 mm internal diameter polyethylene tubing (used to connect the ethylene gas to the discharge hose of the high pressure pump).
- d) 4.5 kg. cylinder of ethylene gas with a regulating valve.

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\* A reach of the Speed River, Ontario was used with a study length of 3561 meters, flow of 2.12 m<sup>3</sup>/sec, width of 35 meters, average depth of 0.5 meters and a total travel time of seventeen hours.



- e) 15 m of 1.2 cm internal diameter garden hose. In some cases more than 15 m may be required. This length varies with the width of the river and is used as the discharge hose of the high pressure pump.
- f) 15 m of 1.2 cm internal diameter garden sprinkler hose. This length varies with the width of the stream or river and forms the porous tube diffuser. Porous tube diffusers up to 50 m have been used effectively.
- g) 1 fluorometer.
- h) 1 Jabsco bilge pump.
- i) 1 - 12 volt battery.
- j) 3 short lengths (each approx. 2 meters long) of 1.2 cm internal diameter garden hose, opaque type. (One length is used to connect to the intake of the fluorometer, another to the discharge end of the fluorometer and intake of the bilge pump and the third length to the discharge end of the bilge pump).
- k) Coolers for storing water samples.
- l) 2 hand crimpers for clamping aluminum seals over the butyl rubber septa on the hypo-vials.
- m) 72 bacti bottles for dye samples.
- \* n) 72 hypo-vials for ethylene samples #12944.
- \* o) 72 butyl rubber septa #13050 used for sealing hypo-vials.
- \* p) 72 aluminium seals #13214.
- q) 3-25 ml pipettes.
- r) 1 thermometer.
- s) 72 labels.
- t) 3 sample buckets.
- u) 1 small Honda generator - 1 H.P. or similar.
- v) 1 canoe or boat.

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\* Available from Chromatographic Specialties Ltd. The capacity of the hypo-vials is shown as 30 ml in the catalogue, but the actual capacity is 36 ml.

On small streams, a minimum of three persons is required, but on large rivers, it may be necessary to have a crew of four or five. In the example given above, three persons and four sampling locations were used. One person was assigned to look after the injection of the tracers while the other two performed the sampling.

#### 4.1.2 Preparation Prior To Survey

Prior to the start of a survey, the fluorometer should be calibrated with appropriate dye standards over the largest possible expected range. Calibration curves of dye concentration (in  $\mu\text{g/L}$ ) vs. fluorescence (in % full scale reading) can then be plotted.

Selection of the general location of the injection point and measuring sites should also be planned ahead of the survey, and can be done on a topographical map. The initial weight of the gas cylinder must be measured before the survey starts.

The amount of dye to be injected into the stream should also be determined beforehand. A guide for determining volume of dye to be used at various flows is given in Figure 1 and is based on very limited studies carried out in the Speed, Grand and Abitibi rivers.

#### 4.1.3 Equipment Set-Up at the Injection Point

The arrangement of equipment at the injection point is shown in Figure 2. The sprinkler hose is stretched across the stream and kept in position near the bottom of the stream by weights. The desired amount of dye (determined beforehand from Figure 1) is measured and poured into the Mariotte unit. The unit is then filled with ambient stream water. About 50 ml of detergent should also be added to the dye solution to minimize adsorption of the dye on the side walls of the hoses and the Mariotte unit. The unit is then attached to the suction hose of the pump. Ethylene is fed directly from a high pressure cylinder through a two-stage regulating valve and a pressure gauge to the discharge hose of the pump, which is then connected to the sprinkler hose.

#### 4.1.4 Injection Procedure

As shown in Figure 2, water is taken from the stream by a high pressure pump and mixed with Rhodamine WT dye. This mixture is then saturated with ethylene gas and

returned to the stream through a porous tube diffuser. The injection procedure is as follows:

- 1) The pump is turned on and allowed to run for 5 minutes to clear the hoses of any residual dye deposits left from previous use.  
Note: The equipment should be well cleaned at the end of each test to minimize this problem.
- 2) The valve controlling the flow of dye is then opened slowly.
- 3) After making sure that the dye flow is distributed evenly across the sprinkler hose, the two-stage regulating valve controlling the flow of ethylene gas is slowly opened until a good balance between the dye and ethylene gas can be observed at the sprinkler hose (i.e., a good mix of gas bubbles and dye colour). If the pressure from the ethylene gas is greater than that of the output of the pump, the gas could flow backwards through the pump.
- 4) Injection duration is in the range of 30-60 minutes. This depends on the flow and level of concentration anticipated at downstream stations.

## 4.2 Sampling the Tracers

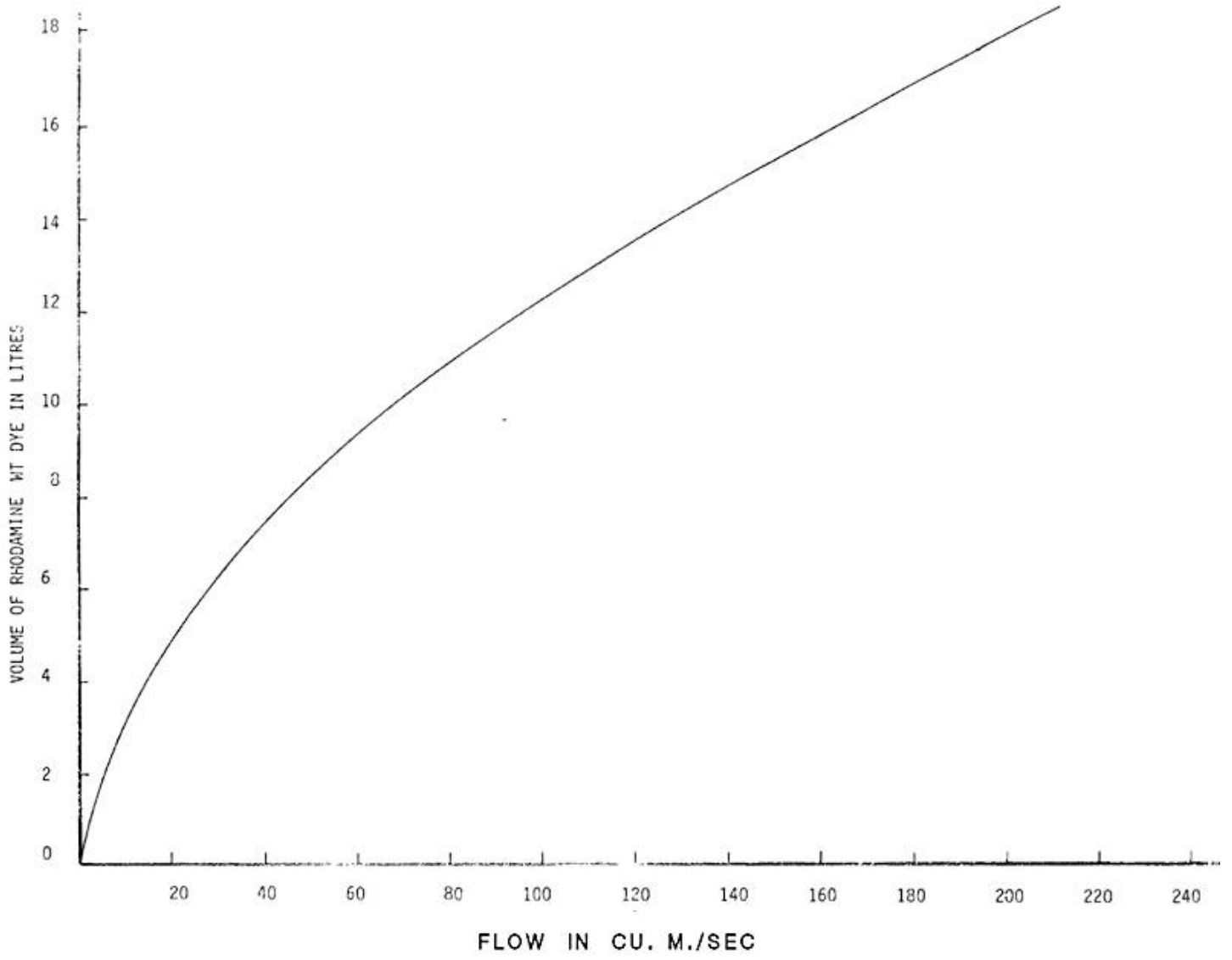
### 4.2.1 Selection of Sampling Sites

Many factors enter into the selection of dye-injection and measuring sites. Every study reach is unique in some way; however, the following description of the effects of some of these factors viz., channel characteristics of the stream, potential loss of dye, tributary inflow and stream discharge - will aid in the selection of injection and measuring sites (9).

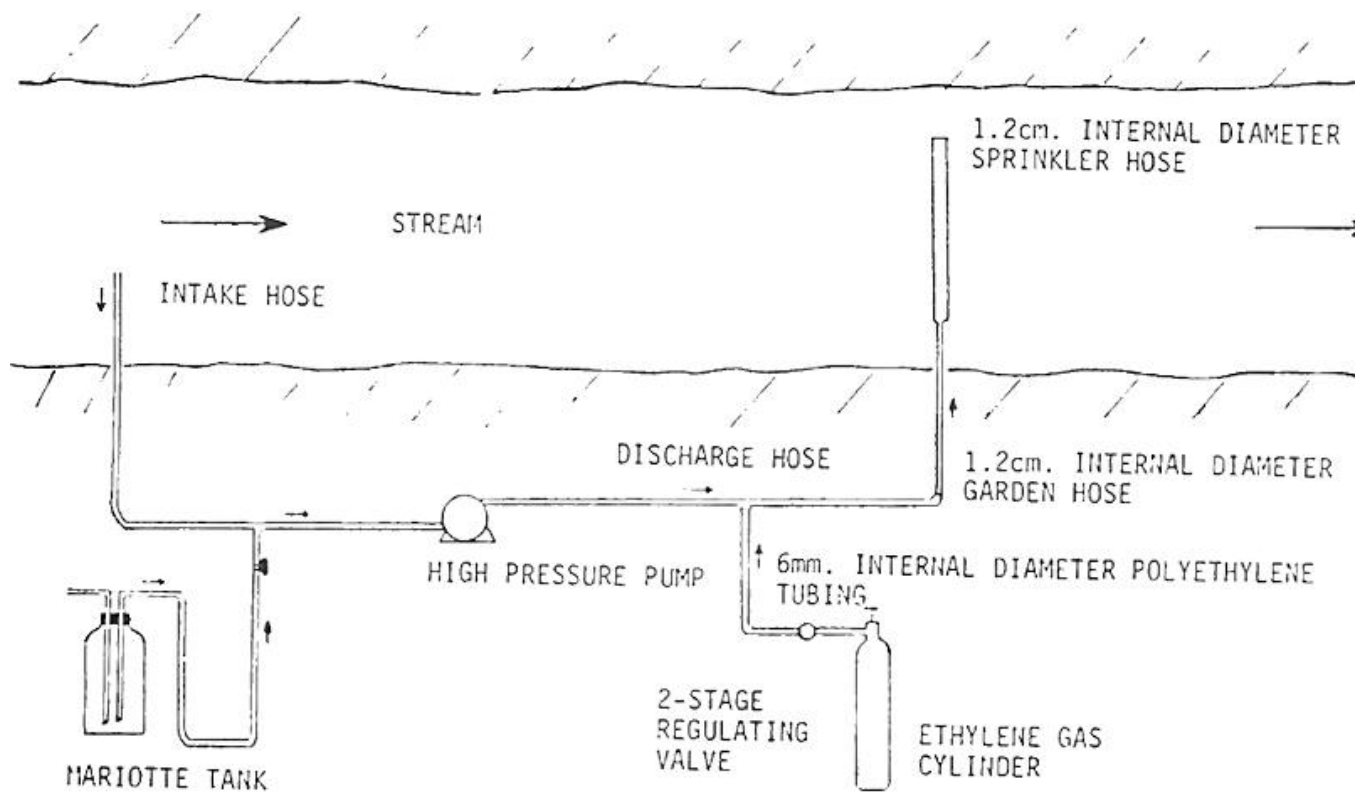
#### Channel Characteristics of the Stream

(Note: The following paragraphs are excerpted in large part from USGS Water Supply Paper #1892 (Ref. 9).)

- 1) Measuring sites may be spaced farther apart on streams with steep gradients.



**FIGURE 1:** Plot of volume of dye vs. Streamflow.



**FIGURE 2:** Schematic diagram of injection of tracers.

- 2) In rivers and streams with sorbent channel materials such as clay, silt and, to a lesser extent, sand, measuring sites should be spaced more closely, and the progress and concentration of the dye checked as often as possible. Additional injection points may be selected if the dye is lost.
- 3) Delays caused by passage of dye through vegetated and swampy areas may cause multiple peaks or, at least, peaks of low concentration occurring for longer duration.
- 4) Passage of dye through a very large storage area (e.g., a reservoir) should be bypassed and studied separately.

### Potential Loss of Dye

In addition to natural dilution which ultimately renders the dye undetectable, the dye is subject to a number of physical and chemical processes which tend to diminish the amount detected at a measuring site. The most important of these are sorption and photochemical decay; various chemical reactions also play a site-specific role.

The loss of dye by sorption and/or chemical reaction is partly or wholly remedied by using Rhodamine WT dye, since this dye has a low sorptive tendency and low acidity.

Photochemical decay is caused by the exposure of the dye samples to sunlight and is a function of time exposed. This is a minor problem and can easily be minimized by storing samples in a dark area and analyzing them as soon as possible.

### Tributary Inflow

Measuring sites directly below tributaries should be selected with care because these tributaries may be contributing pollutant to the main stream, and mixing of the main stream and the tributary may or may not occur immediately below the confluence. An improper selection of a cross-sectional sampling position in the river may result in inconsistent concentrations in the samples; for instance, the samples may be diluted

to a level which has a lower measurement accuracy or the dye and ethylene peaks may not be sampled at all.

### Stream Discharge

During a field study, the stream discharge should remain relatively constant. If the flow changes significantly during the study, the characteristic reaeration coefficient for that particular flow will not be obtained.

#### 4.2.2 Equipment Set-up at a Sampling Station

Figure 3 shows the arrangement of equipment at a typical sampling station. This arrangement is set up in a canoe or a boat some distance downstream of the injection point, at a location where the dye is uniformly dispersed. A fluorometer with a flow-through cuvette is hooked up to a small generator and a short length of garden hose (about 2 meters long and 1.2 cm diameter) is attached to the intake end of the cuvette. The other end is put into the stream. Another short length of the same diameter hose is attached to the exhaust end of the cuvette and the suction end of the bilge pump. A third length is attached to the discharge end of the pump and the other end is put into the stream. A 12-volt battery is used to power the bilge pump. Samples could also be taken in the centre of the dye plume and analysed on shore.

If a flow-through cuvette is not available, only the fluorometer and generator are required; however, the flow-through set-up in a boat has the advantage of giving continuous longitudinal and lateral profiles of the dye.

#### 4.2.3 Sampling Procedure

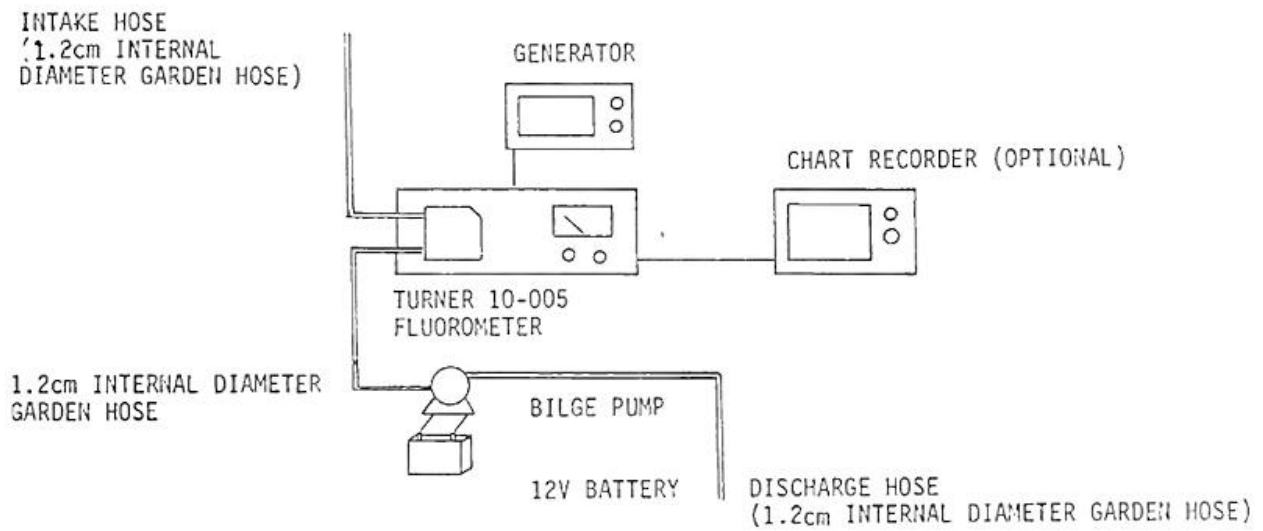
Before the dye arrives at a sampling station, a sample should be taken to measure background fluorescence. Time of arrival of the dye can be estimated from previous time of travel studies, if available. The fluorometer and pump are turned on, then on arrival of the dye, samples are collected in the centre of the dye plume or centre of

flow. If the recorder plot shows spiky dye readings (i.e. short-term changes in concentration) then the sampling station is probably too close to the injection site for representative sampling. This type of reading indicates that the tracers have not been mixed sufficiently with the stream water and that the station should be moved further downstream.

Sampling interval is a function of flow: the higher the flow, the faster the dye will pass through the sampling station. At medium flows, the sampling interval is usually about 10-15 minutes. Each time a sample is collected, 35 ml is pipetted into a hypo-vial, sealed with butyl rubber septa and aluminium seal and placed in a cooler. This sample will be analysed later for ethylene gas. A bacti bottle is also filled at the same time for dye analysis and placed in the cooler to prevent photochemical decay of the dye. This sample will also be analysed later and used as a check against the trace obtained from the fluorometer.

Sampling should continue until the dye concentration at the point of measurement reaches a plateau and starts to recede or until the dye cloud completely passes the point of measurement. If there is variation in the injection, the entire dye cloud should be sampled. On large rivers where the travel time is many hours, sampling can be accelerated by travelling upstream until the dye cloud is found and boating through it, sampling and recording concentrations continuously. The position of the cloud should be noted or located on a map to determine reach length later on.





**FIGURE 3:** Schematic diagram of dye detection system.

## 5. ANALYTICAL PROCEDURES

Dye samples are analysed for fluorescence in a standard (i.e. Turner 10-005) fluorometer. Calibration curves, obtained from analysis of known dye concentrations, are then used to determine the sample dye concentrations.

To measure the ethylene gas present in the water samples, the 'Headspace Analysis' method is used. The following is excerpted in large part from an Internal File Report (Ref. 10).

The 'Headspace Analysis' is performed on a gas chromatograph. Since the hypo-vials were filled with 35 ml of sample, 1 ml headspace is left. These vials are heated in a 50°C water bath for one-half hour to drive off the ethylene gas. A 100 µL volume of this sample is then taken and injected into a stream of nitrogen gas flowing at 20 mL/min through the chromatograph. The gases are carried this way to a column called PORAPAK-N, which is kept at 45°C, and which was specifically developed to separate the gases; gases are detected in the column by flame ionization. Results from this analysis appear as peak heights on a recorder with the first peak height an extremely large one proving the existence of nitrogen. Following this are peak heights representing any other gases present. The time lag (reaction time) after the start of the analysis is used to determine which gas the peak height represents, i.e., if ethylene is present, its peak will appear only once, always a uniform distance from the nitrogen peak. If there is no peak at this distance, there is no ethylene in the sample.

Standards at 22°C are run to obtain peak heights in all ranges. From this a graph of peak height vs. concentration of sample is plotted. To determine the ethylene concentration of a stream sample, its peak height is compared to the graph and the concentration is read off.

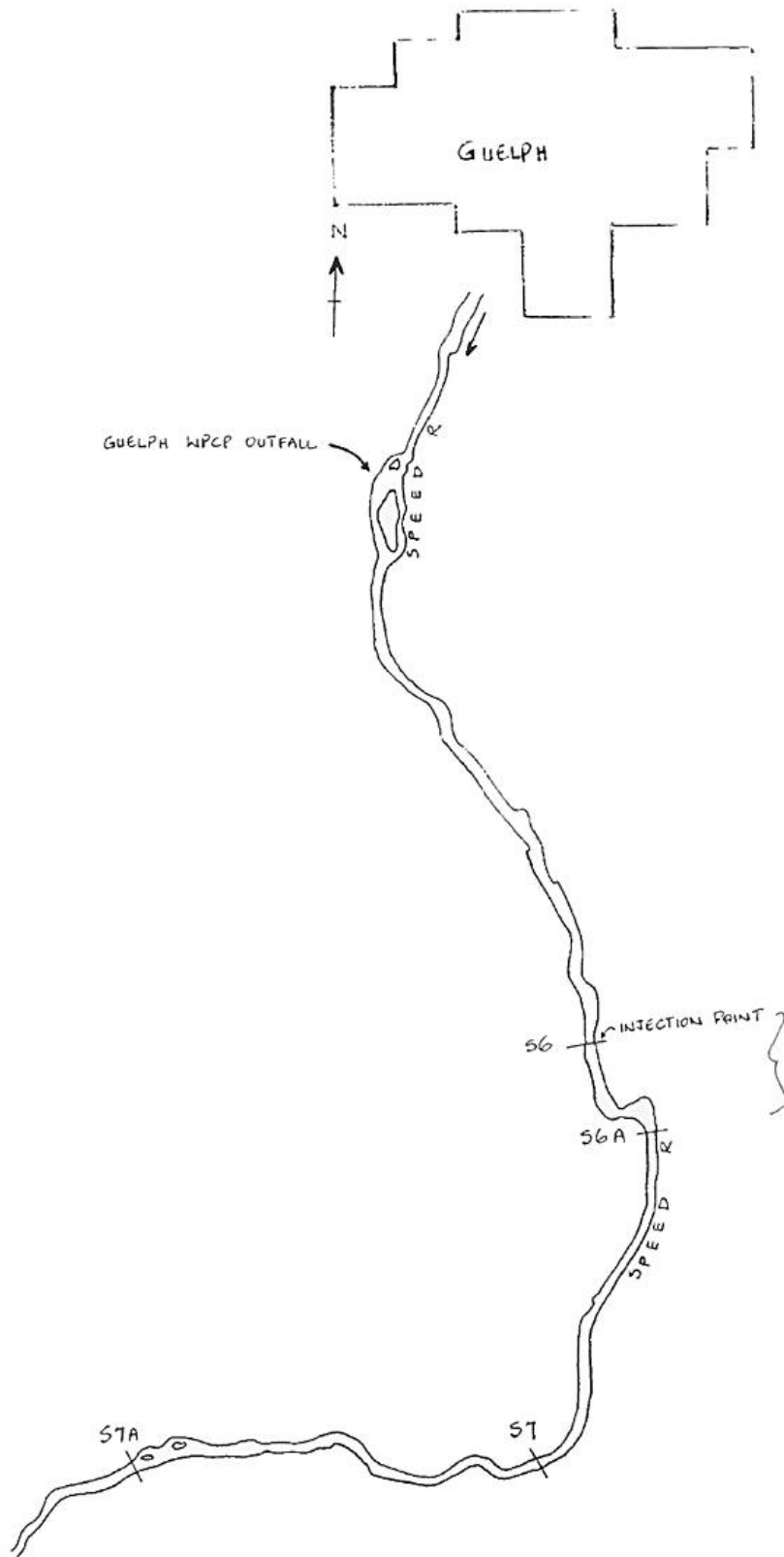
## 6. CASE STUDY: REAERATION IN SPEED RIVER

### 6.1 Description of the Study Area

The reaeration rate coefficients for several reaches of the Speed River below the Guelph Water Pollution Control Plant were measured on August 10, 1978, using the modified tracer technique outlined. The study area is located near the townships of Puslinch and Guelph in the County of Wellington, south of Waterloo Park. A sketch of the study area is shown in Figure 4. The study reach is 3561 m long. The first reach, S6-S6A is 359 m, the second, S6A-S7 is 1480 m and the third, S7-S7A is 1722 m. Flow over these reaches varies between 1.2 and 3.5 m<sup>3</sup>/sec. Channel alignment is mainly straight, with average stream width about 56 m, and streambed composition mainly sand, rock, and gravel.

### 6.2 Field Survey Details

For the case study, 950 cc of the stock solution of Rhodamine WT dye was diluted with river water to 15 litres. 3.5 pounds of ethylene gas were then mixed with the solution and injected over a one-hour period into the stream. Fifteen samples each for ethylene and dye analyses were collected at the first station, eighteen at the second, thirteen at the third, and eleven at the fourth. Time of travel for the first reach was 0.028 day, 0.243 day for the second, 0.347 day for the third, and 0.125 day for the fourth. Water temperature during the survey was 16.7°C. Stream discharge was 2.12 m<sup>3</sup>/sec and the river varied in depth from 0.3 m to 4.0 m between S6 and S7A and in width from 33.6 m to 35.6 m. There was a dense growth of aquatic plants between S6A and S7A.



**FIGURE 4:** A Sketch of the study area.

### 6.3 Data Analysis Procedure and Results

The mean ratio method was used to calculate  $k_2$  using equations (2) and (3) presented above. The following equation was then used to express the reaeration coefficient,  $k_2$ , for a standard temperature of 20°C for comparison purposes

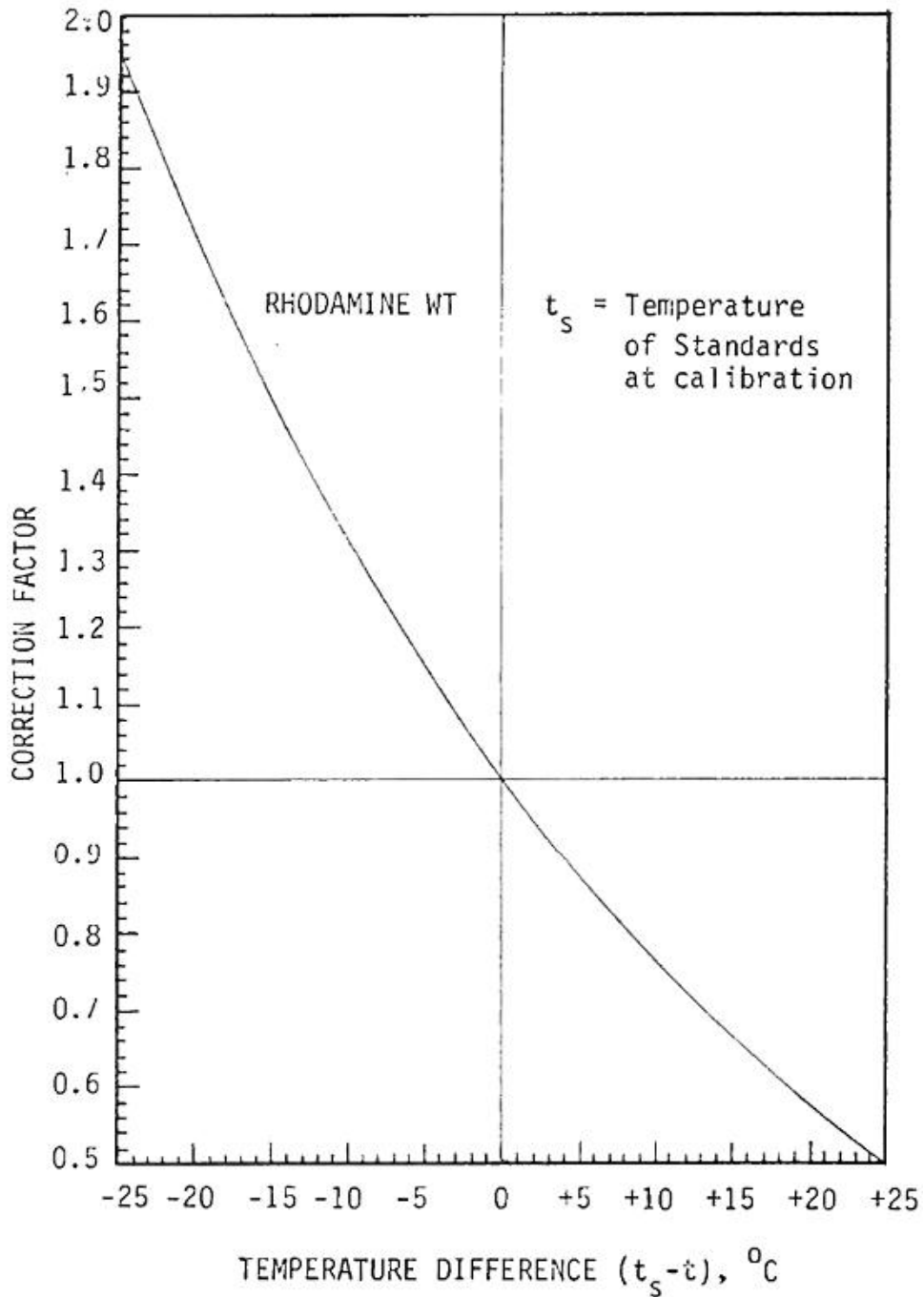
$$k_{2_T} = k_{2_{20}} \theta^{(T-20^\circ\text{C})} \text{ day}^{-1} \quad (4)$$

where  $\theta = 1.0241$   
 $T = \text{temperature in degrees celsius}$

A computer program, HGREDYET, was developed to compute the reaeration rate coefficient based on the mean ratio method. A listing of the program and a description of the variable names are presented in the Appendix.

The steps involved in calculating the reaeration rate coefficients are as follows:

- i) Fluorometer dial readings are converted to dye concentrations in ppb by applying the following 3 steps:
  - (a) Background readings are subtracted from the dial readings of samples;
  - (b) The straight line relationship established between dial readings and concentrations is used to obtain concentrations and;
  - (c) A temperature correction factor is applied if samples are at a different temperature during analysis than the standards used in the calibration of the fluorometer (see Figure 5 for temperature correction curve). Results of the fluorometric analyses are presented in Tables 1-3.
- ii) Ethylene gas concentrations are reported in ppm by the Lab but this is a volume measure and must be multiplied by a factor of  $(1.17 \times 10^{-3})$  to convert to mass. This factor assumes a standard temperature of 22°C. Any change in temperature would require a different factor. See Tables 4-6; units are ppb.
- iii) Gas concentrations are divided by dye concentrations to determine the gas/dye ratios for individual times. The mean ratio for each station is then calculated from these ratios (Table 7).



**FIG. 5:** Temperature correction curve for Rhodamine-WT dye.

(After: Donald L. Feuerstein and Robert E. Selleck, Fluorescent Tracers for Dispersion Measurements, Journal of the Sanitary Engineering Division, Proceedings of the ASCE, Aug. 1963)

- iv) Times of travel between stations are summarized in Table 8. These are obtained from the difference in time that it takes the dye to reach maximum concentration from station to station. See Figures 6-8.
- v) Table 9 summarizes the reaeration rate coefficients for reaches S6A-S7, S7-S7A and S6A-S7A, respectively. For demonstration purposes, the following example shows the calculations involved in calculating  $k_2$  for reach S6A-S7 only.

$$k = (1/0.243) \ln [1.5777/0.6778] = 3.477$$

where  $t = 0.243$   
 $c_g/c_1 = 1.5777$ , at S6A  
 $c_g/c_1 = 0.6778$ , at S7

Substituting in Equation (3)  $k_{2_T} = 3.477/0.89 = 3.91 \text{ day}^{-1}$

Finally, by substituting in Equation (4)  $k_{2_{20}} = 3.91 / \theta^{(16.67-20^\circ\text{C})} = 4.23 \text{ day}^{-1}$

where  $\theta = 1.0241$   
and  $T = 16.67^\circ\text{C}$

#### 6.4 Discussion

Data for the first station were not used as the location was found to be too close to the injection point. This resulted in the tracers not being completely mixed laterally by the time they arrived at the station. Other data points that did not follow a smooth progression or regression were not used. This decision was based on the knowledge that while the tracers were being injected, the pump faltered at times, thus producing a differential emission rate.

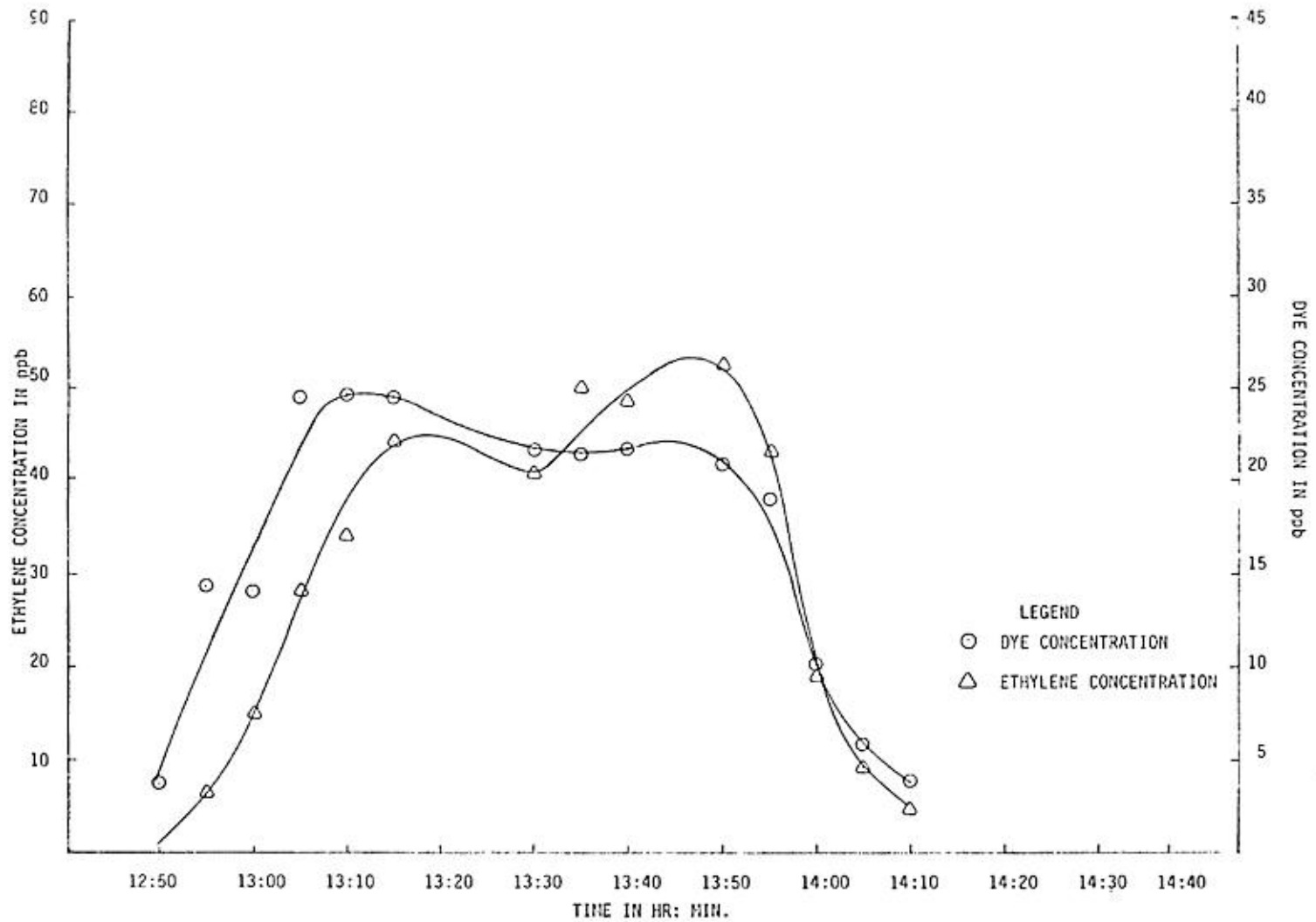
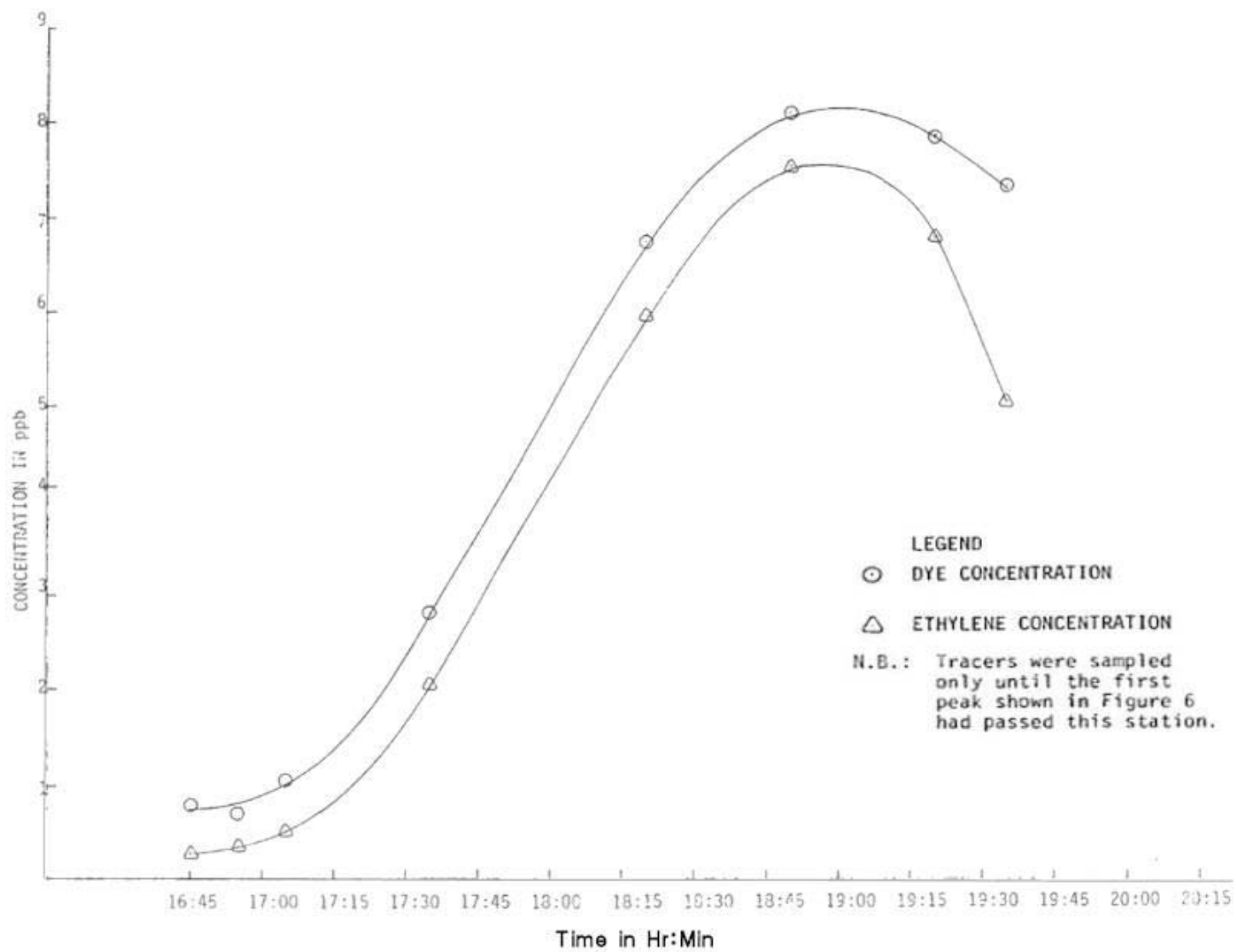
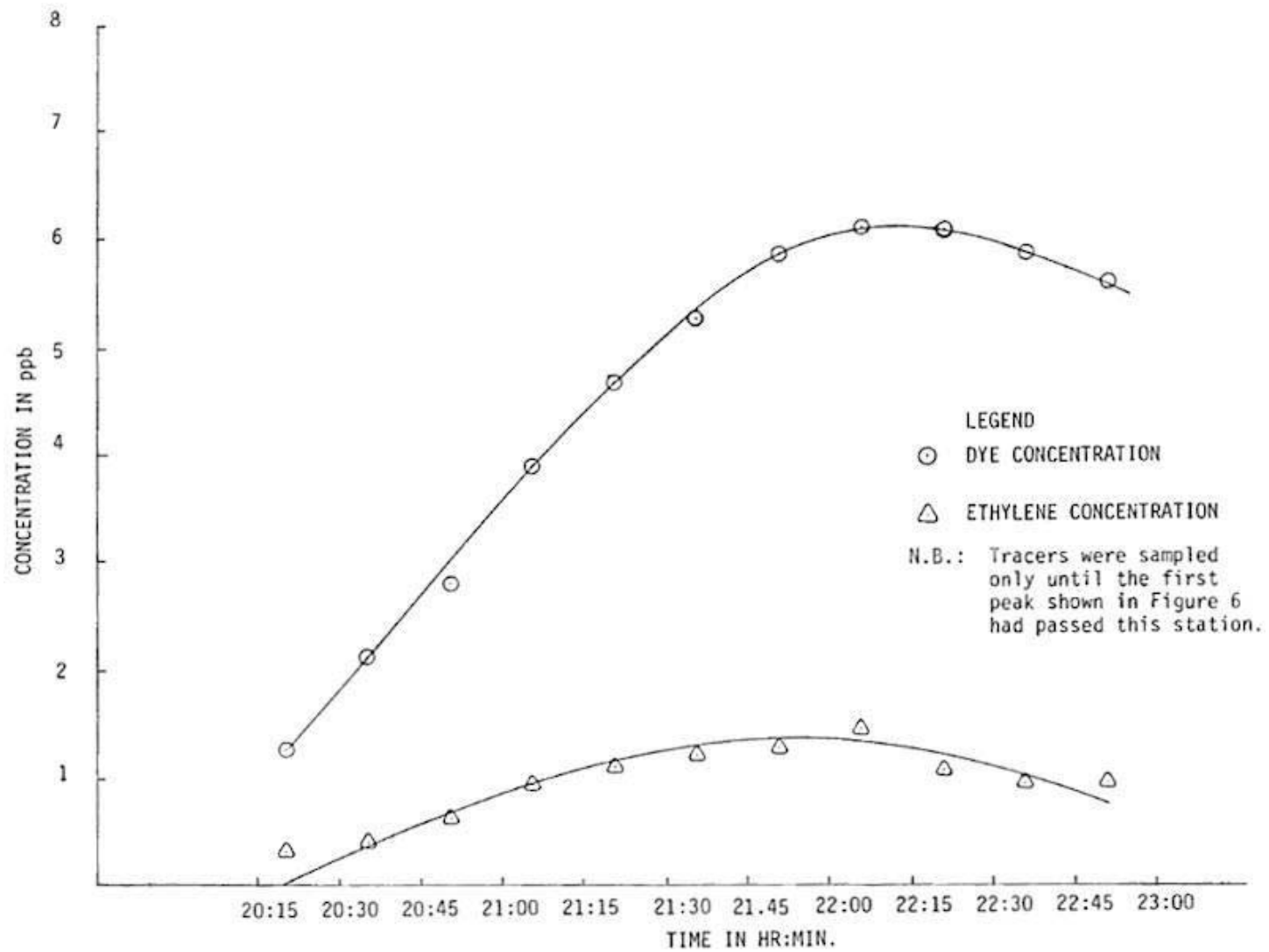


FIGURE 6: Ethylene & dye concentrations vs time for the Speed River, station S6A.





**FIGURE 7:** Ethylene & dye concentrations vs time for the Speed River, station S7.



**FIGURE 8:** Ethylene & dye concentrations vs time for the Speed River, station S7A.

**TABLE 1:** Results of Fluorometric Analyses of Dye Samples.

RIVER: SPEED SURVEY DATE Aug 10/78  
 STATION: S6A ANALYSIS DATE Aug 11/78  
 BACKGROUND READING: 0  
 TEMPERATURE OF SAMPLES: 24.5°C (during Analysis)

Sample	Time	Fluorometer Readings (% Full Scale)								Dye Conc (ppb)
		X1	X3.16	X10	X31.6	X100	X316	X1000	X3160	
B-1	12:40									
B- 2	12:50					6.48				3.75
B- 3	12:55					25.0				14.45
B- 4	13:00					24.5				14.16
B- 5	13:05					42.5				24.57
B- 6	13:10					42.8				24.74
B- 7	13:15					42.5				24.57
B- 8	13:20					37.5*				-
B- 9	13:25					38.5*				-
B-10	13:30					37.5				21.68
B-11	13:35					37.0				21.39
B-12	13:40					37.5				21.68
B-13	13:45					37.5*				-
B-14	13:50					36.0				20.81
B-15	13:55					33.0				19.07
B-16	14:00					17.5				10.12
B-17	14:05					10.0				5.78
B-18	14:10					6.64				3.84

\* Not used in calculation

N.B. Temperature Correction was not necessary since the correction factor was close to unity.

**TABLE 2:** Results of Fluorometric Analyses of Dye Samples.

RIVER: SPEED SURVEY DATE: Aug 10/78  
STATION: S7 ANALYSIS DATE: Aug 11/78

BACKGROUND READING: 0  
TEMPERATURE OF SAMPLES: 24.5° C (during Analysis)

Sample	Time	Fluorometer Readings (% Full Scale)								Dye Conc (ppb)
		X1	X3.16	X10	X31.6	X100	X316	X1000	X3160	
C-1	16:45						4.6			0.78
C-2	16:55						4.1			0.70
C-3	17:05						6.2			1.05
C-4	17:20						10.0*			-
C-5	17:35						16.5			2.81
C-6	17:50						25.5*			-
C-7	18:05						33.5*			-
C-8	18:20						39.5			6.72
C-9	18:35						45.5*			-
C-10	18:50						47.5			8.08
C-11	19:05						48.5*			-
C-12	19:20						46.0			7.82
C-13	19:35						43.0			7.31

\* Not used in calculation.

**TABLE 3:** Results of Fluorometric Analyses of Dye Samples.

RIVER: SPEED SURVEY DATE: Aug 10/78  
STATION: S7A ANALYSIS DATE: Aug 11/78

BACKGROUND READING: 0  
TEMPERATURE OF SAMPLES: 24.5° C (during Analysis)

Sample	Time	Fluorometer Readings (% Full Scale)								Dye Conc (ppb)
		X1	X3.16	X10	X31.6	X100	X316	X1000	X3160	
D-1	20:20						7.5			1.28
D- 2	20:35						12.5			2.13
D-3	20:50						16.5			2.81
D- 4	21:05						23.0			3.91
D- 5	21:20						27.5			4.68
D- 6	21:35						31.0			5.27
D- 7	21:50						34.5			5.87
D- 8	22:05						36.0			6.12
D- 9	22:20						35.8			6.09
D-10	22:35						34.5			5.87
D-11	22:50						33.0			5.61

**TABLE 4:** Ethylene gas concentration for Station S6A.

SAMPLE	Ethylene (ppm)**	Ethylene Mass (ppb)
B1	0.14	*0.16
B2	0.99	1.16
B3	5.52	6.46
B4	12.83	15.01
B5	24.28	28.41
B6	29.32	34.30
B7	37.99	44.45
B8	29.43	*34.43
B9	33.62	*39.34
B 10	34.87	40.80
B 11	42.86	50.15
B 12	41.48	48.53
B 13	vial half full only	
B 14	44.94	52.58
B 15	36.88	43.15
B 16	15.95	18.66
B17	8.03	9.40
B 18	3.87	4.53
B 19	1.96	*2.29

\*\* This is a volume measure and must be multiplied by 1.17 to convert to mass in ppb.

\* values not used in calculations

**TABLE 5:** Ethylene gas concentration for Station S7.

SAMPLE	Ethylene (ppm)**	Ethylene Mass (ppb)
C1	0.22	0.26
C2	0.30	0.35
C3	0.44	0.51
C4	0.18	*0.21
C5	1.75	2.05
C6	2.37	*2.77
C7	3.63	*4.25
C8	5.08	*5.94
C9	5.69	*6.66
C10	6.43	7.52
C11	5.09	*5.96
C12	5.78	6.76
C 13	4.31	5.04

\*\* This is a volume measure and must be multiplied by 1.17 to convert to mass in ppb.

\* values not used in calculations

**TABLE 6:** Ethylene gas concentration for Station S7A.

SAMPLE	Ethylene (ppm)**	Ethylene Mass (ppb)
D1	0.28	0.33
D2	0.35	0.41
D3	0.53	0.62
D4	0.80	0.94
D5	0.96	1.12
D6	1.03	1.20
D7	1.08	1.26
D8	1.21	1.42
D9	0.92	1.08
D 10	0.82	0.96
D 11	0.83	0.97

\*\* This is a volume measure and must be multiplied by 1.17 to convert to mass in ppb.



**TABLE 7:** Summary of dye and gas concentrations gas/dye ratio and mean ratio.

Station	Dye Concentration (ppb)	Gas Concentration (ppb)	Gas/dye Ratio	Mean Ratio
S6A	3.75	1.16	0.3093	
	14.45	6.46	0.4469	
	14.16	15.01	1.0600	
	24.57	28.41	1.1564	
	24.74	34.30	1.3867	
	24.57	44.46	1.8099	
	21.68	40.83	1.8839	
	21.39	50.19	2.3470	
	21.68	48.56	2.2401	
	20.81	52.53	2.5247	
	19.07	43.17	2.2634	
	10.12	18.72	1.8507	
	5.78	9.36	1.6194	
	3.84	4.56	1.1889	1.5777
S7	0.78	0.26	0.3292	
	0.70	0.35	0.5036	
	1.05	0.51	0.4884	
	2.81	2.05	0.7299	
	6.72	5.94	0.8851	
	8.08	7.52	0.9317	
	7.82	6.76	0.8648	
	7.31	5.04	0.6898	0.6778
S7A	1.28	0.33	0.2569	
	2.13	0.41	0.1927	
	2.81	0.62	0.2211	
	3.91	0.94	0.2394	
	4.68	1.12	0.2403	
	5.27	1.21	0.2287	
	5.87	1.26	0.2154	
	6.12	1.42	0.2313	
	6.09	1.08	0.1769	
	5.87	0.96	0.1636	
	5.61	0.97	0.1731	0.2127

**TABLE 8:** Time of travel in Speed River - August 10, 1978.  
Stream Flow = 2.12 m<sup>3</sup>/sec.

Station	Peak Time		Reach	Time Of Travel			
	Ethylene	Dye		Dye		Ethylene	
				(Mins.)	(Days)	(Mins.)	(Days)
S6A	13:10	13:15	S6A-S7	350	0.243	340	0.236
S7	18:50	19:05	S6A-S7A	530	0.368	535	0.372
S7A	22:05	22:05	S7 -S7A	180	0.125	195	0.135

**TABLE 9:** Computation of atmospheric reaeration coefficient for three reaches on the Speed River - Aug. 10, 1978.

Desorption Coefficient,  $k = (1/\Delta t) \ln [(c_g / c_l)_u] / [(c_g / c_l)_d]$	Reaeration Coefficient, $k_2 = k/0.89$	
	$k_2$ at 16.67°C (base e)	$k_2$ at 20°C (base e)
Reach		
S6A - S7, $k = 1/0.243 \quad \ln (1.5777 / 0.6778) = 3.477$	3.91	4.23
S7 - S7A, $k = 1/0.125 \quad \ln (0.6778 / 0.2127) = 9.272$	10.42	11.28
S6A - S7A, $k = 1/0.368 \quad \ln (1.5777 / 0.2127) = 5.445$	6.12	6.62

$$k_{2(T)} = k_{2(20)} 1.0241^{(T-20)}$$

$$T = 16.67^\circ\text{C}$$

## **7. COMPARISON BETWEEN MEASURED AND PREDICTED REAERATION RATES**

Table 10 shows a comparison between measured and predicted  $k_2$  values for the Speed and Grand rivers (11). The standard error for  $k_2$  associated with the predictive equation from O'Connor *et al.*'s (1) is 6.0; for Churchill *et al.* (2) it is 5.0. On a case by case basis, values predicted by (1) are much lower than the measured ones, whereas the values predicted by (2) are relatively closer to the observations. The author chose these two predictive equations because of the similarity in bulk hydraulic conditions between the rivers where the measured  $k_2$  data were generated and the rivers for which the equations were developed.

The discrepancy between the measured and predicted rate coefficients could be explained by the conditions under which the indirect methods were developed. Generally, indirect methods are developed in the laboratory with controlled hydraulic conditions; natural channels at best only approximate these hydraulic conditions. Hydraulic parameters can be measured directly in the field, but the field surveys required to do so are laborious, time-consuming and expensive; on streams with rapidly changing morphology, the data collection is especially difficult. The direct measurement technique overcomes many of the limitations of the predictive equations, including the approximation of hydraulic parameters in natural channels; however, there are inherent errors in the direct measurement technique as well. There seems to be no infallible method for the determination of atmospheric reaeration coefficient, against which one can compare results obtained from other techniques (*viz*; predicted or measured as outlined in this report). However, a possible approach is to consider the atmospheric reaeration coefficient values obtained from a calibrated-verified DO model to be accurate and to use them as a basis for comparison with the results of other methods.

## **8. CONCLUSION**

Direct measurement of the atmospheric reaeration coefficient by the tracer technique is much preferred over indirect methods, since the latter require laborious morphological and hydraulic data collection and could also result in erroneous

predictions as discussed in Section 7. The results of several tests carried out in the same reaches of a specific river have shown that the tracer technique is reliable and produces consistent results. This method is less expensive and time-consuming in comparison to data collection for predictive methods, and is therefore recommended for the direct measurement of the atmospheric reaeration capacity of streams.

**Table 10:** Comparison Between Measured and Predicted  $K_2$  Values for the Speed and Grand Rivers (Basu, 1979).

Date of Survey	River	Subreach	Length of Reach (meters)	Average Depth (meters)	Mean Velocity (m/sec)	Streamflow (m <sup>3</sup> /sec)	Time of Travel (hr)	Reaeration Rate Coefficient $K_2$ To Base e at 20°C (Day <sup>-1</sup> )		
								Measured	Predicted	
									O'Connor	Churchill
June 7/78	Speed	6A-7	1480	1.05	0.14	3.36	3.0	1.10	1.25	3.61
		6A-7A	3200	1.10	0.20	3.36	4.46	4.73	1.41	4.79
		6A-8	3860	1.10	0.26	3.36	6.13	4.88	1.60	6.17
		7-7A	1720	1.14	0.33	3.36	1.46	10.71	1.70	7.25
		7-8	2380	1.13	0.21	3.36	3.13	8.46	1.38	4.81
		7A-8	650	1.12	0.08	3.36	1.67	5.47	0.86	1.89
Aug.10/78	Speed	6A-7	1480	1.04	0.08	2.12	5.83	4.23	0.94	2.05
		6A-7A	3200	0.74	0.10	2.12	8.83	6.62	1.83	4.89
		7-7A	1720	0.44	0.15	2.12	3.20	11.28	4.80	16.81
Aug.24/78	Speed	6A-7	1480	1.04	0.08	2.43	5.20	7.00	0.96	2.14
		6A-7A	3200	0.59	0.12	2.43	7.38	7.64	2.78	8.28
		6A-8	3860	0.74	0.11	2.43	9.58	9.34	1.91	5.30
		7-7A	1720	0.44	0.22	2.43	2.18	9.20	5.82	24.22
		7-8	2380	0.44	0.15	2.43	4.38	12.05	4.82	16.90
		7A-8	650	0.44	0.08	2.43	2.20	14.64	3.57	9.46
June 2/78	Grand	A-C	2500	0.67	0.19	4.09	3.68	3.04	2.91	10.62
July 11/78	Grand	A-C	2500	0.69	0.21	4.27	3.43	8.17	2.86	10.74
		B-C	2440	0.70	0.20	4.27	3.33	7.55	2.79	10.34
Aug. 23/78	Grand	A-C	2500	0.77	0.27	7.29	2.67	11.03	5.18	11.48
		B-C	2440	0.79	0.27	7.29	2.55	10.94	4.99	11.01

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## **APPENDIX**

### **A. COMPUTER PROGRAM - HGREDYET**

- A.1 Description of Variable Names
- A.2 Listing of Program
- A.3 Sample Input and Output



## A. COMPUTER PROGRAM - HGREDYET

### A 1. DESCRIPTION OF VARIABLE NAMES

#### Input Variables

Some of the inputs are self-explanatory; the others are:

TOT: Time of Travel

NDA: No. of Data Points

XRNG: Slope of the straight line relationship between fluorometer dial readings and dye concentrations (dye calibration curve)

CIPT: Intercept of dye calibration curve. If the curve passes through zero, enter 0.

TCORF: Temperature correction factor.

N.B. When entering data points, fluorometer dial readings are entered on the first line followed by a corresponding number of data points for ethylene gas on a second line. Input ethylene concentrations as reported by the Lab, i.e., volume/volume in ppm. The program converts V/V in ppm to mass concentration in ppb.

## A2. LISTING OF PROGRAM

ENQL.81.015.14 40 41.ENQL.RSW.FORTRAN.FORT(REDYET)

```

00010000    C    PROGRAM NAME      HGREDYET
00020000    C    PROGRAMMER      T.P.H.GOWDA      WATER MODELLING SECTION
00030000    C    CALCULATES REAERATION RATE COEFFICIENT FROM DYE & ETHYLENE DATA
00040000    C
00050000          DIMENSION DESC(20).NDATA(10)
00060000          REAL*8 TOT(10).RMEAN(10).RKT(10).RK20(10).SUM
00070000          REAL*8 FACTR.RATIO(20).G(20).D(20).TTEMP.GC(20).DC(20)
00780000    99    CONTINUE
00090000    C    READ IN DATA
00100000          WRITE(8.24)
00110000    24    FORMAT(// 'ENTER DESCRIPTION OF STUDY')
00120000          READ(3.10) DESC
00130000    10    FORMAT(20A4)
00140000          WRITE(8.12)
00150000    12    FORMAT(' ENTER NO. OF STATIONS & TEMPERATURE DURING TEST.'.
00160000          */' ON NEW LINE ENTER TOT VALUES OF SUCCESSIVE REACHES')
00170000          READ(3 *) NSTN.TEMP
00180000          NS1=NSTN-1
00190000          READ(3.*) (TOT(N).N=1.NS1)
00200000          WRITE(8.14)
00210000    14    FORMAT (' FOR EACH STATION ENTER NDATA.XRNG.CIPT.TCORF"/' ON NEW
00220000          1 LINE ENTER FLUOROMETER DIAL READINGS & ON NEXT LINE ENTER ETHYLENE
00230000          VALUES')
00240000          DO 30 I=1.HSTN
00250000          WRITE(8.16) I
00260000    16    FORMAT(//5X.' STATION ' .I2)
00270000          READ(3.*) NDATA(I).XRNG.CIPT.TCORF
00280000          NDI=NDATA(I)
00290000          READ(3.*) (D(J).J=1.NDI)
00300000          READ(3.*) (G(J)..J=1.NDI)
00310000          SUM=0.
00320000          DO 32 J=1.NDI
00330000          DC(J)=XRNG.(TCORF.D(J)-CIPT)
00340000          GC(J)=1.17*G(J)
00350000          RATIO(J) =GC(J)/DC(J)
00300000    32    SUM= SUM + RATIO(J)
00370000          WRITE(0.101)
003C0000    101   FORMAT(13X.' DYE CONC'.4x.'GAS CONU.3X.'GAS/DYE RATIO')
00390000          DO 80 J=1.NDI
00400000    00    WRITE(0.100)DC(J).GC(J).RATIO(J)
00410000    100   FORMAT(10X.F10.2.2X.F10.2.2X.F10.4)
00420000          RMEAN(I)= SUM/NDATA(I)
00430000    30    WRITE(0.102) RMEAN(I)
00440000    102   FORMAT(/10X.'MEAN RATIO =' .F0.4)
00450000    C
00460000          WRITE(8.10) DESC
00470000    18    FORMAT(///5X.20A4.///5X.'REACH'.0X..'K2T'.6X.'K2 AT 20 DEG. C'/1BX.

```

```

00480000      *'PER DAY (TO BASE E)')
00490000      C  CALCULATE REAERATION RATE COEFFICIENTS & WRITE OUTPUT
00500000      DO 34 I=1.NS1
00510000      I1=I+1
00520000      RKT(I)= DLOG(RMEAN(I)/RMEAN(I1))/(0.09*TOT(I))
00530000      TTEMP=TEMP-20.
00540000      RK20(I)= RKT(I)/(1.0241**TTEMP)
00550000      34  WRITE(0.20) I.I1.RKT(I).RK20(I)
00560000      20  FORMAT(/4X.I2,' - '.I2.2(3X.F10.3))
00570000      WRITE(8.22)
00580000      22  FORMAT(///'  TO START NEW RUN ENTER 1. OTHERWISE ENTER 0')
00590000      READ (3 *) NEWRUN
00600000      IF(NEWRUN.GO.1) GO TO 20
00610000      STOP
00620000      END

```

### A3. SAMPLE INPUT AND OUTPUT

#### INPUT

```

00000100 SPEED RIVER REAERATION STUDY - AUG 10/80
00000200 3 16.67
00000300 .243 .125
00000400 14 .578 0 1
00000500 6.48 25 24.5 42.5 42.8 42.5 37.5 37 37.5 36 33 17.5 10 6.64
00000600 .99 5.52 12.83 24.28 29.32 38 34.9 42.9 41.5 44.9 36.9 16 8 3.9
00000700 8 .17 0 1
00000800 4.6 4.1 6.2 16.5 39.5 47.5 46 43
00000900 .22 .3 .44 1.75 5.08 6.43 5.78 4.31
00001000 11 .17 0 1
00001100 7.5 12.5 16.5 23 27.5 31 34.5 36 35.8 34.5 33
00001200 .28 .35 .53 .8 .96 1.03 1.08 1.21 .92 .82 .83
00001300 0
  
```

#### OUTPUT

STATION #1

DYE CONC	GAS CONC	GAS/DYE RATIO
3.75	1.16	0.3093
14.45	6.46	0.4469
14.16	15.01	1.0600
24.57	28.41	1.1564
24.74	34.30	1.3867
24.57	44.46	1.8099
21.68	40.83	1.8839
21.39	50.19	2.3470
21.68	48.56	2.2401
20.81	52.53	2.5247
19.07	43.17	2.2634
10.12	18.72	1.8507
5.78	9.36	1.6194
3.84	4.56	1.1889

MEAN RATIO = 1.5777

STATION2

DYE CONC	GAS CONC	GAS/DYE RATIO
0.78	0.26	0.3292
0.70	0.35	0.5036
1.05	0.51	0.4884
2.81	2.05	0.7299
6.72	5.94	0.8851
8.08	7.52	0.9317
7.82	6.76	0.8648
7.31	5.04	0.6898

MEAN RATIO = 0.6778

STATION 4 : 3

DYE CONC	GAS CONC	GAS/DYE RATIO
1.28	0.33	0.2569
2.13	0.41	0.1927
2.81	0.62	0.2211
3.91	0.94	0.2394
4.68	1.12	0.2403
5.27	1.21	0.2287
5.87	1.26	0.2154
6.12	1.42	0.2313
6.09	1.08	0.1769
5.87	0.96	0.1636
5.61	0.97	0.1731

MEAN RATIO = 0.2127

REACH	K2T PER DAY	K2 AT 20 DEG. C (TO BASE E)
1 - 2	3.906	4.229
2 - 3	10.419	11.279

TO START NEW RUN ENTER 1, OTHERWISE ENTER 0

NB: REACH 1 -2 : S6A-S7  
REACH 2-3: S7-S7A