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GEOLOGICAL SURVEY

VELOCITY AND DEPTH MEASUREMENTS FOR USE IN THE DETEMINATION OF REAERATION COEFFICIENTS

By

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VELOCITY AND DEPTH MEASUREMENTS FOR USE IN COMPUTATION OF REAERATION COEFFICIENTS

By John S. Zogorski, Peter W. Anderson,
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Abstract.--Empirical computation of reaeration coefficients generally requires knowledge of mean velocity and mean depth of a stream. A practical method for obtaining this knowledge is described herein. The method involves time-of-travel, streamflow, and cross-sectional measurements, the development of discharge-velocity curves, streamflow profiles, and the computation of cross-sectional areas. Values for mean velocity and mean depth are determined and related to mean discharge.

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INTRODUCTION

Many investigators use mathematical modeling techniques to determine the ability of surface waters to assimilate waste-water discharges. This ability is generally defined as the amount of waste-water discharge required to lower dissolved oxygen (DO) to a predetermined level. Modeling techniques are used to simulate the many intrinsic hydrologic, physical, chemical, and biological factors that affect DO within water bodies. Such factors are divided into two major classifications: (1) those that create a deoxgenation effect, commonly referred to as oxygen sinks; and (2) those that create a reoxgenating effect, frequently designated as oxygen sources. The former processes mainly consist of the stabilization of ammonia, dissolved and suspended matter, and benthic deposits, whereas algal photosynthesis and atmospheric reaeration constitute the latter group. One model commonly used (O'Connor, 1971) to simulate the influence of waste water on a stream's DO profile is given below:

$$D_t = \frac{K_d L_o}{K_a - K_r} \left(e^{-K_r t} - e^{-K_a t}\right) + \frac{KnNo}{K_a - K_n} \left(e^{-K_n t} - e^{-K_a t}\right) \tag{1}$$

$$+Do \left(e^{-K_a t}\right) + \frac{S}{K_a} \left(1 - e^{-K_a t}\right) - \frac{P-R}{K_a} \left(1 - e^{-K_a t}\right),$$

where D_t designates the DO deficit at time t; D_o, the initial deficit; L_o, the ultimate biochemical-oxygen demand (BOD) at t=0; K_d, the deoxgenation coefficient, which represents the fraction

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of the remaining BOD that is exerted per unit of time; K_a, the atmospheric reaeration coefficient, which equals the fraction of the DO deficit remaining that is satisfied per unit of time; K_r, the overall BOD removal coefficient for the stream, which is the numerical sum of K_d and K_c, where K_c is the removal coefficient due to adsorption, sedimentation, etc.; N_o, ultimate oxygen demand due to the oxidation of ammonia to nitrate within the flowing water; K_n, the deoxgenation coefficient for the oxidation of ammonia to nitrate, which represents the remaining nitrogenous demand exerted per unit of time; P-R, the net production of oxygen, as a result of algal photosynthesis; and S, the benthal-oxygen demand.

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As atmospheric reaeration generally constitutes the major source of oxygen, as well as the frequent occurrence of its coefficient in the DO model equation above, it is imperative that the coefficient be accurately defined. Current methods for measuring or predicting atmospheric reaeration under natural conditions were reviewed recently by Bennett and Rathbun (1972), Zogorski (1972), and Zogorski and Faust (1973). These investigators report that seven methods have been applied to prediction or measurement of this coefficient. Of the seven methods, three directly measure the mass of oxygen passing through the air-water interface. Among the authors who discuss such methods are Gameson and others (1955), Gameson and Truesdale (1959), Juliano (1969), Edwards and others (1961), Copeland and Duffer (1964), and Churchill and others (1962). The remaining four methods attempt to describe the reaeration process through hydraulic parameters and oxygen-balance techniques. In addition to authors referenced on table 1, Odum (1956), Tsivoglou (1967), Thackston and Krenkel (1969), and Dobbins (1964) are among those who have discussed such methods.

Most of the empirical approaches relate the reaeration coefficient to measurable hydraulic parameters, such as mean depth, mean velocity, slope, resistance coefficient, density, dynamic and kinematic viscosity, surface tension, molecular-diffusion coefficient, or longitudinal-dispersion coefficient. An equation relating this coefficient to the mean velocity and mean depth is generally preferred because "it is the simplest, more accurate than some, and essentially as accurate as any...and because the effects on reaeration of other hydraulic variables, such as energy slope and channel roughness, are automatically included through the correlation of these variables with the mean velocity and/or mean depth" (Churchill and others, 1962). These equations can be expressed in the general form:

$$k_2 = C \frac{V^n}{H^m} \qquad (2)$$

where k_2 is the coefficient of atmospheric reaeration at 20°C, in reciprocal days; V, the mean velocity, in feet per second; H, the mean depth, in feet; and C, n, and m are constants. For comparison, the C, n, and m values developed by nine groups of investigators are given in table 1. The constant k_2 is given in base 10 logarithmic units, but can be converted to base e units (K_a) as follows:

$$k_2 = \frac{K_a}{2.303} \qquad (3)$$

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Table 1.--Empirical-equation constants that define reaeration coefficient in base 10 logarithmic units as a function of stream velocity and depth

C	n	m	Reference
5.616	0.5	1.5	O'Connor and Dobbins (1958)
5.026	.969	1.673	Churchill and others (1962)
10.09	.73	1.75	Owens and others (1964)[1/]
9.4	.67	1.85	Owens and others (1964)[2/]
3.3	1.00	1.33	Langbein and Durum (1967)
3.739	1.00	1.50	Isaacs and Gaudy (1968)
4.748	.85	.85	Negulescu and Rojanski (1969)
2.983	.73	1.05	Gloyna and others (1969)
2.443	1.00	1.50	Krenkel and Orlab (1962)
8.76	0.607	1.689	Bennett and Rathbun (1972)

1/ For low velocities (0.1-1.8 feet per second) and shallow depths (0.4-2.4 feet).

2/ For high velocities (0.1-5.0 feet per second) and greater depth (0.4-11.0 feet).

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As part of its own modeling efforts, the N.J. State Department of Environmental Protection requested the U.S. Geological Survey to undertake a cooperative project to obtain mean velocity and mean depth information on selected streams in the State. The main stem and several major tributaries in the Passaic River basin (fig. 1) in northeastern New Jersey were chosen for initial study.

Figure 1 (caption on next page) near here.

The purpose of this paper is to present some of the techniques used in the Passaic River basin to obtain information on depth and velocity for use in the computation of reaeration coefficients.

BACKGROUND MATERIAL

Several investigators have reported techniques for obtaining velocity and depth. For example, Steacy (1961) reported an indirect method to predict stream velocity based on streamflow-frequency information, cross-sectional area measurements, and stage-profiles information. The mean velocity within a stream reach was calculated from the basic relation:

$$Q = AV \qquad (4)$$

where Q is the mean discharge within the reach; A, the reach's mean cross-sectional area; and V, the reach's mean velocity.

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Figure 1.--Passaic River basin map showing stream reaches investigated. Reach numbers refer to descriptive tabulations on table 2.

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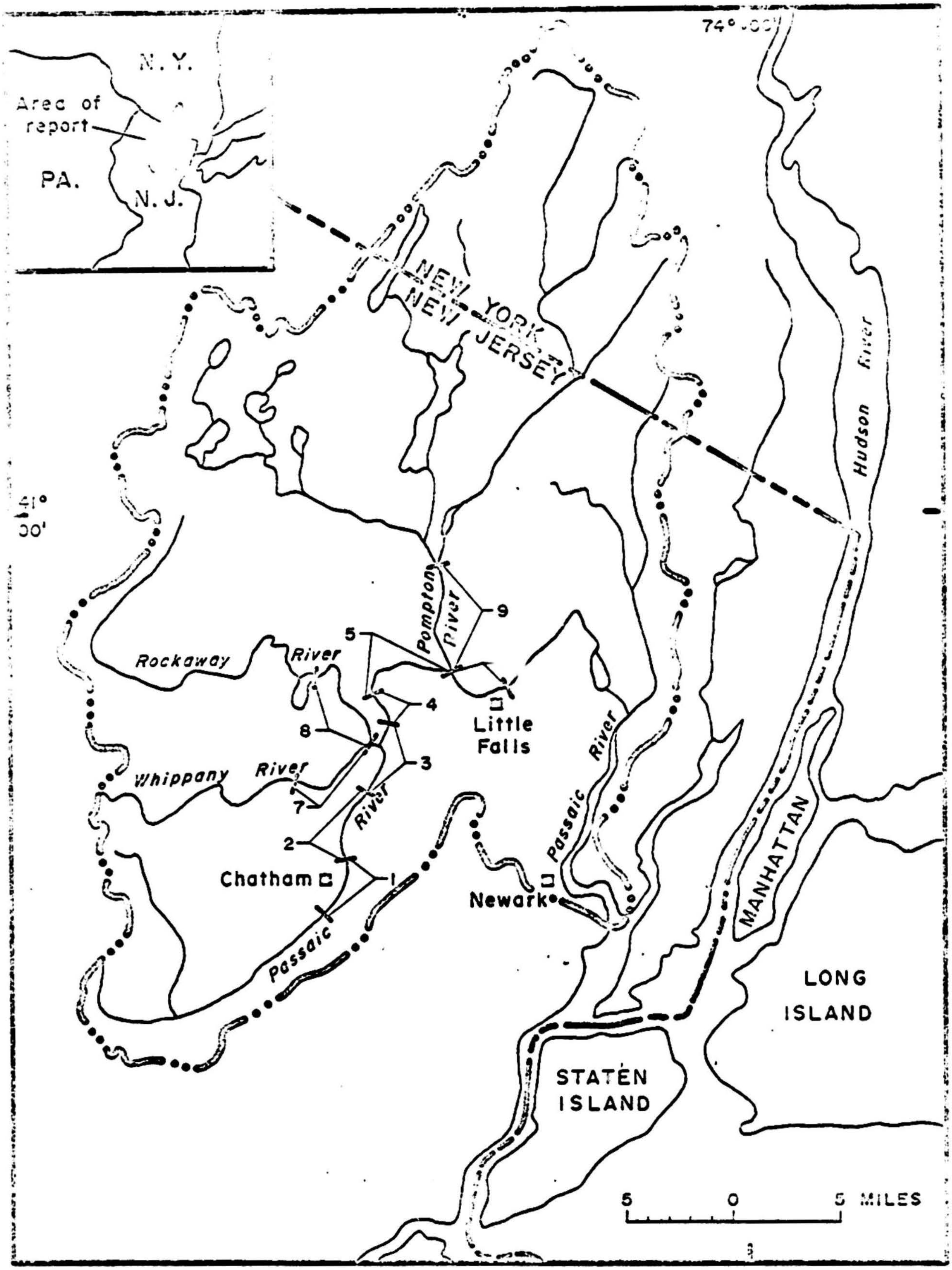

74° 00'
N.Y.
Area of report
PA.
N.J.
NEW YORK
NEW JERSEY
Hudson River
41° 00'
Pompton River
9
5
Rockaway River
4
Little Falls
8
3
Whippany River
7
Passaic River
2
Chatham
1
Passaic River
Newark
Passaic
MANHATTAN
LONG ISLAND
STATEN ISLAND
5 0 5 MILES

3

Buchanan (1968), as part of the present cooperative project, suggested an "inexpensive and rapid" method for obtaining representative mean depth and mean velocity data. In brief, Buchanan (p. 43) obtained mean velocity information by the technique described by Steacy, although much shorter stream reaches were selected so that "each subreach had a constant discharge and a more or less constant cross-sectional area." Using measured cross-sectional areas (A), the mean depth was calculated as follows:

$$H = \frac{A}{W} \qquad (5)$$

where H represents the reach's mean depth and W the reach's mean width (water surface).

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An example of the procedure used by Buchanan to adjust the measured cross-sectional area for other streamflow conditions is presented in figure 2. Buchanan's technique utilizes a gage height-

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Figure 2 (caption on next page) near here.

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water discharge relation observed at a gaging station or partial record station (upper curve) to adjust the river stage-river width relation (lower curve) measured at ungaged sites. For example, the change in gage height at 50 ft^3/s (142 l/s) from that observed during a cross-sectional area measurement is 3 ft (0.9 m) (line A, upper curve). This change in gage height was applied directly to adjust the cross-sectional area at an ungaged site (lower curve), and represents a decrease in river stage from 5.5 ft (1.7 m) to 2.5 ft (0.8 m) in the example shown.

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Figure 2.--Example of procedure used by Buchanan (1968) to adjust the measured cross-sectional area to other streamflow conditions.

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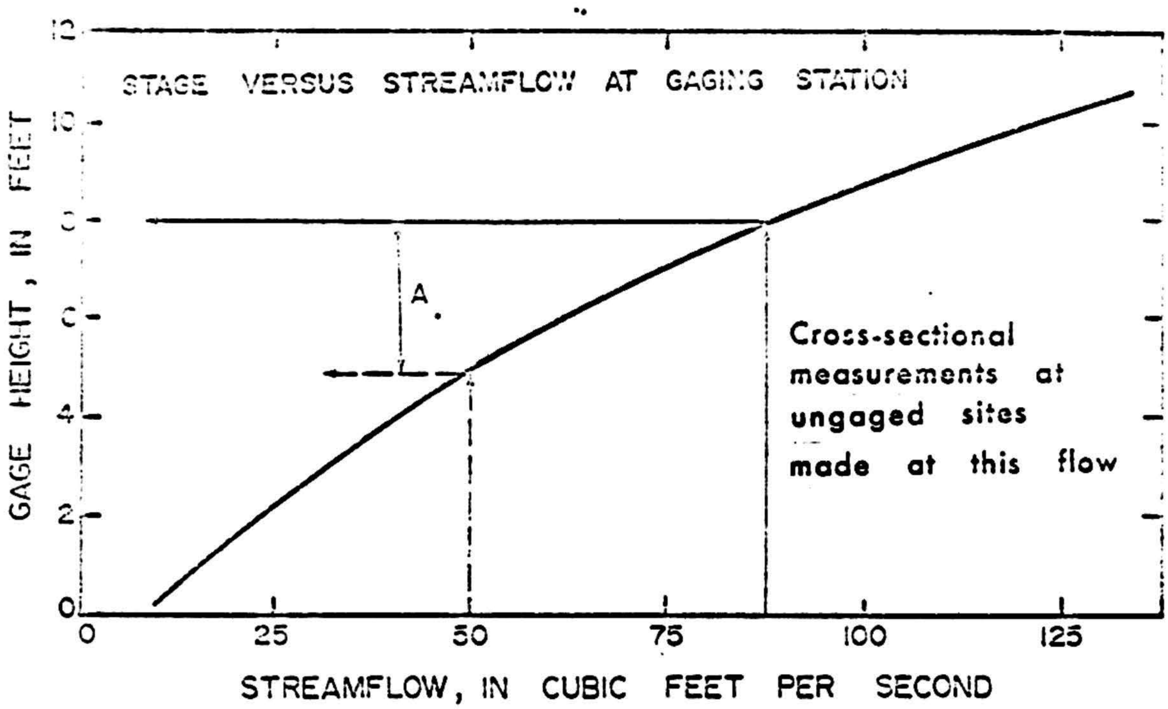
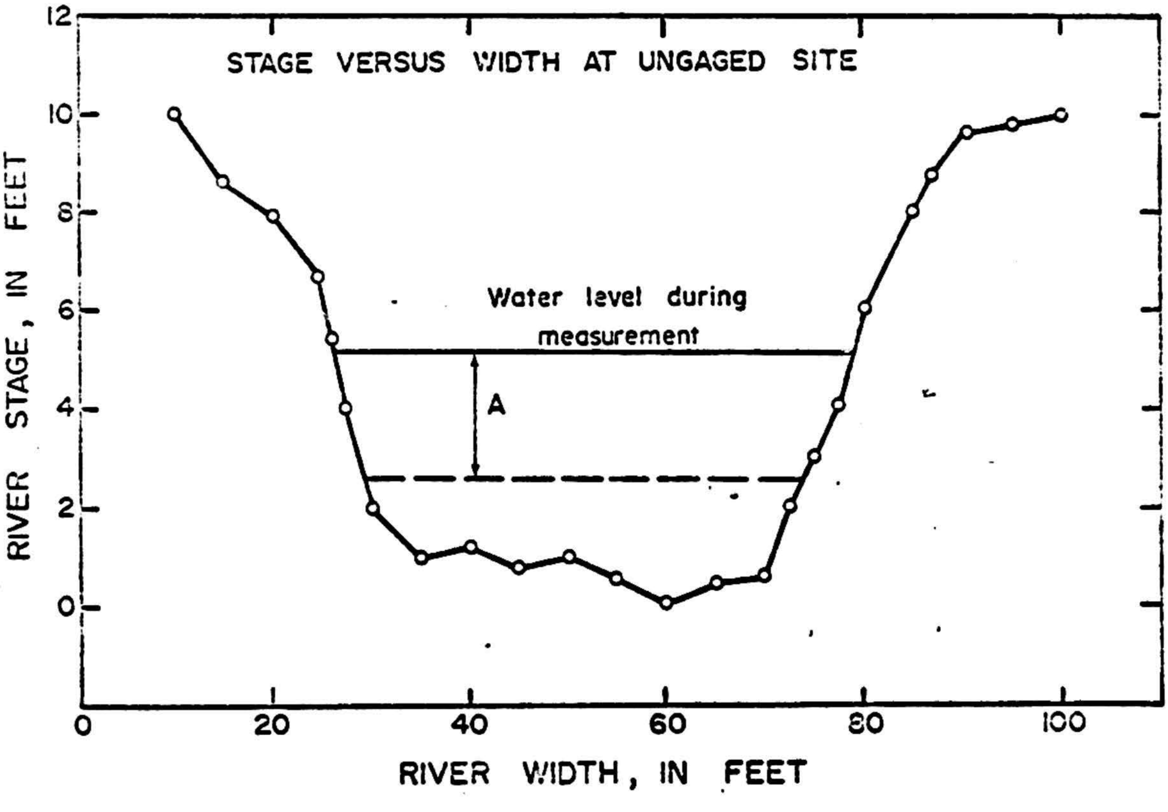

STAGE VERSUS STREAMFLOW AT GAGING STATION
GAGE HEIGHT, IN FEET
A
Cross-sectional measurements at ungaged sites made at this flow
STREAMFLOW, IN CUBIC FEET PER SECOND


STAGE VERSUS WIDTH AT UNGAGED SITE
RIVER STAGE, IN FEET
Water level during measurement
A
RIVER WIDTH, IN FEET

Although Buchanan's technique is rapid, its accuracy and degree of applicability is questionable, for the following reasons:

1. The application of a gaging station's stage-discharge relation to adjust the measured cross-sectional area at another ungaged site to other streamflow conditions is debatable. This adjustment assumes that the relation monitored at a gaging station is representative of the stream reach under study. (That is, the relation assumes uniformity in the reach.) As artificial controls, which alter channel characteristics, especially velocity and depth, are usually used at gaging stations, the validity of the adjustment made at ungaged sites is questionable.
2. The method of determining velocity results in underestimation, if any "stagnant" water exists in the measured cross section. Also, considerable error results when channel geometry is erratic (Wilson and Forest, 1965).

For these reasons and also recognizing the inherent problems in choosing a single point to represent a reach's mean velocity and mean depth, an effort was made to obtain other techniques for measuring these two parameters.

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PROCEDURE

The procedure employed first requires the development of a family of curves (fig. 3) to define variations in streamflow along the stream channel. These curves and a known value of discharge at any point in the reach will provide the mean discharge in the reach. Curves of relation of velocity to discharge (fig. 4) and depth to discharge (fig. 5) will be used to obtain the two desired parameters. The techniques used to develop these curves are described below.

Mean Discharge

The initial step was to determine the mean discharge in each reach investigated. These were determined from discharge profiles obtained by combining data from streamflow-gaging and low-flow partial-record stations with any direct discharge measurements. Examples of discharge profiles for reach 7 (fig. 1) on the Whippany River at three streamflow rates are shown in figure 3.

Figure 3 (caption on next page) near here.

Similar profiles were developed for other reaches investigated on the Pompton, Rockaway, and Passaic Rivers (fig. 1). For the purpose of the present study, at least three discharge profiles, representing a range between low and median flow rates, were computed for each reach.

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Figure 3.--Discharge profiles, Whippany River between Whippany (mile 0) and Pine Brook (mile 7), N.J.

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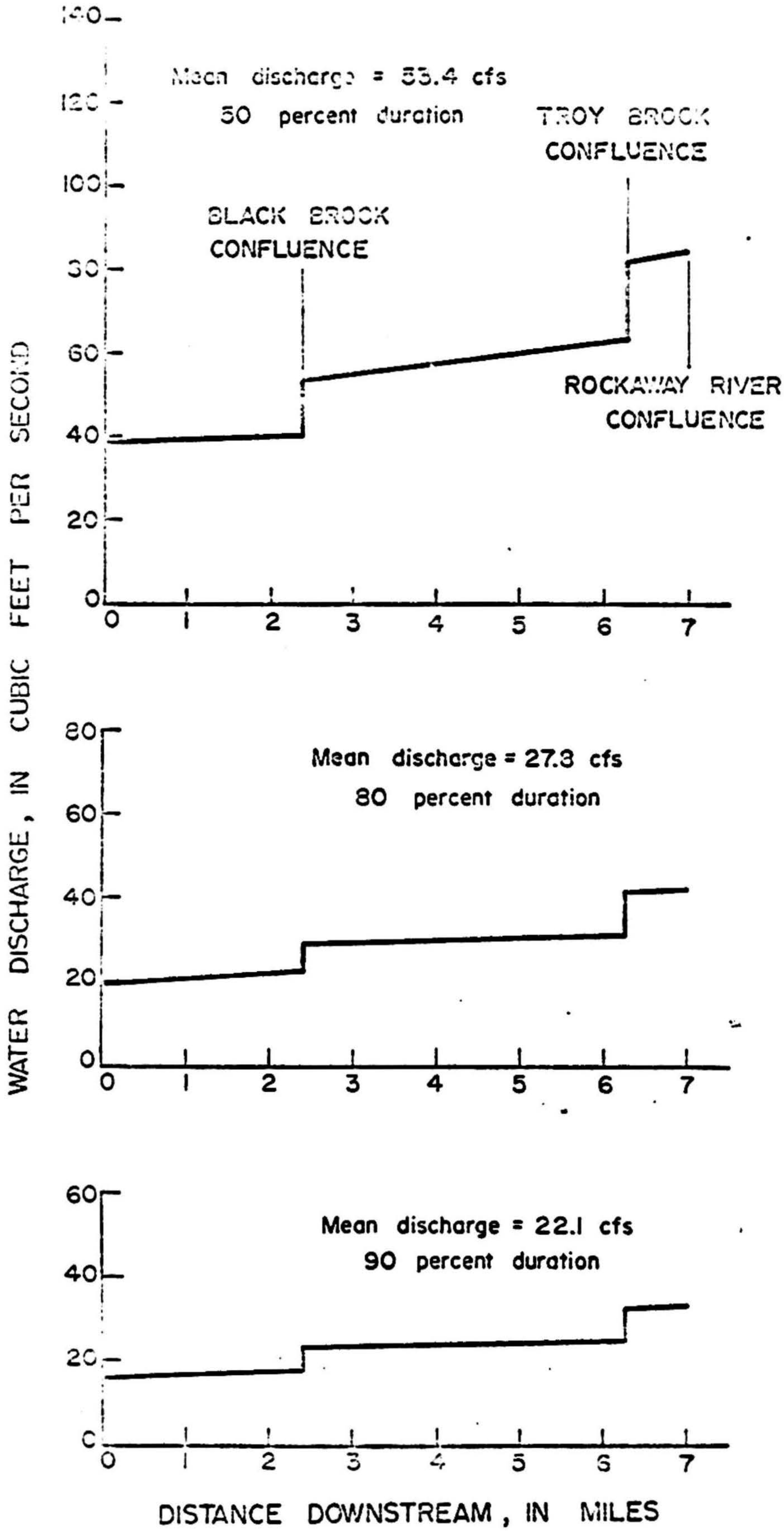

Mean discharge = 53.4 cfs
50 percent duration
TROY BROOK CONFLUENCE
BLACK BROOK CONFLUENCE
ROCKAWAY RIVER CONFLUENCE
Mean discharge = 27.3 cfs
80 percent duration
Mean discharge = 22.1 cfs
90 percent duration
WATER DISCHARGE, IN CUBIC FEET PER SECOND
DISTANCE DOWNSTREAM, IN MILES

Mean Velocity

Excellent values of mean velocities are reported to be given by time-of-travel measurements (Buchanan, 1964, Wilson, 1968). Several such measurements on over 300 miles of stream channel have been made to date (1973) in New Jersey, most of which have been made in the Passaic River basin (Horwitz and Anderson, 1966, Anderson and Faust, 1973). Estimates of mean velocity were made by injecting a fluorescent dye at the upper end of a reach and monitoring its passage at another point downstream. The distance traveled divided by the elapsed time between injection and arrival of the peak dye concentration, assuming no longitudinal dispersion, is equal to the mean velocity of water for that reach. A more accurate mean traveltime would be defined by the difference in elapsed time of the centroids of the concentration-time curves for the upstream and downstream sections of the reach; however, such data were not available for use herein.

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Traveltime in the basin were measured under varying flow conditions. These measurements enabled the development of a mean velocity-water discharge relation, from which the mean velocity at any flow can be interpolated. Velocity can be related to the mean discharge either in the reach or at a nearby gaging station. In the present investigation, velocity was related to the discharge in the reach, in that later computation of depth requires a discharge value for the measured reach. An example of the results obtained for reach 7 (fig. 1) on the Whippany River is shown in figure 4.

Figure 4 (caption on next page) near here.

Once such a relation is developed, the velocity at any flow rate can be determined. Note that a linear relation develops when the data are plotted on log-log scale. This linear relation is typical of all the stream reaches studied.

Figure 4.--Relation between mean velocity and water discharge on lower Whippany River.

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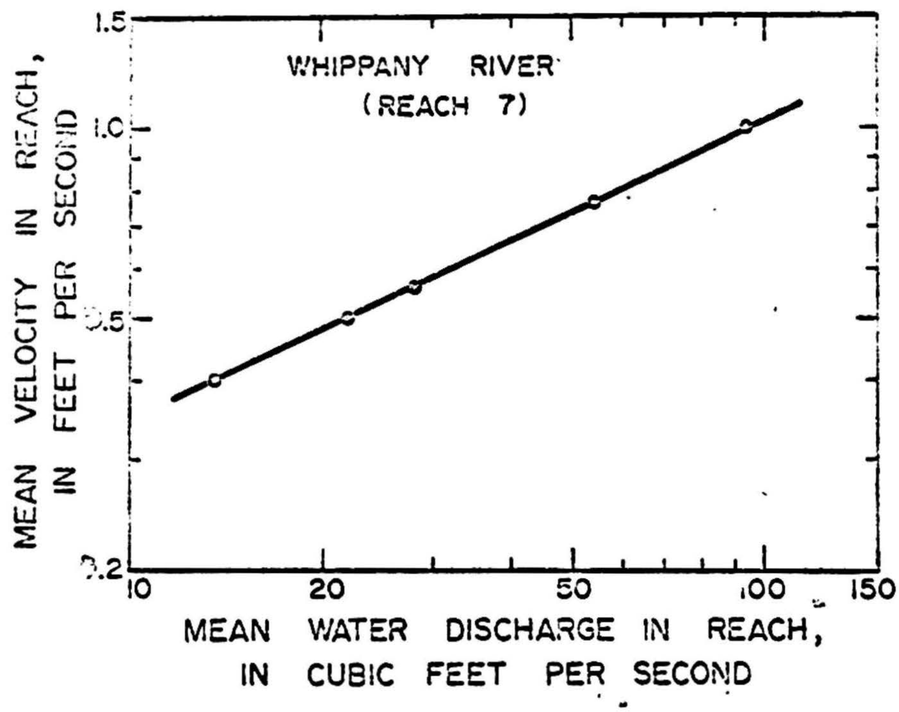
WHIPPANY RIVER
(REACH 7)
MEAN VELOCITY IN REACH, IN FEET PER SECOND
1.5
1.0
0.5
0.2
10
20
50
100
150
MEAN WATER DISCHARGE IN REACH, IN CUBIC FEET PER SECOND

Mean Depth

The next step was to calculate the mean area (A) of the reach being studied. This value for any flow rate is easily determined using equation (4). The mean discharge (Q) for each reach is determined from profile data (fig. 3), and the mean velocity (V) from time-of-travel data (fig. 4).

Once a mean area was calculated, equation (5) was used to compute the mean depth in the following manner: several cross-sectional measurements, such as that illustrated in figure 2, were made in each stream reach. The number of such measurements made depended upon length of reach and variation in channel hydraulics and geometry within the reach. Except in extreme nonuniform reaches, where more frequent measurements were obtained, approximately one cross-sectional area measurement per river mile was considered sufficient.

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These cross-sectional measurements were then used to define the relation between area (cross section) and width (water surface) at each measurement site. This allowed the determination of width at any preselected area. The widths for all measurements in a particular reach were then averaged to obtain a mean width. The mean depth of each reach was computed by equation (5).

Because computer application of velocity and depth in determining k_2 necessitated their being related to streamflow, graphs describing these relations were developed. Typical plots of mean depth versus streamflow are shown on figure 5. As previously

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Figure 5 (caption on next page) near here.

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observed for velocity-discharge relations (fig. 3), the depth-discharge relations in stream reaches studied exhibit linear relations when plotted on a log-log scale.

Figure 5.--Relation between mean depth and water discharge on lower Whippany River.

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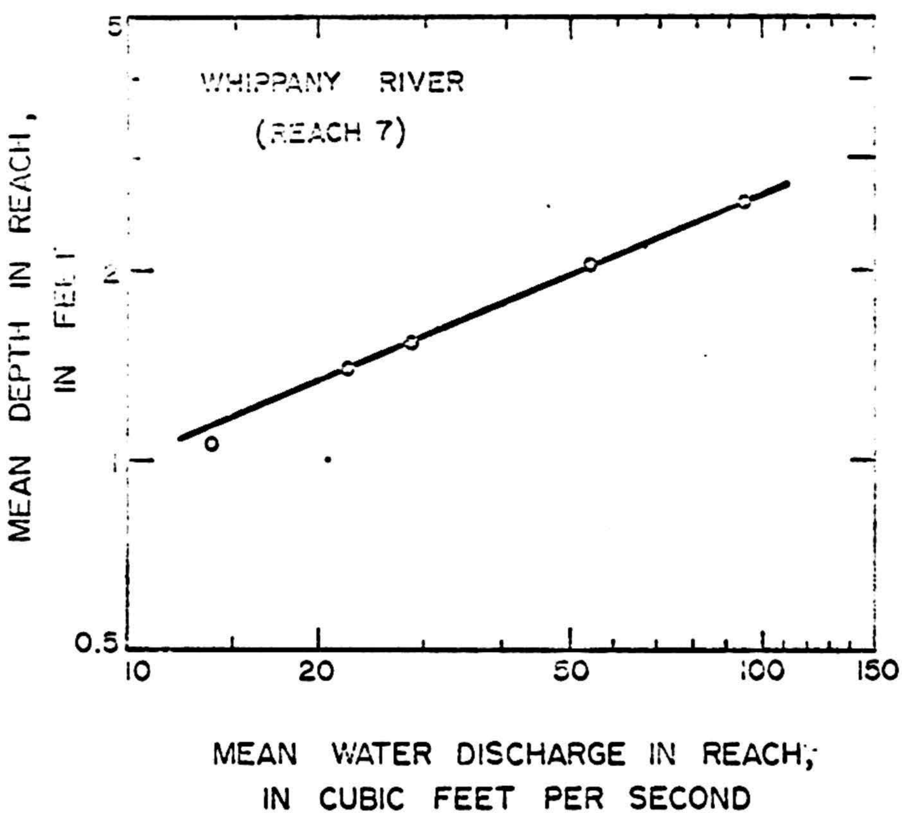
WHIPPANY RIVER
(REACH 7)
MEAN DEPTH IN REACH, IN FEET
5
2
1
0.5
10
20
50
100
150
MEAN WATER DISCHARGE IN REACH, IN CUBIC FEET PER SECOND

RESULTS AND DISCUSSION

Stream reaches investigated are illustrated on figure 1. They include 30.9 mi (49.7 km) on the Passaic River main stem; 5.7 mi (9.2 km) on the Whippany River; 5.8 mi (9.3 km) on the Rockaway River; and 6.8 mi (10.9 km) on the Pompton River.

Length of reach, and mean depth and mean velocity data at three selected flow rates, expected to be equaled or exceeded 50, 80, and 90 percent of the time, are tabulated in table 2. Mean depth ranged from 0.75 to 7.6 ft (0.23-2.32 m), and mean velocities from 0.14 to 0.83 ft/s (0.04-.25 m/s). Accurate definition of mean widths for high-flow conditions in stream reaches that drain a large swamp--such as in reach 5 (fig. 1)--was difficult because of ill-defined embankments. Thus, a mean depth was not computed for the higher streamflows in such reaches.

Table 2.--Summary tabulation of mean depths and mean velocities, at indicated streamflows, for selected reaches in the Passaic River basin.

Stream and reach	Reach no. (fig. 1)	Length (mi)	Mean discharge (ft^3/s)	Flow duration (percent)	Mean depth (ft)	Flow velocity (ft/s)
			PASSAIC RIVER			
Chatham to Florham Park	1	4.2	77.4	50	1.2	0.83
			24.0	80	1.0	.36
			12.0	90	.75	.25
Florham Park to Hanover	2	4.9	88.8	50	2.0	.45
			27.5	80	1.3	.27
			15.0	90	1.1	.22
Hanover to Pine Brook	3	6.0	152	50	2.5	.58
			58.0	80	2.0	.30
			37.1	90	1.7	.23
Pine Brook to Clinton	4	3.4	277	50	4.2	.54
			112	80	2.6	.42
			76.0	90	2.1	.38
Clinton to Two Bridges	5	9.0	--	50	--	--
			120	80	4.2	.26
			76.0	90	3.6	.25
Two Bridges to Little Falls	6	3.4	620	50	7.6	.32
			235	80	4.8	.19
			151	90	4.1	.15

Table 2.--Summary tabulation of mean depths and mean velocities, at indicated streamflows, for selected reaches in the Passaic River basin--Continued.

Stream and reach	Reach no. (fig. 1)	Length (mi)	Mean discharge (ft^3/s)	Flow duration (percent)	Mean depth (ft)	Flow velocity (ft/s)
			WHIPPANY RIVER			
Whippany to Pine Brook	7	5.7	53.4	50	2.0	0.76
			27.8	80	1.5	.56
			22.1	90	1.4	.50
			ROCKAWAY RIVER			
Boonton below res. to Pine Brook	8	5.8	40.0	--	1.6	.45
			10.0	--	.97	.21
			5.0	--	.80	.14
			POMPTON RIVER			
Pompton Plains to Two Bridges	9	6.8	284	50	3.2	.74
			126	80	2.6	.43
			90.0	90	2.5	.34

Relations between mean velocity (fig. 4) and mean depth (fig. 5) and mean discharge in each reach were developed. Leopold and Maddock (1953) have reported similar relations throughout the country with the following general equations:

$$H = aQ^b \qquad V = cQ^d \qquad (6)$$

where the constants a, b, c, and d are dependent upon the hydraulic characteristics of the stream reach. Values of these constants derived for stream reaches studies in the Passaic River basin and the discharge range over which they were developed are tabulated in table 3.

Table 3.--Summary of equation constants for mean depth-discharge and mean velocity-discharge relations.

River	Reach no. (fig. 1)	Streamflow range ft^3/s	Constants a	b	c	d
Passaic	1	10-80	0.45	0.24	0.050	0.64
	2	15-90	.40	.36	.068	.41
	3	35-150	.74	.25	.021	.66
	4	75-280	.23	.51	.120	.27
	5	75-120	.96	.31	.170	.093
	6	150-620	.41	.45	.011	.52
Whippany	7	20-55	.34	.44	.120	.47
Rockaway	8	5-40	.46	.34	.055	.57
Pompton	9	90-285	.94	.22	.017	.67

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The expression of mean velocity and mean depth in terms of streamflow is advantageous when determining the reaeration coefficient from empirical relations such as that given in equation (2). For example, arbitrarily selecting constants reported by O'Connor and Dobbins (1958) from table 1, equation (2) becomes:

$$k_2 = 5.616 \frac{V^{0.5}}{H^{1.5}} \tag{7}$$

However, for the Whippany River (reach 7), V and H can be expressed, based on data in table 3, in terms of streamflow as follows:

$$V = 0.12\, Q^{0.47} \tag{8}$$

$$H = 0.34\, Q^{0.44} \tag{9}$$

Substituting these two equations (8 and 9) into equation (7) results in the following expression for the reaeration coefficient:

$$k_2 = 9.83\, Q^{-0.97} \tag{10}$$

Thus, the reaeration coefficient can be determined based only on streamflow values. For example, flow-duration, recurrence-interval, or preselected values of streamflow can be used to determine this coefficient. A typical plot of the variation of the reaeration coefficient with flow is illustrated on figure 6.

Figure 6 (caption on next page) near here.

Figure 6.--Relation between reaeration coefficient and streamflow in lower Whippany River basin.

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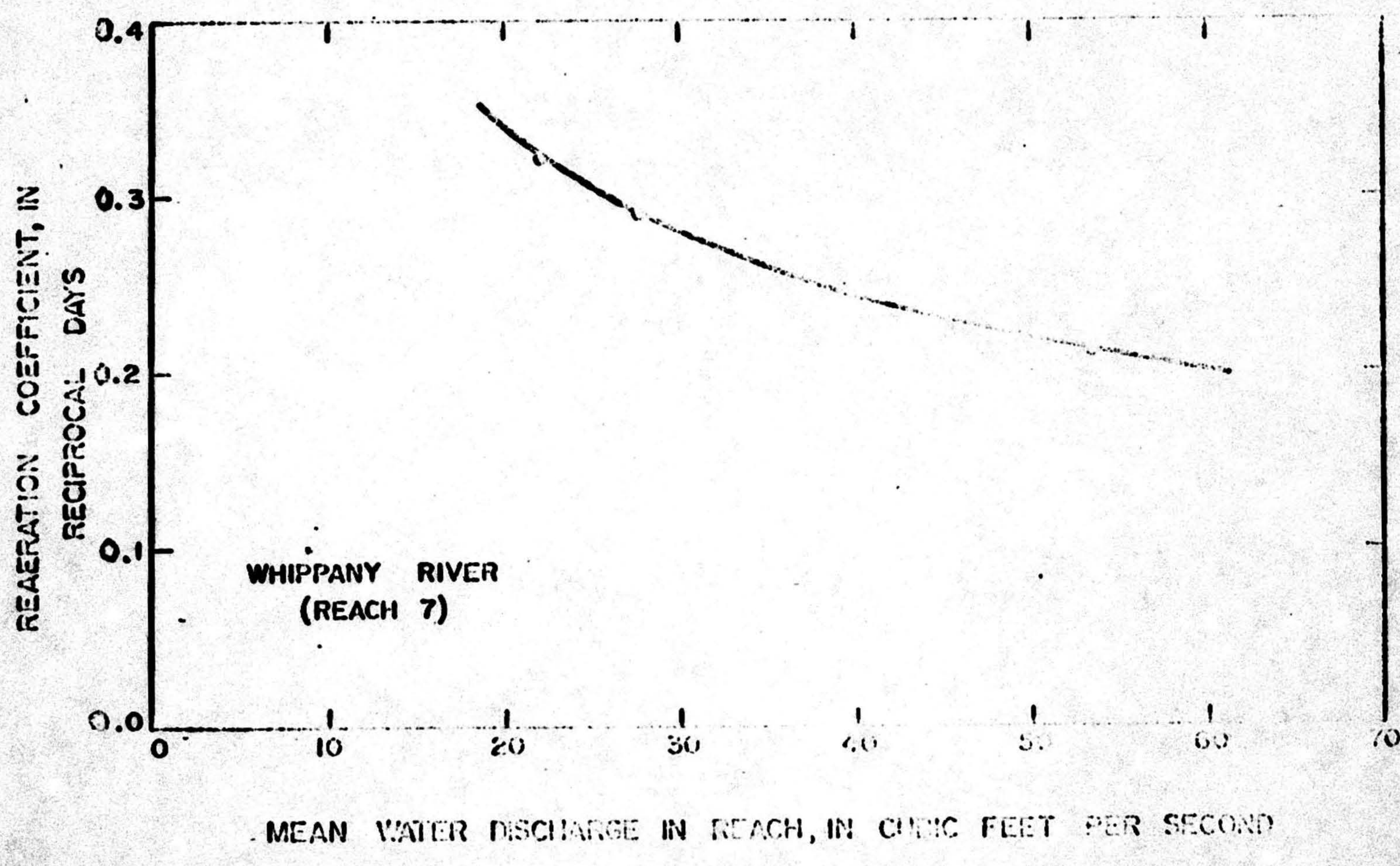

REAERATION COEFFICIENT, IN RECIPROCAL DAYS
0.4
0.3
0.2
0.1
0.0
WHIPPANY RIVER
(REACH 7)
0
10
20
30
40
50
60
70
MEAN WATER DISCHARGE IN REACH, IN CUBIC FEET PER SECOND

SUMMARY

Methods were developed to estimate mean velocities and mean depths for use in computation of reaeration coefficients for selected reaches of the Passaic River basin. Time-of-travel, streamflow, and cross-sectional data are needed for the method. The procedure developed assumes base-flow conditions, as this assumption simplifies both field and office computations. The procedure described is thought by the authors to give better results than the procedure earlier reported by Buchanan (1968), primarily in that mean velocity is measured, and mean depth is derived from several field observations and not estimated from a point value. In addition, field and office work are simplified, as a stage-discharge relation need not be established for each reach.

U. S. GOVERNMENT PRINTING OFFICE

REFERENCES

Anderson, P. W., and Faust, S. D., 1973, Characteristics of water quality and streamflow, Passaic River above Little Falls, N.J.: U.S. Geol. Survey Water-Supply Paper 2026, 80 p.

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

Buchanan, T. J., 1964, Time of travel of soluble contaminants in streams: Amer. Soc. Civil Engineers Proc., Jour.. Sanitary Eng. Div., v. 90, no. SA 3, p. 1-12.

__________1968, Computation of reaeration coefficients for a river system in northeastern New Jersey in Geological Survey Research, 1968: U.S. Geol. Survey Prof. Paper 600-D, p. 42-44.

Churchill, M. A., Elmore, H. L., and Buckingham, R. A., 1962, The prediction of stream reaeration rates: Amer. Soc. Civil Engineers Proc., Jour. Sanitary Eng. Div., v. 88, no. SA 4, p. 1-46.

Copeland, B. J., and Duffer, W. R., 1964, Use of a clear plastic dome to measure gaseous diffusion rates in natural waters: Limnol, Oceanogr., v. 9, p. 494-499.

Dobbins, W. E., 1964, BOD and oxygen relationships in streams: Amer. Soc. Civil Engineers Proc., Jour. Sanitary Eng. Div., v. 90, no. SA 3, p. 53-78.

Edwards, R. W., Owens, M., and Gibbs, J. W., 1961, Estimates of surface aeration in two streams: Inst. Water Engineers Jour., v. 15, p. 393-405.

Gameson, A. L. H., and Truesdale, G. A., 1959, Some oxygen studies in streams: Inst. Water Engineers Jour., v. 13, p. 175-187.

Gameson, A. L. H., Truesdale, G. A., and Downing, A. L., 1955, Reaeration studies in a lakeland bech: Inst. Water Engineers Jour., v. 9, p. 571-594.

Gloyna, E. F., Yousef, Y. A., and Padden, T. J., 1969, Transport of organic and inorganic materials in small ecosystems: Envir. Health Engineering, Univ. of Texas.

Horwitz, G. M., and Anderson, P. W., 1966, Time-of-travel measurements on the Passaic and Pompton Rivers, New Jersey in Geological Survey Research 1966: U.S. Geol. Survey Prof. Paper 550-B, p. 199-203.

U. S. GOVERNMENT PRINTING OFFICE : 19[illegible]

Isaacs, W. P., and Gaudy, A. F., Jr., 1968, Atmospheric oxygenation in a simulated stream: Amer. Soc. Civil Engineers Proc., Jour. Sanitary Eng. Div., v. 94, no. SA 2, p. 319-344.

Juliano, D. W., 1969, Reaeration measurements in an estuary: Amer. Soc. Civil Engineers Proc., Jour. Sanitary Eng. Div., v. 95, no. SA 6, p. 1165-1178.

Krenkel, P. A., and Orlab, G. T., 1962, Turbulant diffusion and the reaeration coefficient: Amer. Soc. Civil Engineers Proc., Jour. Sanitary Eng. Div., v. 88, no. SA 2, p. 53-83.

Langbein, W. B., and Durum, W. H., 1967, The aeration capacity of streams: U.S. Geol. Survey Circ. 542, 6 p.

Leopold, L. B., and Maddock, Thomas, Jr., 1953, The hydraulic geometry of stream channels and some physiographic implications: U.S. Geol. Survey Prof. Paper 252, 57 p.

Negulescu, M., and Rojanski, V., 1969, Recent research to determine reaeration coefficients: Water Research, v. 3, no. 3, p. 189-202.

O'Connor, D. J., 1971, Stream and estuarine analysis: Manhattan Col., New York, N.Y., 16th Summer Instit. in Water Pollution Control.

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

Odum, H. T., 1956, Primary production in flowing waters: Limnol. Oceanogr., v. 1, p. 102-117.

Owens, M., Edwards, R. W., and Gibbs, J. W., 1964, Some reaeration studies in streams: Internal. Jour. Air and Water Pollution, v. 8, p. 469-486.

Steacy, R. E., 1961, Time of travel of water in the Ohio River, Pittsburg to Cincinnati: U.S. Geol. Survey Circ. 439, 14 p.

Thackston, E. L., and Krenkel, P. A., 1969, Reaeration prediction in natural streams: Amer. Soc. Civil Engineers Proc., Jour Sanitary Eng. Div., v. 95, no. SA 1, p. 65-94.

Tsivoglou, E. C., 1967, Tracer measurements of stream reaeration: Fed. Water Pollution Control Adm. Rept., June, 86 p.

U. S. GOVERNMENT PRINTING OFFICE:

Wilson, J. F., Jr., 1968, Time-of-travel measurements and other applications of dye tracing: Internat. Assoc. Sci. Hydrol., Pub. 76, p. 252-262.

Wilson, J. F., Jr. and Forrest, W. E., 1965, Potomac River time-of-travel measurements: Proc. Symposium on Diffusion in Oceans and Fresh Waters, Lamont Geol. Observatory, p. 1-18.

Zogorski, J. S., 1972, The reaeration capacity of streams - a critical review: Rutgers Univ., New Brunswick, N.J., MS thesis.

Zogorski, J. S., and Faust, S. D., 1973, Atmospheric reaeration capacity of streams: Environmental letters, no. 4, p. 35-85.

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