TRAVELTIME, LONGITUDINAL-DISPERSION, REAERATION, AND BASIN CHARACTERISTICS OF THE WHITE RIVER, COLORADO AND UTAH

by Jeanne M. Boyle and Norman E. Spahr

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METRIC CONVERSION FACTORS

For the convenience of readers who may want to use the International System of Units (SI), the data may be converted using the following factors:

Multiply inch-pound units	*By*	*To obtain SI units*
cubic foot per second	0.02832	cubic meter per second
degree	0.01745	radian
foot	0.3048	meter
foot per foot	1.000	meter per meter
foot per mile	0.1894	meter per kilometer
foot per second	0.3048	meter per second
foot per square mile	0.1177	meter per square kilometer
inch	25.40	millimeter
mile	1.609	kilometer
mile per hour	1.609	kilometer per hour
ounce, fluid	29.57	milliliter
pound	0.4536	kilogram
square foot per second	0.09290	square meter per second
square mile	2.590	square kilometer

Degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) by using the following equation:

$$°F = 9/5°C + 32$$

The following term is also used in this report: micrograms per liter.

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ABSTRACT

The White River basin contains extensive energy resource developments which might affect the quantity and quality of the basin's water resources. The purpose of this study was to determine traveltime, longitudinal-dispersion, reaeration, and basin characteristics of the White River which can be used in making decisions concerning the energy developments.

Traveltime and longitudinal-dispersion characteristics were measured for the White River using dye tracers. Discharges ranged from 281 to 1,840 cubic feet per second and velocities ranged from 1.26 to 3.17 miles per hour. Traveltimes were determined for discharges other than measured discharges by a graphical method and a linear-regression method. Longitudinal-dispersion coefficients ranged from 284 square feet per second at a discharge of 539 cubic feet per second to 3,560 square feet per second at a discharge of 1,580 cubic feet per second.

Reaeration was measured using a modified-tracer technique in four reaches of the White River during a medium-flow period in August 1982. Reaeration coefficients at 20° Celsius ranged from 5.3 to 25.3 per day. The results of a comparison with measured reaeration coefficients and reaeration coefficients predicted using empirical equations showed that the most accurate equations were by Bennett and Rathbun (1972) and Isaacs and Gaudy (1968).

Basin characteristics were determined using U.S. Geological Survey topographic maps, precipitation data from the National Weather Service, and aerial photographs taken on September 11, 1981.

INTRODUCTION

The White River basin contains extensive energy resources consisting of oil, natural gas, coal, and oil shale. Existing and planned energy development might affect the quantity and quality of the basin's water resources. This report is part of a 4-year assessment of the White River basin from water years 1981 through 1984. The objectives of the assessment were to describe the existing hydrology of the basin and to evaluate some of the potential environmental effects of energy-resource development on the quantity and quality of the water resources in the basin.

A growth in population probably would be associated with an increase in energy development, causing a possible increase of wastes discharged into streams (Wentz and Steele, 1980). This increase in wastes might cause water-quality problems. Information on traveltime, longitudinal-dispersion, reaeration, and basin characteristics may prove useful to State and local officials, planners, and managers in making decisions concerning energy developments. The traveltime, longitudinal-dispersion, and reaeration data provide information on how fast wastes move downstream, how they are dispersed longitudinally in streams, and how rapidly streams can assimilate certain forms of treated wastes. The basin-characteristics data provide information on the land surface, stream channels, and the water available within the basin.

Purpose and Scope

The main purpose of the study was to determine traveltime and longitudinal-dispersion characteristics for streamflow in designated reaches of the White River for a range of stream-discharge conditions. A second purpose was to determine the reaeration coefficient (K2) for four reaches on the White River and to compare them with computed reaeration coefficients using various empirical equations. Only brief descriptions of traveltime and reaeration measurement techniques are included in this report. Explanations of these techniques are described in detail in referenced reports. Basin characteristics were included in this report to provide baseline data on the physical and climatic conditions of the basin and the channel geometry prior to energy resource development in the White River basin. A description of the geologic characteristics in the White River basin was not included in this report, but is given in Boyle and others (1984).

Study Area

The White River basin is located in northwestern Colorado and northeastern Utah (see fig. 1). The surface area of the basin is 5,120 square miles, 74 percent of which is in Colorado and 26 percent in Utah. The White River flows to the west and drains into the Green River in Utah. Most of the tributaries, such as the South Fork White River, Piceance Creek, and Yellow Creek, drain from the south into the White River. An average of 70 percent of the annual flow of the White River occurs during the spring months as a result of snowmelt runoff.

The White River basin contains extensive energy resources consisting of oil, natural gas, coal, and oil shale. Existing energy production within the basin consists primarily of oil and natural gas, and some coal. Rio Blanco County, Colo., containing the Rangely oil and natural gas fields, ranks first in Colorado for production of these two resources. The most underdeveloped natural resource in the basin is the extensive oil-shale deposits. A secondary land use in the basin is agriculture. The land is used for livestock production and to grow hay and grain.

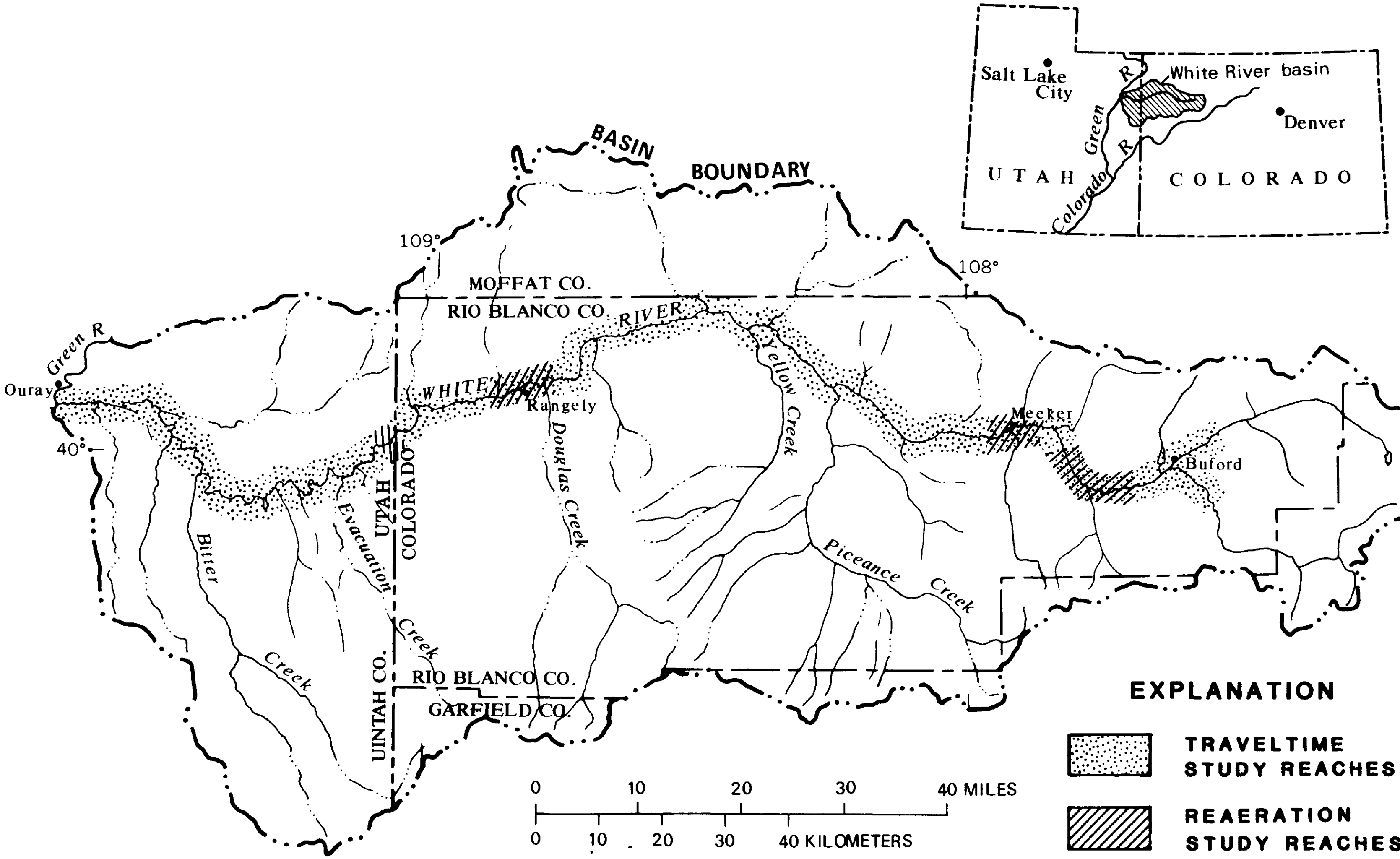

Figure 1.--Location of study reaches for traveltime and reaeration measurements in the White River basin.

Acknowledgments

The authors extend their appreciation to the many residents along the White River for permitting access to sites on the river for data collection. The authors are also grateful to Donald M. Batty, U.S. Geological Survey, Vernal, Utah, for his assistance in locating access points to the river in the remote areas of the basin in Utah. Assistance in collecting the data provided by personnel of the Colorado offices of the U.S. Geological Survey is also appreciated. The contributions of Richard A. Nielsen, Sean M. Bryn, and James B. Horn are gratefully acknowledged for their assistance in computing the basin characteristics and analyzing the aerial photographs.

LOCATION AND EXTENT OF STUDY REACHES FOR TRAVELTIME AND REAERATION MEASUREMENTS

The location of the dye-tracer traveltime study reaches are shown in figure 1. They extend for 7 miles of the North Fork White River and 6 miles of the South Fork White River upstream from their confluence and downstream on the White River for 198 miles to its mouth near Ouray, Utah. Tracer studies were conducted during May 1981; May, April, and August 1982; and July and September 1983. The May 1981, April and August 1982, and September 1983 discharges were characterized as medium (400 to 1,000 cubic feet per second), whereas the May 1982 and July 1983 discharges were characterized as high (greater than 1,000 cubic feet per second). Only one dye-tracer measurement was made on the section of the White River in Utah, because a low flow (less than 400 cubic feet per second) did not occur during this study.

Reaeration measurements were made on four reaches of the White River (see fig. 1). The first reach extends from about 5.5 miles downstream from the confluence of the North Fork White River and South Fork White River downstream for 6 miles. The second reach extends from about 3 miles upstream to 5 miles downstream from Meeker, Colo. The third reach extends from about 1 mile upstream to 9 miles downstream from Rangely, Colo. The fourth reach extends from about 0.5 miles downstream from the Colorado-Utah State line downstream for 2.5 miles. All the reaeration measurements were made during August 1982, which was characterized as a medium discharge. The injection and sampling sites at which the measurements were made are listed in table 1 and are shown in figure 2.

DETERMINATION OF TRAVELTIME AND LONGITUDINAL-DISPERSION CHARACTERISTICS

Traveltime and longitudinal-dispersion characteristics of a stream are different for various flow conditions. Therefore, measurements of the rate of movement and dispersion are necessary for a range of flows.

Table 1.--*Dye-tracer and gas injection and sampling sites*

Site (number in fig. 2)	Flow conditions[1]	Site type[2]	Distance from mouth (miles)	Station name
1	H,M	I	205.51	North Fork White River 7.03 miles above gage at Buford, Colo.
2	H,M	S	202.93	North Fork White River 4.45 miles above gage at Buford, Colo.
3	H,M	S	198.31	North Fork White River 0.10 miles below gage at Buford, Colo.
4	M	I	192.69	White River 5.79 miles below North Fork gage at Buford, Colo.
5	M	S	191.72	White River at Tru Sport Lodge, Colo.
6	M	S	190.13	White River 8.35 miles below North Fork gage at Buford, Colo.
7	H,M	S	187.59	White River above mouth of Miller Creek, Colo.
8	H,M	I,S	181.37	White River at gage above Coal Creek, near Meeker, Colo.
9	H,M	I,S	177.61	White River at gage near Meeker, Colo.
10	M	S	176.22	White River 1.39 miles below gage near Meeker, Colo.
11	H,M	S	174.53	White River at city park in Meeker, Colo.
12	H,M	S	169.52	White River at State Highway 13, Colo.
13	H,M	S	158.76	White River at gage below Meeker, Colo.
14	H,M	I,S	147.79	White River at Piceance Creek Road, Colo.
15	H,M	S	135.59	White River 5.19 miles above mouth of Yellow Creek, Colo.
16	H,M	S	130.40	White River above mouth of Yellow Creek, Colo.
17	H,M	S	125.89	White River 1.47 miles above mouth of Wolf Creek, Colo.
18	H,M	S	117.50	White River at County Road 73, Colo.
19	H,M	I,S	106.55	White River at County Road 65, Colo.
20	H,M	I,S	102.00	White River at gage above Rangely, Colo.
21	M	I	95.65	White River 0.85 miles above old water treatment plant in Rangely, Colo.
22	H,M	S	94.80	White River at old water treatment plant in Rangely, Colo.
23	H,M	S	92.63	White River at White Avenue in Rangely, Colo.
24	H,M	I,S	91.00	White River 1.06 miles below State Highway 64, Colo.
25	H,M	S	85.38	White River 6.68 miles below State Highway 64, Colo.
26	H,M	S	79.43	White River 12.5 miles above gage near the Colorado-Utah State line, Colo.
27	H,M	I,S	73.92	White River 7.02 miles above gage near the Colorado-Utah State line, Colo.
28	M	I	69.49	White River 2.59 miles above gage near the Colorado-Utah State line, Utah
29	M	S	68.08	White River 1.18 miles above gage near the Colorado-Utah State line, Utah
30	H,M	S	66.90	White River at gage near the Colorado-Utah State line, Utah
31	M	S	60.60	White River 2.92 miles above Ignatio Stage Stop, Utah
32	M	I,S	57.68	White River at Ignatio Stage Stop, Utah
33	M	S	55.54	White River 5.06 miles below Ignatio Stage Stop, Utah
34	M	S	49.52	White River at mouth of Southam Canyon, Utah
35	M	S	43.50	White River at gage below Asphalt Wash, Utah
36	M	S	38.41	White River at mouth of Atchees Wash, Utah
37	M	S	30.21	White River below mouth of Bitter Creek, Utah
38	M	I,S	20.77	White River at Mount Fuels Bridge, Utah
39	M	S	12.30	White River 12.0 miles above gage at mouth, near Ouray, Utah
40	M	S	5.39	White River below mouth of Cottonwood Wash, Utah
41	M	S	.28	White River near gage at mouth, near Ouray, Utah
42	M	I	203.89	South Fork White River at South Fork gage near Buford, Colo.
43	M	S	200.46	South Fork White River at YZ Ranch, Colo.
44	M	S	197.57	South Fork White River at South Fork gage at Buford, Colo.

[1]H=high flow; M=medium flow.
[2]I=injection site; S=sampling site.

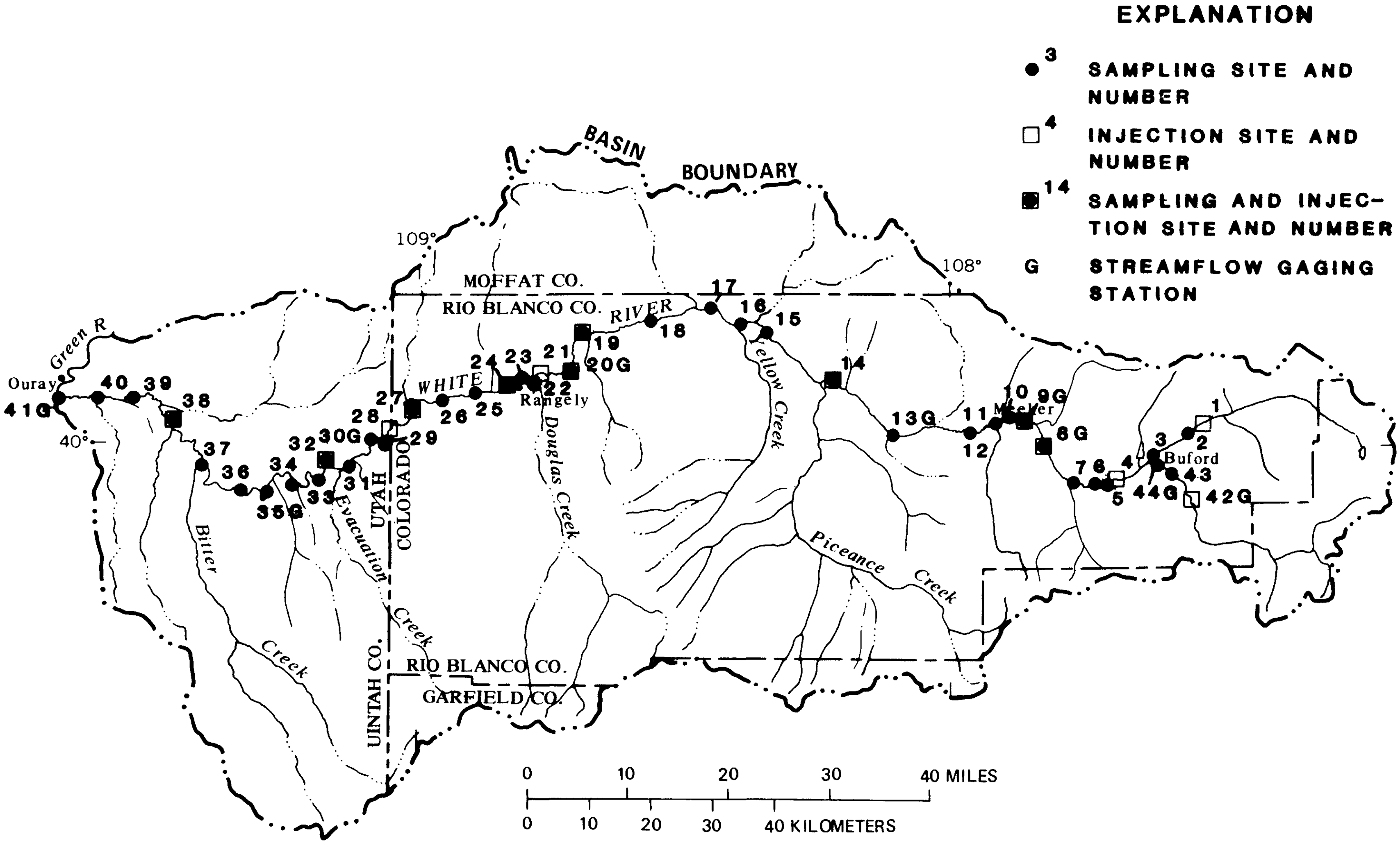

Figure 2.--Location of dye-tracer and gas injection and sampling sites on the study reaches of the White River.

Dye-Tracer Technique

The traveltime characteristics were measured by injecting a fluorescent dye, rhodamine-WT, into the river and monitoring the shape and speed of the dye cloud as it moved downstream. The injected dye is a solute that mixes completely with the water and moves in the same manner as the water. Measurement of the movement, concentration, and dispersion of the dye cloud describes the traveltime characteristics of other soluble contaminants that might be introduced into the stream. A complete description of the methods, procedures, dyes, and equipment used in such measurements is found in Hubbard and others (1982).

The dye was injected at selected locations along the White River and the resultant dye clouds were measured at sampling sites downstream (see fig. 2). Water samples were collected at approximately the center of flow whenever possible. The water samples collected at each site were analyzed using a fluorometer as described in Wilson (1968). A fluorometer is an instrument which measures the fluorescence of the dye sample. The amount of fluorescence measured is directly proportional to the concentration of the dye in the sample.

Traveltime

Traveltime is the time it takes a substance, such as dye, to travel from one point to another. Mean velocity in each subreach was computed using the traveltimes of the centroids of the dye clouds and the distance between each adjacent sampling site. This computation could also be done using the traveltimes of the peak concentrations.

Longitudinal Dispersion

Figure 3 shows a graph and sketch of the downstream movement and dispersion of the dye cloud for the May 5, 1982, injection at site 19, which is near Rangely. Dye clouds disperse as they travel downstream; therefore, they take a longer time to pass each successive site and the peak concentrations decrease. As shown in figure 3, the dye cloud took 0.78 hours to pass site 20; this time increased to 2.08 hours for the dye cloud to pass site 25. The peak concentration decreased from 13.5 micrograms per liter at site 20 to 4.65 micrograms per liter at site 25.

Figure 3 also shows the lateral and longitudinal mixing patterns of the dye cloud as it travels downstream. As noted by Bauer and others (1979) and Hubbard and others (1982), the dispersion of the tracer in the stream takes place in all three dimensions of the channel. Complete mixing in the vertical direction normally occurs first. Complete lateral mixing, which depends on the stream width and variations of velocity, occurs second. Longitudinal dispersion, because it has no boundaries, continues indefinitely. The dispersion of primary interest is the longitudinal dispersion. As shown in the sketch in figure 3, particles of dye at the center of the stream travel faster than those near the edges.

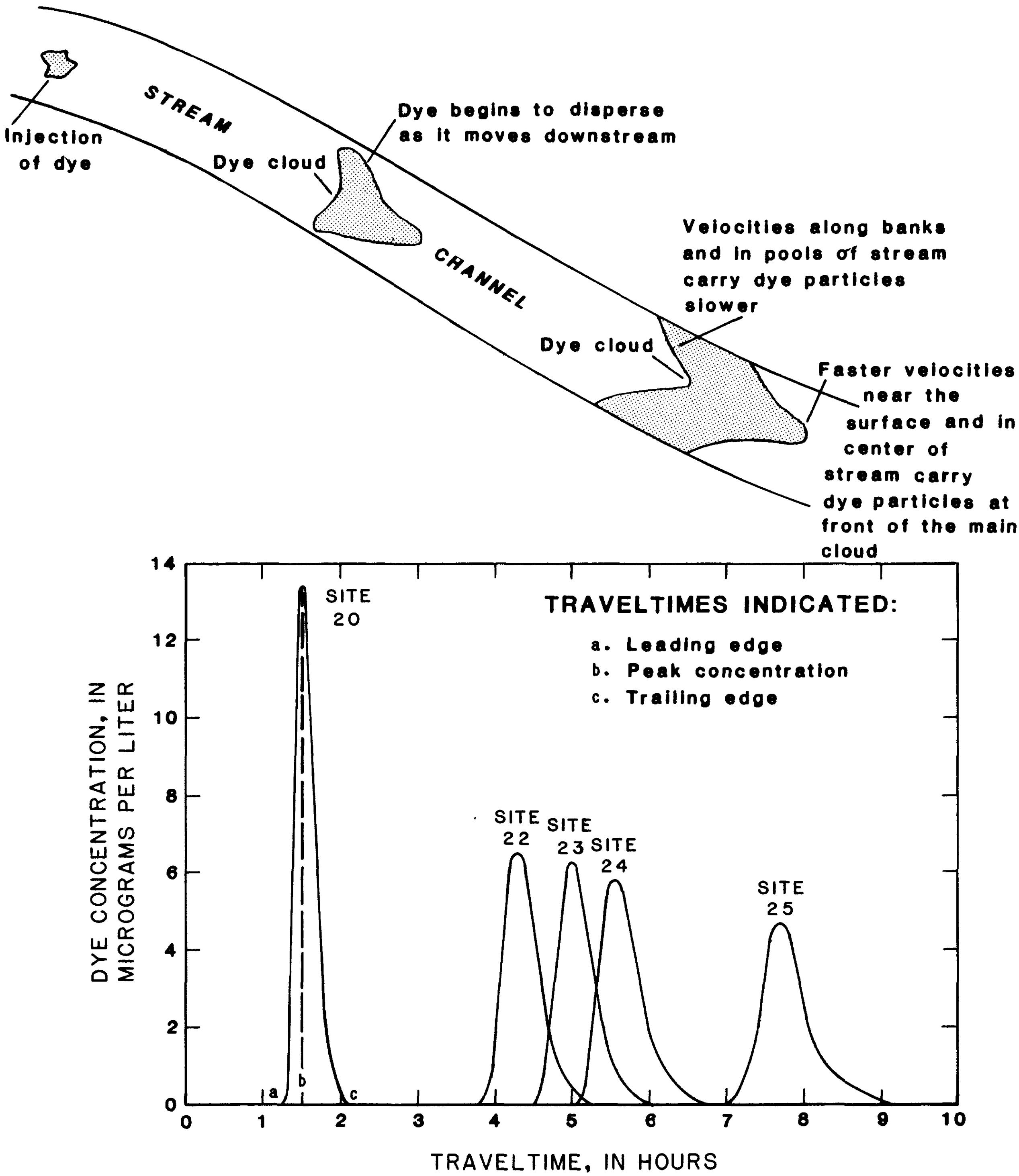

Figure 3.--Downstream movement and dispersion of a dye cloud resulting from a slug injection of dye, May 5, 1982 (site 21 not measured).

Results of Traveltime Studies

Traveltimes at flow conditions other than conditions measured were estimated using two different methods of prediction: graphical relationship and linear regression. The graphical relationship method was done to provide a base from which the linear-regression method could be compared. The linear-regression method is presented to provide traveltimes for the reaches in Utah at flows other than the measured flow and because it is more practical for some applications.

Mean Velocity and Discharge

Data from the dye-tracer measurements, including basic time-concentration curve characteristics and stream discharge, are given in table 2. Mean traveltime velocities ranged from 1.26 to 3.17 miles per hour. Measured velocities of dye clouds between injection sites and the first measurement site downstream are greater than the actual mean velocity of the water because the dye goes through a mixing period during which it travels faster than the water mass. During spring and summer measurements, variations in discharge between sites 7 and 14 were evident because of withdrawals of water for irrigation and return flows. The increase in discharge from sites 14 to 20 of 90 cubic feet per second during the May 1982 measurement is due to snowmelt runoff. The increase in discharge of 260 cubic feet per second from sites 14 to 15 during the July 1983 measurement is caused by the flow of Piceance Creek into the White River. For the April 1982 measurement in Utah, sites 30 to 41, discharge in most of the reaches decreased because of infiltration of water into the ground and evaporation.

There was a discrepancy in the area of dye curve for the injection on September 27, 1983, at site 24. Normally, the area of dye curve decreases downstream, but between sites 26 and 27 the area increased from 8.76 to 10.08 micrograms per liter times hours. This discrepancy was due to an error in fluorometric technique or errors in sampling.

The percentage recovery (PR) of dye cannot increase and normally decreases with distance downstream from an injection site. A decrease in measured dye mass is the result of the following factors: (1) Dye loss as a result of absorption on bottom and suspended sediments, adsorption on vegetation and debris, and photochemical decay; (2) dye lag due to a short sampling period during which the entire dye-concentration versus time curve is not obtained; and (3) a chemical reaction of the dye with a substance in the water (for example, chlorine).

Table 2.--*Data collected during traveltime measurements*

Site	Elevation (feet)	Distance downstream of injection (miles)	Stream discharge (cubic feet per second)	Cumulative traveltime of dye clouds: Leading edge (hours)	Cumulative traveltime of dye clouds: Peak (hours)	Mean velocity of dye cloud (miles per hour)	Time for dye cloud to pass site (hours)	Peak dye concentration (micrograms per liter)	Centroid of dye cloud (hours)	Area of dye curve (micrograms-hour per liter)	Percent recovery of dye	Variance of dye cloud (hours-squared)
			Slug injection of 1.40 liters of 20-percent dye solution at 0530 hours on May 12, 1981, at site 1									
1	7322	0.0	322	----	-----	----	----	-----	-----	----	--	-----
2	7193	2.6	322	0.98	1.22	2.02	1.04	23.2	1.28	8.15	80	0.026
3	6998	7.2	324	2.78	3.23	2.25	1.65	14.5	3.33	8.05	80	.065
7	6602	17.9	590	7.03	7.80	2.33	2.70	3.40	7.94	3.12	56	.173
8	6402	24.1	502	9.67	10.67	1.72	3.16	2.60	10.85	3.06	47	.262
			Slug injection of 1.30 liters of 20-percent dye solution at 0400 hours on May 12, 1981, at site 42									
42	7481	0.0	---	----	-----	----	----	-----	-----	----	--	-----
43	7129	3.4	281	1.65	2.00	1.66	1.25	20.8	2.07	8.12	75	0.030
44	6970	6.3	281	2.98	3.51	1.89	1.67	14.3	3.60	8.12	75	.064
7	6602	16.3	590	6.97	7.78	2.29	2.91	3.18	7.95	3.08	60	.183
8	6402	22.5	502	9.67	10.68	1.73	3.53	2.28	10.84	2.85	47	.312
			Slug injection of 2.10 liters of 20-percent dye solution at 0300 hours on May 14, 1981, at site 8									
8	6402	0.0	---	-----	-----	----	----	-----	-----	----	--	-----
9	6304	3.8	460	1.50	1.70	2.05	1.25	20.6	1.83	8.44	79	0.039
11	6217	6.8	464	2.67	3.17	2.03	2.30	12.5	3.35	8.25	78	.119
12	6118	11.8	470	4.97	5.78	1.87	3.14	7.65	6.00	7.53	72	.228
13	5917	22.6	502	10.17	11.50	1.84	5.66	4.40	11.88	6.89	70	.720
14	5717	33.6	455	15.33	17.33	1.87	8.00	2.75	17.75	5.64	52	1.459
15	5572	45.8	460	22.42	24.75	1.60	9.66	2.15	25.35	5.54	52	1.981
			Slug injection of 6.00 liters of 20-percent dye solution at 0500 hours on May 6, 1982, at site 14									
14	5717	0.0	----	-----	-----	----	----	-----	-----	----	--	-----
15	5572	12.2	1490	3.67	4.12	2.90	1.55	14.5	4.20	7.88	82	0.057
16	5518	17.4	1510	5.52	6.19	2.52	2.13	11.0	6.26	7.66	81	.095
17	5468	21.9	1520	6.83	7.56	3.17	2.40	10.1	7.68	7.66	81	.122
18	5394	30.3	1530	9.63	10.53	2.83	3.00	8.10	10.65	7.66	81	.221
19	5304	41.2	1570	13.57	14.77	2.57	3.87	5.40	14.84	6.72	74	.325
20	5263	45.8	1580	15.00	16.23	3.15	4.00	4.85	16.31	5.74	64	.340
			Slug injection of 4.00 liters of 20-percent dye solution at 0500 hours on May 5, 1982, at site 19									
19	5304	0.0	----	----	----	----	----	-----	----	----	--	-----
20	5263	4.6	1830	1.30	1.53	2.90	0.78	13.5	1.57	4.02	78	0.015
22	5209	11.8	1840	3.82	4.32	2.59	1.36	6.50	4.37	3.34	66	.045
23	5192	13.9	1840	4.53	5.03	3.04	1.45	6.30	5.06	3.34	66	.049
24	5177	15.6	1840	5.08	5.58	2.88	1.60	5.80	5.65	3.34	66	.060
25	5145	21.2	1840	7.02	7.69	2.62	2.08	4.65	7.79	3.01	59	.090

Table 2.--*Data collected during traveltime measurements*--Continued

Site	Elevation (feet)	Distance downstream of injection (miles)	Stream discharge (cubic feet per second)	Cumulative traveltime of dye clouds: Leading edge (hours)	Cumulative traveltime of dye clouds: Peak (hours)	Mean velocity of dye cloud (miles per hour)	Time for dye cloud to pass site (hours)	Peak dye concentration (micrograms per liter)	Centroid of dye cloud (hours)	Area of dye curve (micrograms-hour per liter)	Percent recovery of dye	Variance of dye cloud (hours-squared)
			Slug injection of 5.00 liters of 20-percent dye solution at 0511 hours on May 4, 1982, at site 24									
24	5177	0.0	----	----	----	----	----	-----	-----	----	--	-----
25	5145	5.6	1400	1.93	2.23	2.47	1.00	14.8	2.27	5.18	62	0.023
26	5110	11.6	1410	4.12	4.65	2.45	1.66	9.80	4.71	5.09	62	.057
27	5073	17.0	1420	6.48	7.15	2.16	2.09	7.10	7.23	5.09	62	.091
30	5035	24.1	1440	9.10	9.90	2.45	2.80	5.30	10.11	4.81	59	.175
			Slug injection of 2.50 liters of 20-percent dye solution at 0500 hours on April 29, 1982, at site 27									
27	5073	0.0	---	----	----	----	----	----	----	----	--	-----
30	5035	7.0	827	2.95	3.42	2.01	1.73	6.40	3.49	3.26	46	0.065
31	4972	13.3	825	6.07	6.87	1.76	3.00	3.20	7.05	2.94	42	.204
32	4946	16.2	822	7.40	8.21	2.09	3.90	3.00	8.44	2.94	42	.326
33	4928	18.4	820	8.57	9.50	1.57	4.53	2.80	9.84	2.94	41	.464
			Slug injection of 4.50 liters of 20-percent dye solution at 0500 hours on April 28, 1982, at site 32									
32	4946	0.0	---	-----	-----	----	----	-----	-----	-----	--	-----
33	4928	2.1	875	1.05	1.25	1.63	0.93	37.0	1.31	11.00	92	0.019
34	4902	8.2	878	3.68	4.21	2.02	1.94	18.8	4.29	10.63	89	.078
35	4854	14.2	875	6.42	7.17	1.99	2.66	12.5	7.32	10.28	86	.168
36	4826	19.3	873	8.72	9.53	2.13	2.88	9.70	9.71	9.39	78	.194
37	4751	27.5	869	12.40	13.57	2.02	5.20	5.40	13.77	7.56	62	.600
38	4703	36.9	864	16.60	17.93	2.12	5.80	4.20	18.20	6.38	52	.740
39	4680	45.4	860	21.20	22.88	1.62	7.40	2.80	23.46	5.38	44	1.536
			Slug injection of 3.00 liters of 20-percent dye solution at 0300 hours on April 27, 1982, at site 38									
38	4703	0.0	---	-----	-----	----	----	-----	-----	----	--	-----
39	4680	8.5	720	4.53	5.00	1.65	1.87	10.5	5.14	6.45	66	0.081
40	4660	15.4	722	8.50	9.26	1.53	5.30	6.10	9.68	6.34	65	.732
41	4648	20.5	750	10.90	11.66	1.99	5.80	4.40	12.24	5.62	60	.847
			Slug injection of 1.00 liters of 20-percent dye solution at 1605 hours on August 19, 1982, at site 7									
7	6602	0.0	---	----	----	----	----	----	----	----	--	-----
8	6402	6.2	380	2.48	2.88	2.06	2.05	5.10	3.02	3.09	50	0.090
9	6304	10.0	480	3.43	4.27	2.59	3.00	3.00	4.47	2.66	55	.206
			Slug injection of 3.60 liters of 20-percent dye solution at 1605 hours on August 18, 1982, at site 18									
18	5394	0.0	---	----	----	----	----	-----	----	----	--	-----
19	5304	11.0	500	4.92	5.83	1.88	3.17	10.1	6.03	9.89	59	0.210
20	5263	15.5	500	7.10	8.32	2.09	3.30	8.70	8.38	8.90	53	.224

Table 2.--*Data collected during traveltime measurements*--Continued

Site	Elevation (feet)	Distance downstream of injection (miles)	Stream discharge (cubic feet per second)	Cumulative traveltime of dye clouds: Leading edge (hours)	Cumulative traveltime of dye clouds: Peak (hours)	Mean velocity of dye cloud (miles per hour)	Time for dye cloud to pass site (hours)	Peak dye concentration (micrograms per liter)	Centroid of dye cloud (hours)	Area of dye curve (micrograms-hour per liter)	Percent recovery of dye	Variance of dye cloud (hours-squared)
Slug injection of 2.00 liters of 20-percent dye solution at 0721 hours on July 27, 1983, at site 1												
1	7322	0.0	577	----	----	----	----	-----	----	----	--	-----
2	7193	2.6	577	0.62	0.93	2.66	0.91	24.5	0.97	6.68	82	0.015
3	6998	7.2	577	2.15	2.57	2.83	1.22	14.5	2.60	6.25	77	.035
7	6602	17.9	982	5.80	6.30	2.82	1.88	4.85	6.40	3.28	69	.087
8	6402	24.1	1080	7.87	8.57	2.08	3.13	3.10	8.80	3.20	74	.246
Slug injection of 4.00 liters of 20-percent solution at 0450 hours on July 26, 1983, at site 8												
8	6402	0.0	984	-----	-----	----	-----	-----	-----	----	--	-----
9	6304	3.8	1090	1.00	1.33	2.59	1.30	16.9	1.45	6.07	77	0.036
11	6217	6.8	1240	1.83	2.42	2.85	1.92	11.3	2.53	5.91	78	.076
12	6118	11.8	1310	3.58	4.25	2.65	2.47	7.70	4.40	5.59	79	.133
13	5917	22.6	1320	7.20	8.33	2.54	4.78	4.30	8.65	5.19	73	.498
14	5717	33.6	1320	10.67	12.17	2.47	7.00	2.50	12.84	4.18	59	1.385
15	5572	45.8	1580	14.50	17.25	2.35	8.67	1.55	18.07	4.17	71	2.121
Slug injection of 4.00 liters of 20-percent dye solution at 0200 hours on September 9, 1983, at site 14												
14	5717	0.0	513	-----	-----	----	----	-----	-----	-----	--	-----
15	5572	12.2	513	5.70	6.75	1.77	3.13	14.7	6.90	16.74	92	0.228
16	5518	17.4	513	8.97	10.17	1.49	3.73	11.5	10.38	15.00	82	.333
17	5468	21.9	517	11.00	12.75	1.79	4.72	9.10	12.89	14.81	82	.457
18	5394	30.3	575	15.50	17.37	1.75	5.62	8.10	17.70	14.42	89	.640
19	5304	41.2	575	22.00	24.20	1.60	7.38	6.40	24.53	14.16	87	1.151
Slug injection of 2.00 liters of 20-percent dye solution at 0500 hours on September 28, 1983, at site 20												
20	5263	0.0	539	-----	-----	----	----	----	-----	----	--	-----
22	5209	7.2	539	4.52	5.33	1.31	2.58	9.30	5.49	8.19	94	0.154
23	5192	9.4	539	5.83	6.83	1.50	2.94	8.30	6.94	8.59	99	.201
24	5177	11.0	539	6.82	7.83	1.55	3.15	7.60	7.99	8.44	97	.232
25	5145	16.6	539	10.10	11.58	1.54	3.98	6.25	11.62	8.42	97	.345
Slug injection of 2.50 liters of 20-percent dye solution at 0501 hours on September 27, 1983, at site 24												
24	5177	0.0	580	-----	-----	----	----	-----	-----	-----	--	-----
25	5145	5.6	580	2.85	3.48	1.60	1.77	13.8	3.52	8.95	89	0.073
26	5110	11.6	588	6.70	7.65	1.41	2.93	8.80	7.77	8.76	88	.196
27	5073	17.1	566	10.00	11.65	1.36	4.80	6.30	11.80	10.08	98	.486
30	5035	24.1	566	14.62	16.95	1.26	8.38	3.80	17.34	8.05	78	1.458

Graphical Analysis of Traveltime Data

Dye-cloud centroid traveltimes were plotted against discharge at index stations and are shown in figures 4, 5, and 6. This method can only be used for reaches that have two or more measurements at different flow rates. Therefore, only the reaches in Colorado, sites 1 to 30, are shown. The reaches in Colorado were divided into three groups. The groups of reaches were determined by relating their characteristics with those of the corresponding index-discharge station. Traveltimes from sites 1 to 12 use station 09304500 White River near Meeker, Colo., as an index station; sites 12 to 20 use station 09304800 White River below Meeker, Colo., as an index station; and sites 20 to 30 use station 09306395 White River near Colorado-Utah State line, Utah as an index station. This type of analysis is based on the assumption that the traveltime versus index-discharge relationship is usually linear on log-log paper (Hubbard and others, 1982). There is also an assumption that there is a relationship between the index discharge of a gaging station and the discharge in a given stream reach. Diverting water for irrigation, which usually occurs during the summer months, can significantly affect this relationship if a large percentage of the flow is diverted under medium- and low-flow conditions. The lines on the graphs were extended from 100 to 3,000 cubic feet per second, since the discharge will seldom go below 100 cubic feet per second, and the river is at bankfull at about 3,000 cubic feet per second. The relationships are probably not valid when the river is higher than bankfull.

To determine the traveltime between two sites, the discharges at the corresponding index-discharge stations must first be known. The current index discharges can be obtained by contacting personnel in the U.S. Geological Survey's offices in Meeker, Colo., for stations 09304500 and 09304800, and in Vernal, Utah, for station 09306395.

Traveltime Simulations Using Linear-Regression Relationships

Leading-edge and peak-concentration traveltimes of dye clouds were simulated for flows other than measured flows using linear-regression equations and the data described previously. The traveltimes are linearly related on a logarithmic scale to the mean discharge of the stream reach and the distance from the injection site. The linear-regression equations have the following forms:

$$T_{le}=aQ^{b}L^{c} \qquad (1)$$

and

$$T_{p}=dQ^{e}L^{f}, \qquad (2)$$

where T_{le}=leading-edge traveltime of dye cloud, in hours;

T_{p}=peak-concentration traveltime of dye cloud, in hours;

Q=mean discharge, in cubic feet per second;

L=distance from injection site, in miles; and

a,b,c,d,e,f=linear-regression coefficients.

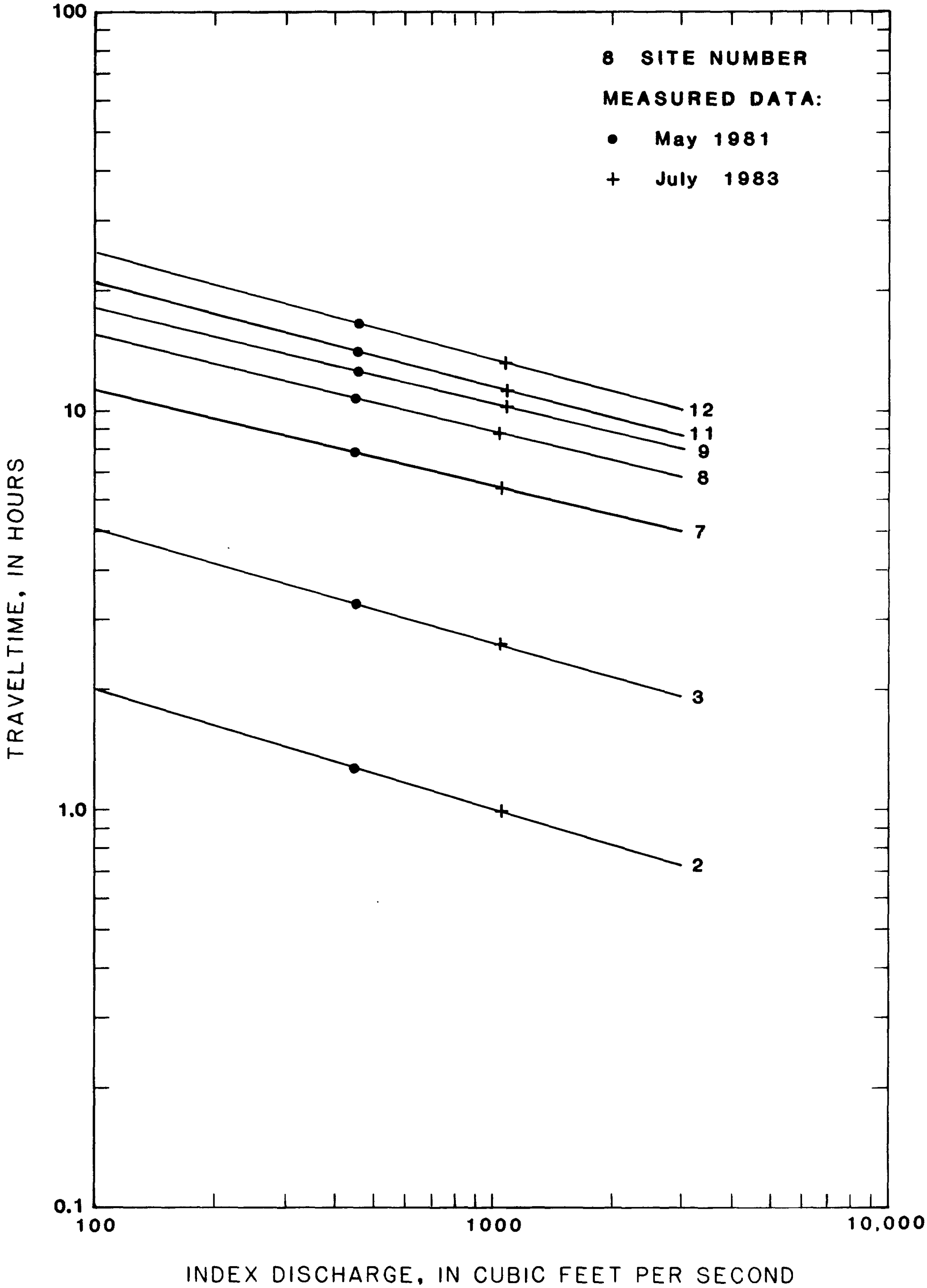

Figure 4.--Cumulative-traveltime curves based on graphical relationships, using index station 09304500 White River near Meeker, Colorado.

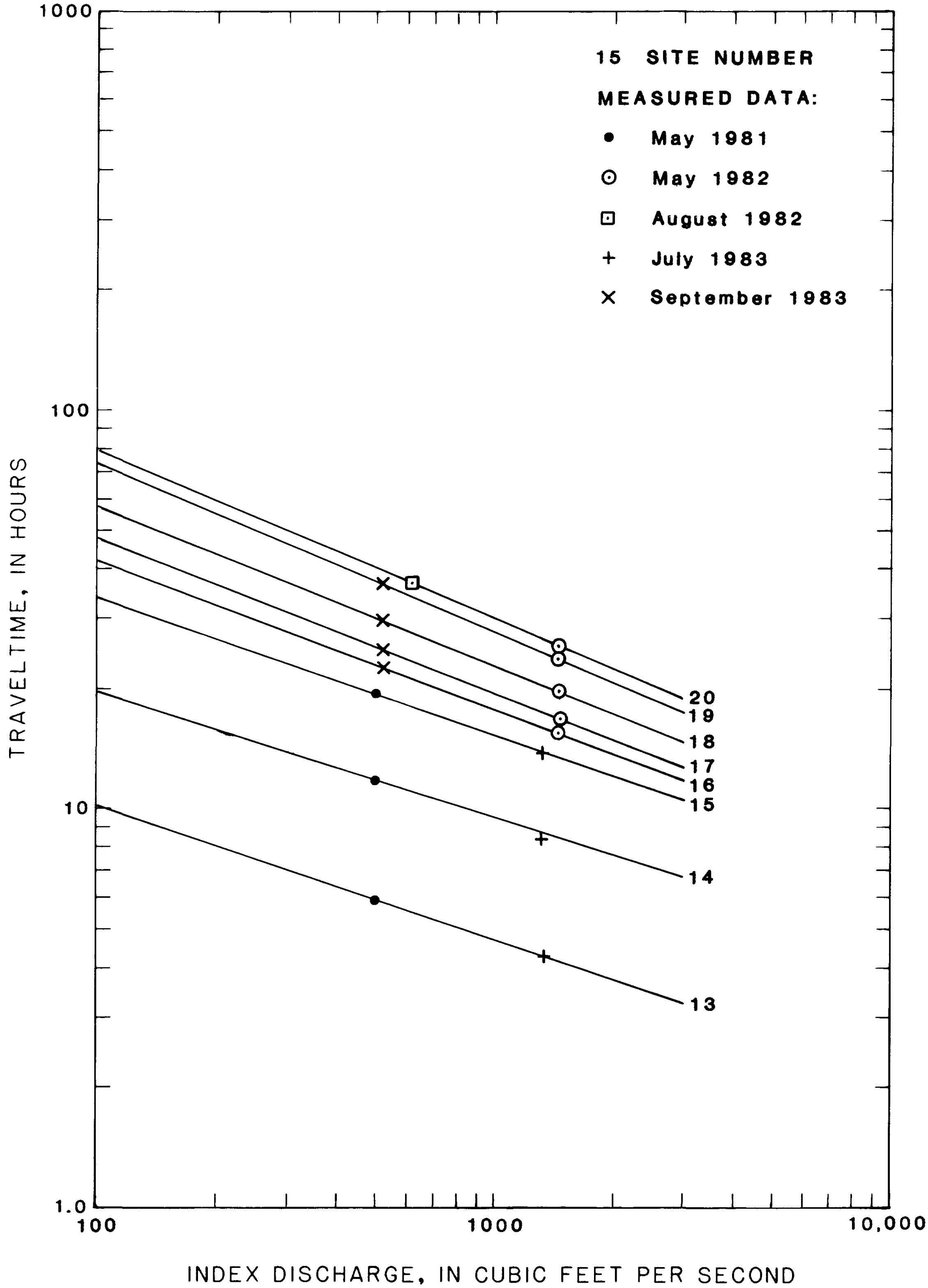

Figure 5.--Cumulative-traveltime curves based on graphical relationships, using index station 09304800 White River below Meeker, Colorado.

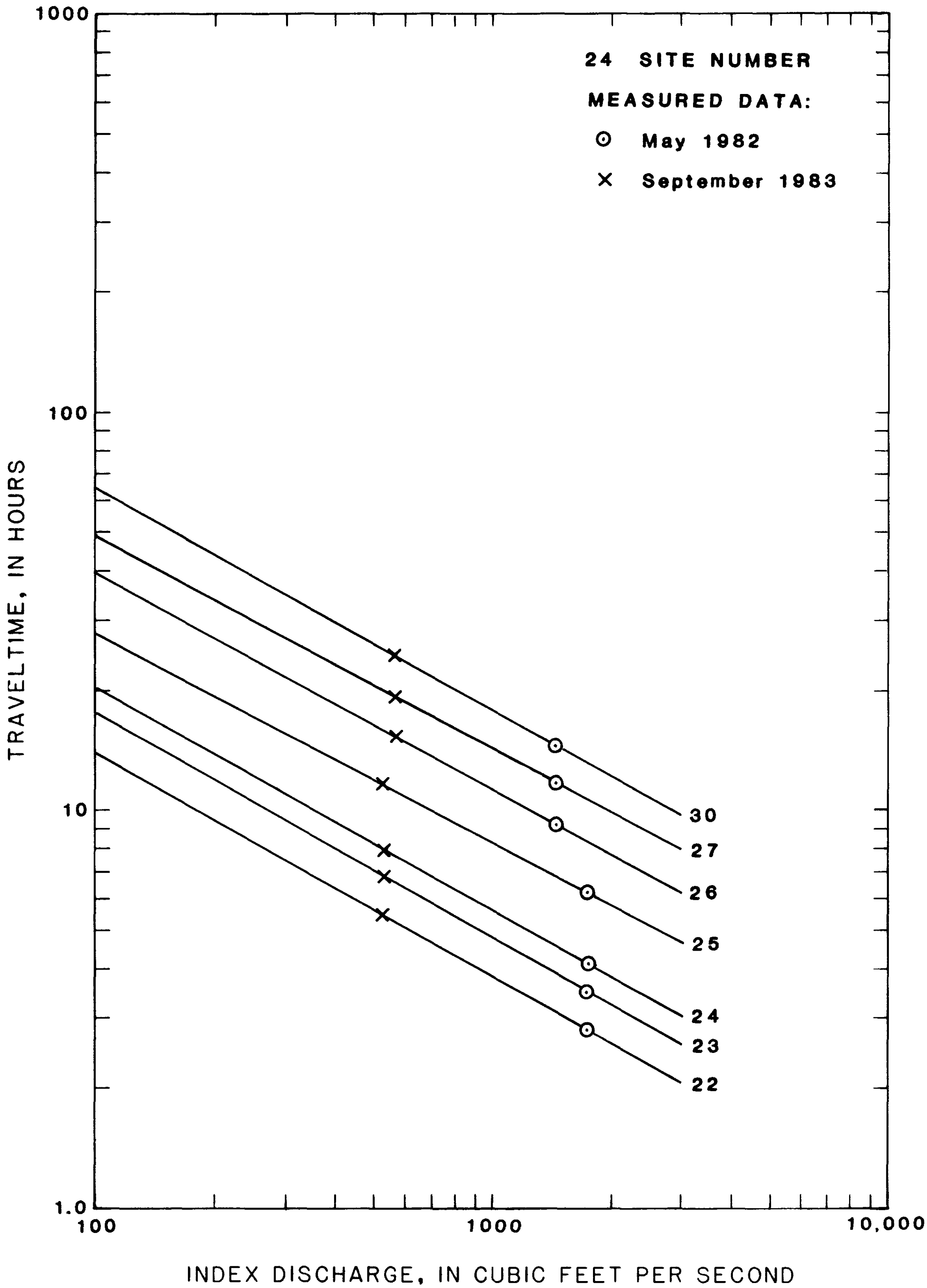

Figure 6.--Cumulative-traveltime curves based on graphical relationships, using index station 09306395 White River near Colorado-Utah State line, Utah.

Linear-regression relationships were developed for each reach in Colorado separately (sites 1-8, 8-15, 14-20, 19-25, and 24-30), for all the reaches in Utah together (sites 27-41), and for all the reaches on the White River together (sites 1-41). The linear-regression coefficients for each relationship are listed in table 3 along with the corresponding correlation coefficient (r). The correlation coefficient is a measure of the degree of closeness of the linear relationship between two variables. Below is an example computation of traveltime from Meeker, Colo., to Rangely, Colo., using the linear-regression coefficients for all the reaches on the White River (sites 1-41). The equations for leading-edge and peak-concentration traveltimes are:

$$T_{le}=2.986(Q)^{-0.330}(L)^{1.080}$$

and

$$T_p=4.016(Q)^{-0.335}(L)^{1.032}.$$

Assume the mean discharge is 500 cubic feet per second. The distance from Meeker (site 11) to Rangely (site 23) is 81.90 miles (see table 1, p. 5). Therefore,

$$T_{le}=2.986(500)^{-0.330}(81.90)^{1.080}=44.7 \text{ hours}$$

and

$$T_p=4.016(500)^{-0.335}(81.90)^{1.032}=47.2 \text{ hours.}$$

Table 3.--*Linear-regression coefficients*

Coefficient	Value determined by regression						
	Reach as defined by site numbers						
	1-8	8-15	14-20	19-25	24-30	27-41	1-41
a	2.690	3.031	10.71	16.86	10.21	210.9	2.986
b	-.394	-.363	-.499	-.552	-.494	-.905	-.330
c	1.191	1.105	1.026	1.073	1.097	.992	1.080
$r(T_{le})$	.9959	.9993	.9919	.9983	.9992	.9979	.9729
d	2.621	2.656	15.66	25.28	18.32	94.24	4.016
e	-.321	-.301	-.523	-.576	-.546	-.756	-.335
f	1.070	1.063	.994	1.026	1.059	.956	1.032
r(Tp)	.9977	.9997	.9939	.9984	.9996	.9982	.9746

When using equations 1 and 2 to simulate traveltimes, reaches having large variations in discharge must be divided into subreaches that have nearly constant discharges. The results of the peak-concentration traveltime simulations made with this method are shown in figures 7, 8, 9, and 10. Figure 7 is based on injections at site 1; figure 8 is based on injections at site 12; figure 9 is based on injections at site 20; and figure 10 is based on injections at site 27.

Longitudinal-Dispersion Coefficients

Longitudinal-dispersion coefficients were computed for all stream reaches where traveltime measurements were made. The coefficients were therefore computed for medium- and high-flow conditions. Longitudinal-dispersion coefficients (K_x) were calculated using a procedure described by Nordin and Sabol (1974). The equation is as follows:

$$K_x=(\bar{U}^2/2)d(\sigma_t{}^2)/dt, \qquad (3)$$

where K_x=longitudinal-dispersion coefficient, in square feet per second;

$\bar{U}$=mean velocity, in feet per second;

$\sigma_t{}^2$=variance of concentration with respect to time, in seconds^2; and

dt=change in time, in seconds.

Equation 3 is a close approximation of the longitudinal-dispersion coefficient (Fischer, 1973) if:

$$t > 1.8U_*L^2/r, \qquad (4)$$

where t=mixing time, in hours;

U_*=shear velocity, in feet per second;

L=distance from the point of maximum surface velocity to the farthest bank, about one-half the stream width, in feet; and

r=hydraulic radius, in feet.

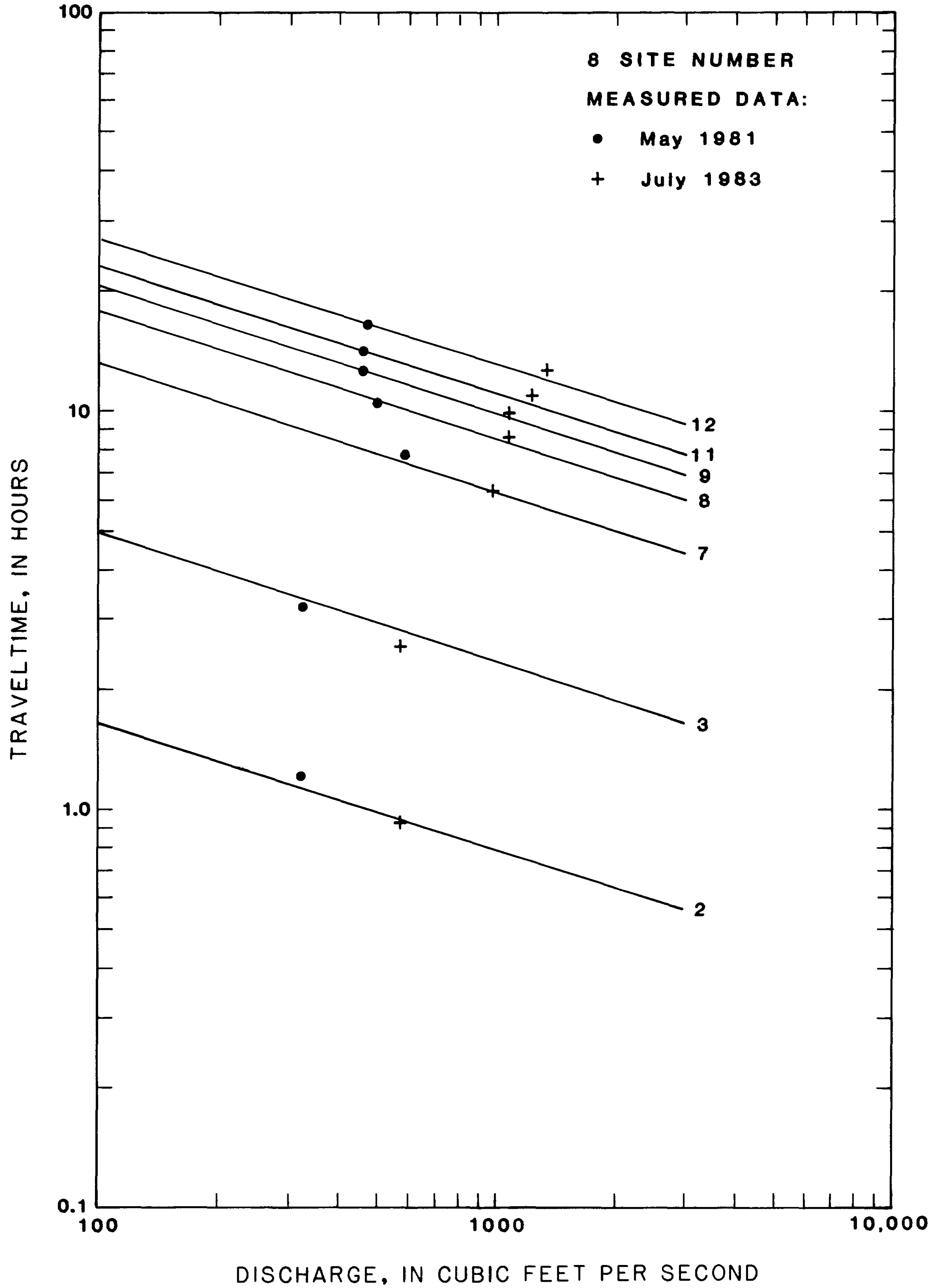

Figure 7.--Simulated cumulative-traveltime curves based on linear-regression relationships, for sites 2 to 12 based on injections from site 1.

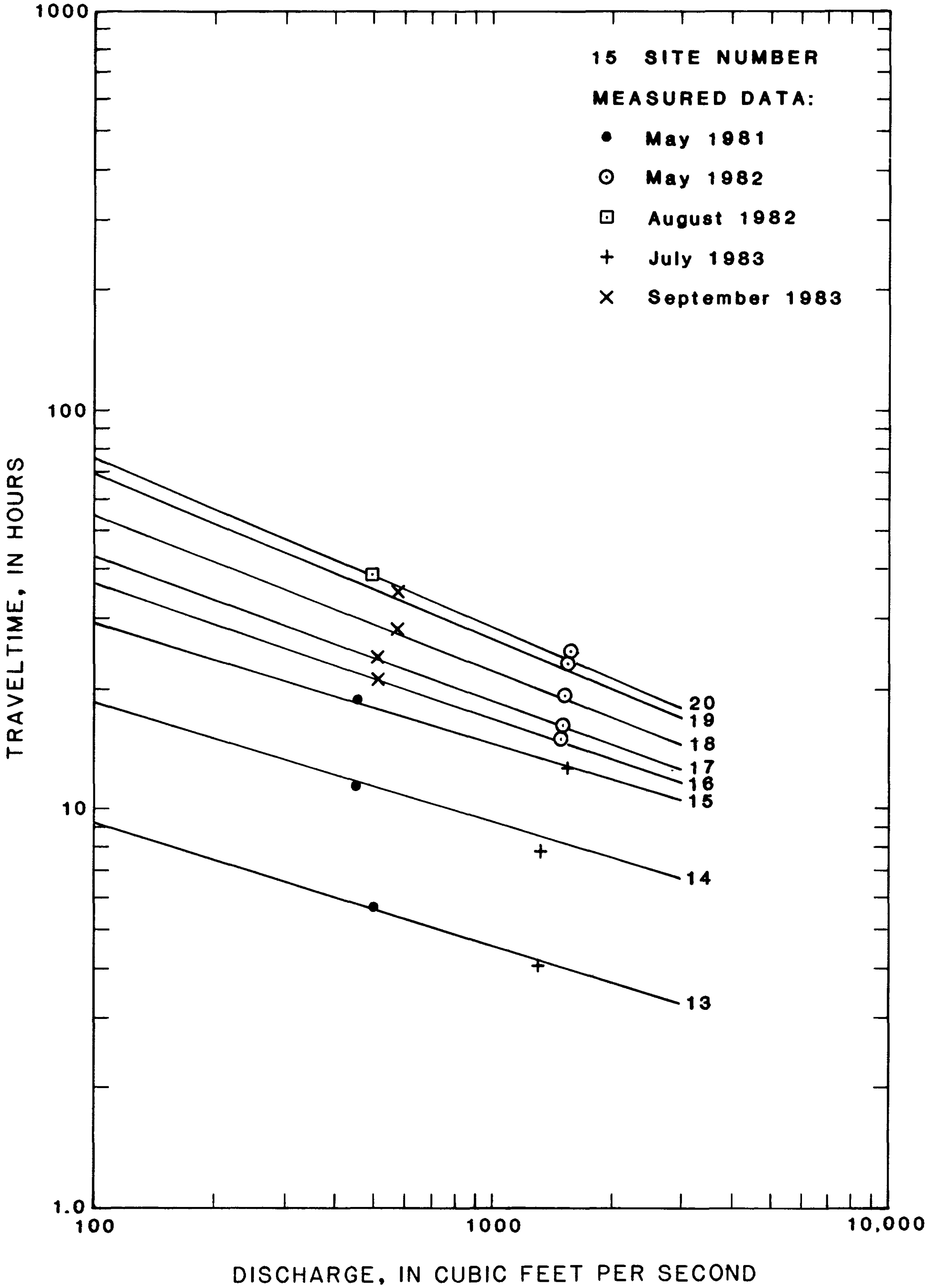

Figure 8.--Simulated cumulative-traveltime curves based on linear-regression relationships, for sites 13 to 20 based on injections from site 12.

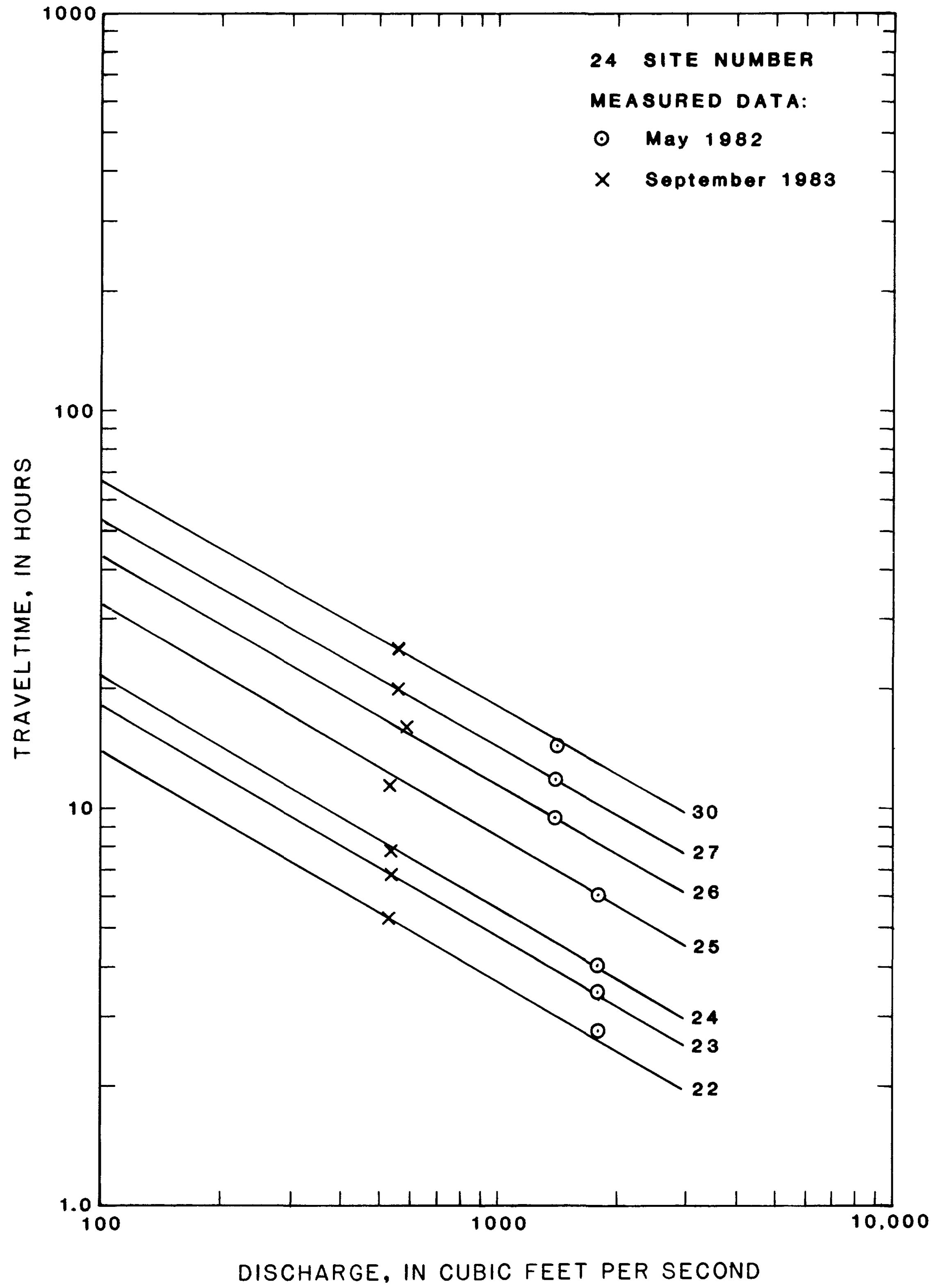

Figure 9.--Simulated cumulative-traveltime curves based on linear-regression relationships, for sites 22 to 30 based on injections from site 20.

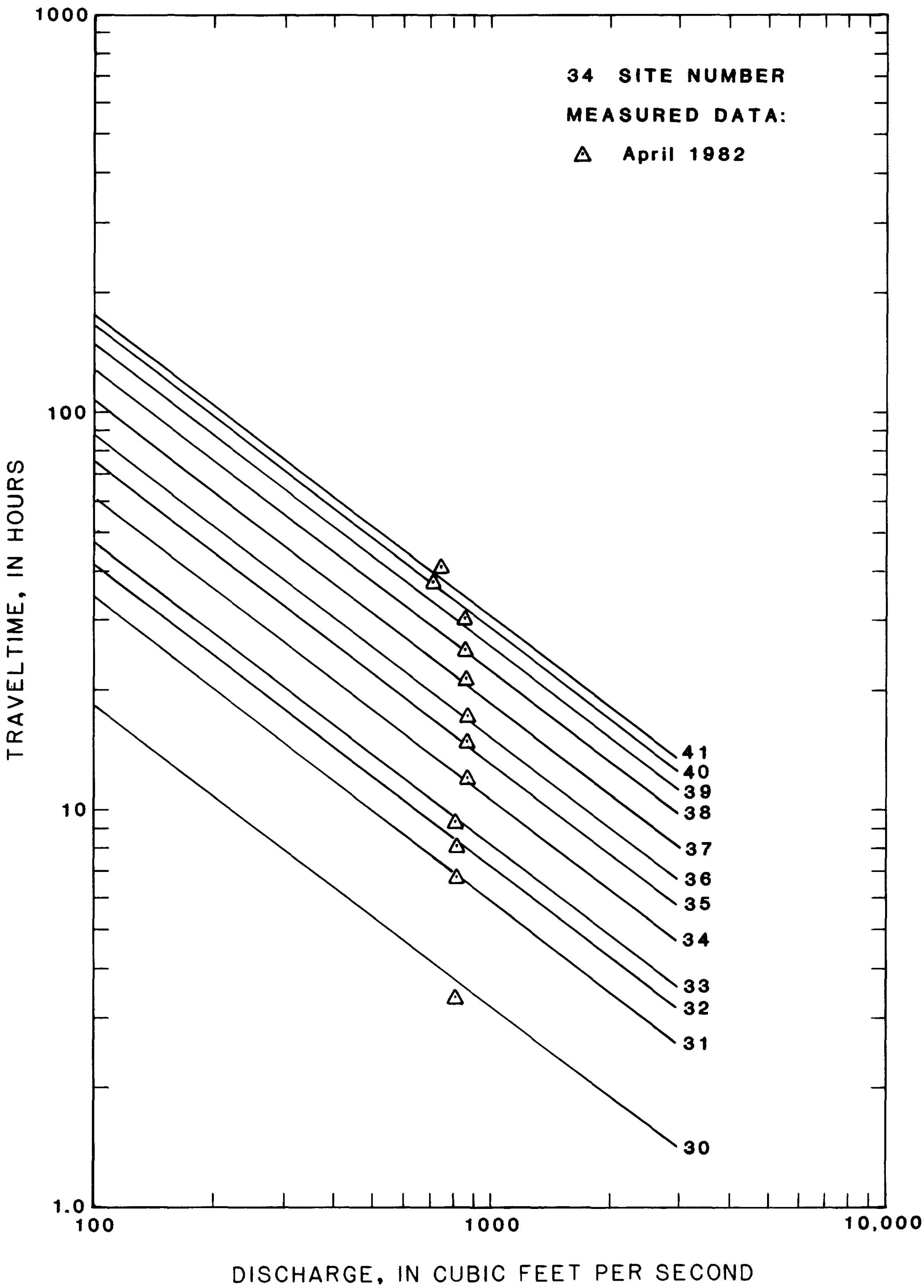

Figure 10.--Simulated cumulative-traveltime curves based on linear-regression relationships, for sites 30 to 41 based on injections from site 27.

An example computation of a longitudinal-dispersion coefficient is given in figure 11. The data in the example are from the April 1982 traveltime measurement from sites 30 to 33 during medium flow. The required mixing time from equation 6 is 2.2 hours. The slope is approximated using the upper part of the curve and has a value of 328 seconds. The slope is used to estimate $d(\sigma_t^2)/dt$ for the reach. K_x was then computed to be 1,130 square feet per second, using equation 3 with a mean velocity of 2.63 feet per second and $d(\sigma_t^2)/dt$. The calculated K_x coefficients along with the discharge and mean velocity for each stream reach are listed in table 4. In this study, longitudinal dispersion increased with an increase in discharge for reaches 2 to 8, 9 to 15, 15 to 20, and 20 to 25, but for reach 25 to 30, the longitudinal-dispersion coefficient decreased (table 4). Equation 3 shows that longitudinal dispersion is a function of the mean velocity and the variance of the dye cloud as it moves downstream. Many factors affect the variance such as the shape and length of the tail of the time-concentration dye curve, the extent or existence of dead-water zones along the river banks, and the percent of the reach length that has pools or riffles. Depending upon the hydraulic characteristics and the analysis of the tail of the time-concentration dye curve of the reach, the longitudinal-dispersion coefficient as calculated by equation 3 may increase or decrease with changing discharge.

Table 4.--*Longitudinal-dispersion coefficients for selected subreaches and varying streamflow conditions*

Subreach as defined by site numbers	Rivermile		Discharge at end of subreach (cubic feet per second)	Mean velocity (feet per second)	Longitudinal dispersion (square feet per second)
	Start	End			
2 - 8	202.93	181.37	502	3.30	512
2 - 8	202.93	181.37	1080	4.03	1000
9 - 15	177.61	135.59	460	2.62	1580
9 - 15	177.61	135.59	1580	3.66	3560
15 - 19	135.59	106.55	575	2.41	531
15 - 20	135.59	102.00	1580	4.07	828
22 - 25	94.80	85.38	539	2.25	284
20 - 25	102.00	85.38	1840	3.93	378
25 - 30	85.38	66.90	566	1.96	647
25 - 30	85.38	66.90	1440	3.46	401
30 - 33	66.90	55.54	820	2.63	1130
33 - 39	55.54	12.30	860	2.87	1220
39 - 41	12.30	0.28	750	2.49	1310

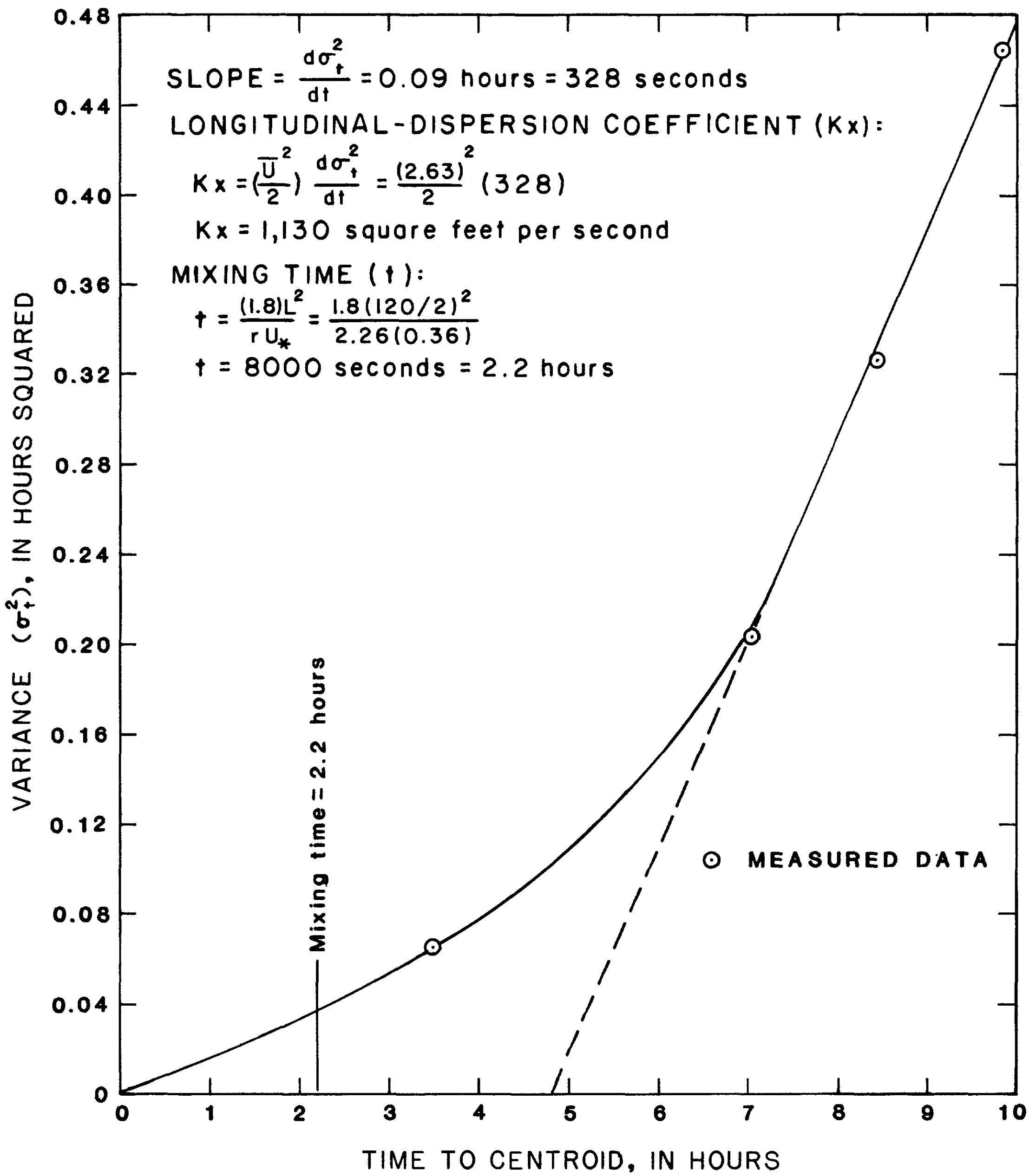

Figure 11.--Sample computation of the longitudinal-dispersion coefficient for the White River, sites 30 to 33.

DETERMINATION OF REAERATION COEFFICIENTS USING A MODIFIED-TRACER TECHNIQUE

Reaeration was measured for four reaches on the White River (fig. 1), using a modified-tracer technique developed by Rathbun and others (1975), which is based on the original radioactive-gas technique developed by Tsivoglou (1967). Ethylene and propane were used as the tracer gases and rhodamine-WT dye was used as the dispersion and dilution tracer. Only a brief description of the modified-tracer technique is included in this report. A complete description is given in Rathbun and others (1975) and in Rathbun and Grant (1978).

The experimental procedure consists of injecting known quantities of the tracer gas and dye into the stream and measuring the gas and dye concentrations at various points downstream. A desorption coefficient for the gas is then determined from the gas concentrations. Using a constant determined in the laboratory, the desorption coefficients for the tracer gases are then converted to reaeration coefficients for oxygen. Two tracer gases can be used simultaneously, permitting two measurements of the reaeration coefficient for oxygen in a single experiment. Dye samples were analyzed using a fluorometer and standard techniques described by Hubbard and others (1982).

The three assumptions inherent in the modified-tracer technique are as follows: (1) The ratio of the desorption coefficient for the tracer gas to the reaeration coefficient is independent of mixing conditions, temperature, and the presence of pollutants in the range of ambient conditions in streams; (2) the dispersion and dilution tracer is conservative; and (3) the tracer gas has the same dispersion and dilution as the conservative tracer and is lost from the stream only by desorption through the water surface to the atmosphere.

Peak concentrations of the tracer gases and the conservative tracer are usually used to compute reaeration coefficients, although the areas under the gas-tracer concentration versus time curves can be used if sufficient samples are obtained to define the complete curves. In this study, only the peak-concentration method was used because the complete gas-tracer concentration versus time curves were not obtained.

Peak Method

The basic equation for the tracer-gas desorption coefficient (K_G) using the peak method is as follows:

$$K_G=1/(t_d-t_u)\ln[(C_{GU}/C_{DU})/(C_{GD}/C_{DD}J_n)], \qquad (5)$$

where K_G=tracer-gas desorption coefficient, per hour;
C_{GU},C_{GD}=peak concentration of the tracer gas at the upstream and downstream ends of the reach, in micrograms per liter;
C_{DU},C_{DD}=peak concentration of the dye at the upstream and downstream ends of the reach, in micrograms per liter;
t_d,t_u=traveltime of the peak concentration of the dye at the downstream and upstream ends of the reach, in hours;
ln=natural logarithm, base e; and
J_n=dye-loss correction factor.

Since assumption (2) is not entirely correct, that is rhodamine-WT dye is not completely conservative, the time-concentration curves must be corrected before the reaeration coefficients are computed. The conservation of mass shows that:

$$Q_1A_1=Q_2A_2=Q_3A_3=\ldots Q_nA_n, \tag{6}$$

where Q=discharge at each cross section where samples are collected; and
A=corresponding area under the dye-concentration versus time curves for each sample cross section where samples are collected.

If there is dye loss, then Q_2A_2 will be less than Q_1A_1, and Q_nA_n will be less than $Q_{n-1}A_{n-1}$. The correction procedure is to multiply each point on the dye-concentration versus time curve by a correction factor (J). Therefore, equation 8 becomes:

$$Q_1A_1=Q_2A_2J_2=\ldots Q_nA_nJ_n, \tag{7}$$

where $J_2=Q_1A_1/Q_2A_2$; and
$J_n=Q_1A_1/Q_nA_n$.

Calculation of Reaeration Coefficients

The tracer-gas desorption coefficient (K_G) is converted to a reaeration coefficient (K_2 -base e logarithmic units) as follows:

$$K_2=RK_G, \tag{8}$$

where R=the ratio of the absorption coefficient for oxygen to the desorption coefficient for the tracer gas (determined in the laboratory).

From laboratory studies by Rathbun and others (1978), the value of R for ethylene is 1.15 and the value of R for propane is 1.39.

Reaeration coefficients are usually reported at a common temperature of 20°Celsius. Measured reaeration coefficients are adjusted to 20°Celsius by the following equation (Elmore and West, 1961):

$$K_{2(20)}=K_{2(t)}(1.0241)^{20-t}, \tag{9}$$

where $K_{2(20)}$=reaeration coefficient at 20°Celsius, in units per time;
$K_{2(t)}$=measured reaeration coefficient, in units per time; and
t=mean reach water temperature, in degrees Celsius.

Experimental Procedure

The experimental procedure consists of three steps: (1) Injecting the gas tracers and dye tracer into the stream; (2) sampling the tracers at points downstream from the injection; and (3) analyzing the samples for concentrations of the tracers. Each step is briefly described in the following sections, but a complete description is given in Rathbun and others (1975) and Rathbun and Grant (1978).

Injection of the Tracers

Ethylene and propane were injected into the stream by bubbling these gases through porous diffuser plates. The diffusers were placed on the stream bottom, generally at the center of flow for the stream cross section. The ethylene and propane were released from high-pressure cylinders through two-stage regulators, then through rotameters for monitoring the gas flows, and then through the diffusers into the stream.

The conservative tracer (rhodamine-WT dye) was injected into the stream at the same point and time as the gas tracers. The dye was continuously injected using a direct-displacement pump. Gas and dye concentrations and rates for injection appropriate for the stream discharges were estimated using equations presented by Rathbun (1979).

Sampling the Tracers

Dye samples were collected in 1.1-fluid ounce bottles with polyseal caps as a function of time at approximately the center of flow. Two samples were collected at the same time, one for analysis in the field and one for analysis in the laboratory.

Water samples were also collected for the determination of tracer-gas concentrations. Samples were collected from the center of flow in 40-milliliter septum-cap vials. The vial was placed in a sampler designed to collect water samples for dissolved gas. The tracer-gas sample was collected from the surface to about mid-depth until the bottle was overfilled. To preserve the sample for later laboratory analysis, 1 milliliter of 37-percent formalin stock solution was added to each sample.

Sample Analysis

Ethylene and propane concentrations in the water samples were determined using a stripping and trapping technique in the laboratory. The procedure consists of: stripping the ethylene and propane from the water sample with helium gas, trapping the tracer gases in a cold trap, and warming the trap to flush the tracer gases from the cold trap into a gas chromatograph equipped with a flame-ionization detector for analysis. A detailed description of the procedure and methods for storing and preserving a sample are in Shultz and others (1976).

Computation of Reaeration Coefficients

Reaeration coefficients were determined for four reaches of the White River during a medium-flow period in August 1982. The four reaches are shown in figure 1 (p. 3) and the injection and sampling sites are listed in table 1 (p. 5). Basic time-concentration curve characteristics resulting from the continuous injections for the reaeration measurements are listed in table 5. Additional characteristics of the dye curves and data from the ethylene and propane concentration versus time curves are listed in table 6.

Table 5.--*Time-concentration curve characteristics for reaeration measurements*

Site	Elevation (feet)	Distance downstream of injection (miles)	Stream discharge (cubic feet per second)	Cumulative traveltime of dye clouds		Mean velocity of dye cloud (miles per hour)	Time for dye cloud to pass site (hours)	Peak dye concentration (micrograms per liter)
				Leading edge (hours)	Peak (hours)			
		Continuous injection of 3.56 liters of 12.0-percent dye solution for 90 minutes beginning at 0930 hours, August 20, 1982, at site 4						
4	6782	0.0	---	----	----	----	----	----
6	6680	2.6	500	0.93	2.08	1.32	2.35	5.90
7	6602	5.1	501	2.12	3.52	1.85	2.83	5.40
8	6402	11.3	421	4.75	6.42	1.61	5.03	4.80
		Continuous injection of 3.50 liters of 12.0-percent dye solution for 90 minutes beginning at 1100 hours, August 19, 1982, at site 9						
9	6304	0.0	---	----	----	----	----	----
10	6264	1.4	482	0.57	1.67	1.51	2.33	5.60
11	6217	3.1	495	1.32	2.33	2.28	2.45	4.80
12	6122	8.1	504	3.53	5.00	4.87	3.49	4.40
		Continuous injection of 2.84 liters of 12.0-percent dye solution for 71 minutes beginning at 0830 hours, August 18, 1982, at site 21						
21	5216	0.0	---	----	----	----	----	----
22	5209	.8	530	0.52	1.33	0.67	1.70	7.40
23	5192	3.0	572	1.67	2.67	1.72	2.18	5.00
24	5177	4.6	604	2.47	3.67	1.63	2.41	5.00
25	5145	10.3	563	5.75	7.08	1.55	3.87	4.10
		Continuous injection of 3.60 liters of 11.2-percent dye solution for 120 minutes beginning at 1005 hours, August 17, 1982, at site 28						
28	5051	0.0	---	----	----	----	----	----
29	5042	1.4	566	0.60	1.92	0.74	2.90	3.80
30	5035	2.6	566	.93	2.42	2.23	3.80	3.30

Table 6.--*Dye, ethylene, and propane concentration versus time-curve characteristics*

Site	Date of measurement (mo/day/yr)	Area of dye-time concentration curve (micrograms-hour per liter)	Traveltime of centroid (hours)	Peak concentration (micrograms per liter)			Traveltime of peak (hours)		
				ethylene	propane	dye	ethylene	propane	dye
6	8/20/82	8.68	1.94	13	4.5	5.90	1.92	1.87	2.08
7	8/20/82	7.93	3.31	3.9	1.4	5.40	3.15	3.00	3.52
8	8/20/82	7.81	6.46	----	---	4.80	----	----	6.42
10	8/19/82	8.41	1.51	14	6.5	5.60	1.47	1.43	1.67
11	8/19/82	7.37	2.28	7.9	1.9	4.80	2.28	2.07	2.33
12	8/19/82	6.84	4.87	1.9	.5	4.40	4.75	4.58	5.00
22	8/18/82	8.79	1.27	40	6.3	7.40	1.35	1.33	1.33
23	8/18/82	5.96	2.53	16	2.4	5.00	2.60	2.57	2.67
24	8/18/82	5.66	3.53	13	1.6	5.00	3.50	3.52	3.67
25	8/18/82	5.03	7.16	4.6	.9	4.10	7.07	7.17	7.08
29	8/17/82	7.79	1.90	19.	2.9	3.80	1.98	1.92	1.92
30	8/17/82	6.82	2.43	15.	1.8	3.30	2.37	2.65	2.42

Each group of sites in table 6 corresponds to the continuous injection data in table 5. Insufficient gas samples were collected during all the measurements to completely define the tracer gas versus time curves. Therefore, the areas and centroid traveltimes for the ethylene and propane curves are not shown in table 6.

Reaeration coefficients were calculated using the data in table 6, equations 5 and 8, and the procedure previously discussed. The resulting reaeration coefficients are listed in table 7 along with the reaeration coefficients adjusted to 20° Celsius, which were calculated using equation 9. A large discrepancy between the reaeration coefficients measured with the ethylene and the propane occurred in many cases. For example, the reaeration coefficient measured using the ethylene at sites 10 to 11 has a value of 23.5; whereas, the measured value was 63.9 using the propane. Unknown substances were found in the gas-tracer samples, making it difficult to determine the gas concentrations, especially the low propane values. Similar problems have occurred in other reaeration studies (Rathbun, R.E., U.S. Geological Survey, oral commun., 1984). The most plausible value, considering all the discrepancies, is the one measured using ethylene. Therefore, only the ethylene values were used in subsequent analyses.

Comparison of Measured Reaeration Coefficients and Values Predicted Using Semi-empirical and Empirical Equations

Measured reaeration coefficients were compared with reaeration coefficients predicted using semi-empirical and empirical equations. These comparisons give some measure of the degree of uncertainty inherent in the prediction equations for the river being studied. The basic components of these two types of equations are as follows: Semi-empirical equations are those based on the rate-of-energy dissipation, and in which the reaeration coefficient is correlated with the longitudinal-dispersion coefficient; and empirical equations are those based on velocity-depth relationships. The form of the empirical equations is as follows:

$$K_2=a\bar{U}^b/H^c, \tag{10}$$

where a,b,c=coefficients of a given equation;
$\bar{U}$=mean velocity of stream; and
H=mean depth of stream.

A complete description of the various semi-empirical and empirical equations is given by Rathbun (1977).

Hydraulic and energy-dissipation properties for the reaeration subreaches were calculated for use in the prediction equations to make the comparison and are listed in table 8. The information needed for these calculations was obtained from traveltime, discharge, and cross-section measurements and from 7.5-minute topographic maps. Following is a summary of the prediction equations used.

Table 7.--*Measured reaeration coefficients for selected subreaches of the White River*

Subreach as defined by site numbers	Date of measurement (mo/day/yr)	Mean discharge (cubic feet per second)	Water temperature (degrees Celsius)	Reaeration coefficient, based on measured water temperatures (day^{-1}) peak method		Reaeration coefficient, adjusted to 20° Celsius (day^{-1}) peak method	
				ethylene	propane	ethylene	propane
6-7	8/20/82	500	16.0	23.0	26.9	25.3	29.6
10-11	8/19/82	488	17.0	21.9	59.5	23.5	63.9
11-12	8/19/82	500	19.0	14.5	16.3	16.3	25.6
10-12	8/19/82	494	19.0	15.9	25.0	16.3	25.6
22-23	8/18/82	551	21.0	17.2	22.1	16.8	21.6
23-24	8/18/82	588	22.0	5.5	14.4	5.3	13.7
24-25	8/18/82	584	23.0	8.3	5.2	7.7	4.8
22-25	8/18/82	567	22.0	9.9	10.8	9.4	10.3
29-30	8/17/82	566	22.0	12.5	31.2	11.9	29.7

Table 8.--*Geometric, traveltime, and velocity data for selected subreachs of the White River*

	Geometric Data				Traveltime Data		Velocity Data			
Subreach as defined by site numbers	Decrease in elevation of water surface through subreach (feet)	Length of subreach (feet)	Slope of subreach (feet per feet)	Mean depth of water in sub-reach (feet)	Traveltime of peak concentration of dye through subreach (minutes)	Traveltime of centroid of dye cloud through subreach (minutes)	Mean velocity of peak concentration of dye (feet per second)	Mean velocity of centroid of dye cloud (feet per second)	Shear velocity (feet per second)	Mean velocity of peak times slope of subreach (feet per second)
6-7	78.1	19,540	0.00400	1.61	86	82	3.79	3.97	0.455	0.01516
7-8	198.9	26,720	.00744	1.42	174	189	2.56	2.36	.583	.01905
6-8	277.0	46,250	.00599	1.47	260	271	2.96	2.84	.532	.01773
10-11	46.9	8,920	.00526	1.54	40	46	3.72	3.23	.511	.01957
11-12	95.0	26,450	.00359	1.72	160	155	2.76	2.84	.446	.00991
10-12	141.9	35,380	.00401	1.70	200	201	2.95	2.93	.468	.01183
22-23	17.8	11,460	.00155	1.64	80	75	2.39	2.55	.286	.00370
23-24	14.9	8,610	.00173	1.58	60	60	2.39	2.39	.297	.00413
24-25	31.2	29,670	.00105	1.78	205	218	2.41	2.27	.245	.00253
22-25	63.9	49,740	.00128	1.71	345	353	2.40	2.35	.265	.00307
29-30	7.5	6,230	.00120	1.84	30	32	3.46	3.24	.267	.00415

Semi-empirical (Energy-Dissipation) Equations

Lau (1972):

$$K_2=0.0126(U_*/\bar{U})^3(\bar{U}/H), \tag{11}$$

where K_2=reaeration coefficient, base 10 units, 20°C, in seconds^{-1};

U_*=mean reach shear velocity, in feet per second;

$\bar{U}$=mean reach velocity, in feet per second; and

H=mean reach stream depth, in feet.

Krenkel and Orlob (1963):

$$K_2=1.141*10^{-4}(\bar{U}_{fm}Sg_{fm})^{0.408}/H^{0.66}, \tag{12}$$

where K_2=reaeration coefficient, base 10 units, 20°C, in minutes^{-1};

$\bar{U}_{fm}$=mean stream velocity, in feet per minute;

S=slope of energy gradient, in feet per foot; and

g_{fm}=acceleration of gravity, in feet per minute^2.

Parkhurst and Pomeroy (1972):

$$K_2=0.96(1+0.17F^2)T_{co}{}^2(\bar{U}_{ms}S/H_m)^{0.375}, \tag{13}$$

where K_2=reaeration coefficient, base e units, 20°C, in hours^{-1};

F=Froude number, defined as $F=\bar{U}_{ms}/(g_{ms}H_m)^{0.5}$;

T_{co}=water-temperature correction factor;

$\bar{U}_{ms}$=mean reach velocity, in meters per second;

H_m=mean reach stream depth, in meters; and

g_{ms}=acceleration of gravity, in meters per second^2.

Tsivoglou and Neal (1976):

$$K_{2(20)}=0.054H_{ch}/t_t, \tag{14}$$

where $K_{2(20)}$=reaeration coefficient, base e units, 20°C, in hours^{-1};

H_{ch}=reach elevation change, in feet; and

t_t=reach traveltime, in hours.

Cadwallader and McDonnell (1969):

$$k_2=25.7E^{0.5}/H, \tag{15}$$

where k_2=reaeration coefficient, base 10 units, 20°C, in days^{-1};

$E=\bar{U}g$, in feet^2 per second^3; and

g=acceleration of gravity, in feet per second^2.

Bennett and Rathbun (1972):

$$k_2=46.05\bar{U}^{0.413}S^{0.273}/H^{1.408}. \quad (16)$$

Thackston and Krenkel (1969):

$$k_2=10.8(1+F^{0.5})U_*/H. \quad (17)$$

Churchill, Elmore, and Buckingham (1962):

$$k_2=1.447\bar{U}^{1.049}H^{-2.262}f^{-0.823}, \quad (18)$$

where f=flow-resistance factor, defined as $f=8gHS/\bar{U}^2$.

Dobbins (1965):

$$k_2=\frac{0.12C_a(30.0S_1\bar{U})^{0.375}A\mathrm{Coth}(BE^{0.126}/C_4)}{C_4{}^{1.5}H}, \quad (19)$$

where $C_a=1.0+F^2$;

S_1=slope, in feet per 1,000 feet;

$A=9.68+0.054(t-20)$; where t=water temperature, in degrees Celsius;

Coth=hyperbolic cotangent angle, in radians;

$B=0.976+0.0137(30-t)^{1.5}$;

$E=30.0S_1\bar{U}$; and

$C_4=0.9+F$.

Empirical (Velocity-Depth) Equations

Churchill, Elmore, and Buckingham (1962):

$$k_2=5.026\bar{U}^{0.969}/H^{1.673}. \quad (20)$$

Langbein and Durum (1967):

$$k_2=3.3\bar{U}/H^{1.33}. \quad (21)$$

Owens, Edwards, and Gibbs (1964):

$$k_2=10.09\bar{U}^{0.73}/H^{1.75} \text{ (equation 1)}. \quad (22)$$

$$k_2=9.41\bar{U}^{0.67}/H^{1.85} \text{ (equation 2)}. \quad (23)$$

Isaacs and Gaudy (1968):

$$k_2=3.739\bar{U}/H^{1.5}. \quad (24)$$

Negulescu and Rojanski (1969):

$$k_2=4.74(\bar{U}/H)^{0.85}. \qquad (25)$$

Bennett and Rathbun (1972):

$$k_2=8.76\bar{U}^{0.607}/H^{1.689}. \qquad (26)$$

O'Connor and Dobbins (1958):

$$k_2=127.6(D_L\bar{U})^{0.5}/H^{1.5}, \qquad (27)$$

where D_L=molecular-diffusion coefficient of oxygen in water, in feet^2 per day.

Padden and Gloyna (1971):

$$k_2=2.98(\bar{U}/H^{1.5})^{0.703}. \qquad (28)$$

Bansal (1973):

$$k_{2(25)}=0.219\bar{U}^{0.6}/H^{1.4}, \qquad (29)$$

where $k_{2(25)}$=reaeration coefficient, base e units, 25°C, in hours^{-1}.

Results of comparison

Comparisons of the measured reaeration coefficients using the ethylene tracer gas and the reaeration coefficients predicted using semi-empirical and empirical equations for each reaeration subreach are presented in tables 9 and 10. The error of estimate (SE) for the various equations is listed in table 11 and is computed as follows:

$$SE=(\text{predicted value} - \text{measured value})/\text{measured value}. \qquad (30)$$

The absolute error of estimate was greatest for the subreach from sites 23 to 24 for 14 of the 19 prediction equations. Results of the error analysis show that the Bennett and Rathbun (1972) and Isaacs and Gaudy (1968) equations yielded the most accurate predictions when compared with measured reaeration coefficients using the ethylene tracer gas.

BASIN CHARACTERISTICS

Ten physical and climatic characteristics were measured using U.S. Geological Survey topographic maps to provide baseline data on the White River basin prior to energy-resource development. These characteristics will serve as valuable data for planners and managers within the basin. Maximum 24-hour precipitation at six recurrence intervals was measured using data from the National Weather Service. On September 11, 1981, aerial photographs were taken of the White River basin. Channel geometry and average stream temperatures were measured from the photographs. Information from these photographs could be used by, for example, fisheries researchers to study the spawning areas.

Table 9.--*Comparison of measured reaeration coefficients and coefficients determined using energy-dissipation equations, for selected subreaches of the White River*

Subreach as defined by site number	Reaeration coefficients (1/day), base e units									
	Determined using measured data	Determined using energy-dissipation equations								
		Lau (1972)	Krenkel and Orlob (1963)	Parkhurst and Pomeroy (1972)	Tsivoglou and Neal (1976)	Cadwallader and McDonnell (1969)	Bennett and Rathbun (1972)	Thackston and Krenkel (1969)	Churchill, Elmore, and Buckingham (1962)	Dobbins (1965)
6-7	25.3	10.2	31.0	6.5	62.8	25.7	20.8	12.1	27.2	1.2
10-11	23.5	15.7	35.4	7.5	81.0	30.5	23.7	14.2	23.6	1.3
11-12	16.3	17.0	24.9	5.1	41.0	19.4	16.2	10.4	10.3	1.0
10-12	16.3	17.4	27.0	5.5	49.0	21.5	17.4	11.2	11.7	1.0
22-23	16.8	6.3	17.2	3.7	15.3	12.5	13.0	6.8	16.2	.8
23-24	5.3	7.3	18.4	4.0	17.1	13.7	14.1	7.4	16.6	.8
24-25	7.7	3.6	14.0	2.9	10.5	9.5	10.4	5.4	17.7	.6
22-25	9.4	4.7	15.5	3.3	12.7	10.9	11.6	6.0	16.8	.7
29-30	11.9	2.2	16.7	3.5	17.2	11.8	12.0	6.0	37.9	.7

Table 10.--*Comparison of measured reaeration coefficients and coefficients determined using velocity-depth equations, for selected subreaches in the White River*

Subreach as defined by site number	Reaeration coefficients (1/day), base e units										
	Determined using measured data	Determined using velocity-depth equations									
		Churchill, Elmore, and Buckingham (1962)	Langbein and Durum (1967)	Owens, Edwards, and Gibbs (1964)[1]	Owens, Edwards, and Gibbs (1964)[2]	Isaacs and Gaudy (1968)	Negulescu and Rojanski (1969)	Bennett and Rathbun (1972)	O'Connor and Dobbins (1958)	Padden and Gloyna (1971)	Bansal (1973)
6-7	25.3	19.0	15.3	26.7	21.9	16.0	22.6	20.3	12.4	10.6	5.3
10-11	23.5	20.1	15.9	28.5	23.5	16.8	23.1	21.6	13.1	11.0	5.6
11-12	16.3	12.5	10.2	18.9	15.7	10.5	16.3	15.0	9.5	7.9	4.0
10-12	16.3	13.6	11.1	20.2	16.8	11.5	17.4	15.9	10.0	8.4	4.2
22-23	16.8	11.8	9.4	18.5	15.6	9.8	15.0	14.8	9.5	7.5	3.9
23-24	5.3	12.5	9.9	19.7	16.7	10.4	15.5	15.8	10.1	7.8	4.2
24-25	7.7	10.3	8.5	16.1	13.4	8.7	14.1	13.0	8.5	6.9	3.5
22-25	9.4	11.0	8.9	17.2	14.4	9.2	14.6	13.9	9.0	7.2	3.7
29-30	11.9	13.9	11.7	19.8	16.1	11.9	18.7	15.3	9.6	8.6	4.2

[1]Equation 1.
[2]Equation 2.

Table 11.--*Error analysis of predicted reaeration coefficients*

Energy dissipation			Velocity and depth		
Equation used	Range of error of estimate	Average error of estimate (absolute value)	Equation used	Range of error of estimate	Average error of estimate (absolute value)
Lau (1972)---------	-0.818 → 0.042	0.43	Churchill, Elmore, and Buckingham (1962).	1.364 → -0.145	0.35
Krenkel and Orlob (1963).	2.481 → .024	.70	Langbein and Durum (1967).	.865 → -.018	.32
Parkhurst and Pomeroy (1972).	-.781 → -.248	.64	Owens, Edwards, and Gibbs[1] (1964).	2.720 → .056	.67
Tsivoglou and Neal (1976).	2.449 → -.087	1.21	Owens, Edwards, and Gibbs[2] (1964).	2.145 → .0003	.45
Cadwallader and McDonnell (1969).	1.578 → -.012	.34	Isaacs and Gaudy (1968)--	.956 .004	.31
Bennett and Rathbun (1972).	1.655 → .006	.30	Negulescu and Rojanski (1969).	1.929 → .001	.46
Thackston and Krenkel (1969).	-.594 → -.305	.41	Bennett and Rathbun (1972).	1.984 → -.026	.44
Churchill, Elmore, and Buckingham (1962).	2.185 → .006	.81	O'Connor and Dobbins (1958).	.903 → -.045	.36
			Padden and Gloyna (1971)-	-.581 → -.099	.42
Dobbins (1965)-----	-.954 → -.842	.93	Bansal (1973)------------	-.789 → -.217	.65

[1]Equation 1.
[2]Equation 2.

Characteristics Measured from Topographic Maps

Ten basin characteristics were measured from 7.5-minute topographic maps for tributary and main-stem stations on the White River. These basin-characteristics station locations are listed in table 12 with drainage area, annual mean discharge, and the period of streamflow record. All the selected basin-characteristics stations were existing or discontinued streamflow-gaging stations on the tributaries and main stem of the White River. The location of these stations is shown on figure 12. The basin characteristics (table 13) measured are: mean basin elevation, mean annual precipitation, main-channel slope, slope orientation, forest cover, storage area, basin relief, relative degree of roughness, area above 6,000 feet, and area above 8,000 feet. The following is a brief description of each basin characteristic and the method of determination.

Mean basin elevation.--This is the average elevation of the area within the drainage basin. Mean basin elevation, in feet, was computed from U.S. Geological Survey topographic maps by averaging the elevations of equal-spaced grid points within the basin.

Mean annual precipitation.--Mean annual precipitation of a basin indicates the amount of water available for potential runoff. The precipitation that infiltrates the soil is the source of base flow for a stream. The mean annual precipitation, in inches, was computed from a map of the White River basin having lines of equal annual precipitation. The annual precipitation data were collected by the National Climatic Data Center (1980a, 1980b).

Main-channel slope.--Main-channel slope is a characteristic that relates to the streamflow of a basin. The slope used in this report is the average slope, in feet per mile, between points 10 percent and 85 percent of the distance along the channel from the streamflow-gaging station to the drainage-basin divide.

Slope orientation.--This is a measure of the average direction which the basin is facing and can indicate the relative amount of sunlight that the basin receives. Slope orientation, in degrees, was computed by measuring the direction, from north, perpendicular to the downstream direction of the channel. The main-stem White River slope orientation was computed by averaging the slope orientation of the separate basins above the main-stem station.

Forest cover.--Forests affect streamflow in several ways. Their major influences on low flow are transpiration and the interception of precipitation before it reaches the ground. Forest cover was computed as the percent of drainage area covered by forests, as shown on the U.S. Geological Survey topographic maps.

Storage area.--Storage area is that part of the drainage area occupied by lakes and marshes. Variations in streamflow can be caused by retention and release of water from basin storage. Storage area was computed as the percent of drainage area covered by lakes and marshes, as shown on U.S. Geological Survey topographic maps.

Table 12.--*Summary of basin-characteristics stations*

[-----=data not available; *=data presently being collected]

Site number on figure 12	U.S. Geological Survey station number	Station name	Drainage area (square miles)	Annual mean discharge (cubic feet per second)	Period of streamflow record (water years)
1	09302400	North Fork White River below Trappers Lake, Colo	19.5	27.8	1956-65
2	09302420	North Fork White River above Ripple Creek, near Trappers Lake, Colo	62.5	90.7	1965-73
3	09302450	Lost Creek near Buford, Colo	21.5	21.6	1964-*
4	09302500	Marvine Creek near Buford, Colo	59.7	89.6	1903-06, 1972-*
5	09302800	North Fork White River near Buford, Colo	220	289	1903-06, 1956-72
6	09303000	North Fork White River at Buford, Colo	260	306	1910-15,1919-20, 1951-*
7	09303300	South Fork White River at Budges Resort, Colo	52.3	98.0	1975-*
8	09303320	Wagonwheel Creek at Budges Resort, Colo	7.36	7.88	1975-*
9	09303340	Patterson Creek near Budges Resort, Colo	11.2	4.98	1976-*
10	09303400	South Fork White River near Budges Resort, Colo	128	186	1976-*
11	09303500	South Fork White River near Buford, Colo	152	258	1903-06,1910-15, 1942-47,1967-*
12	09304000	South Fork White River at Buford, Colo	177	252	1919-20,1951-*
13	09304100	Big Beaver Creek near Buford, Colo	34.1	14.9	1955-64
14	09304150	Miller Creek near Meeker, Colo	57.6	18.4	1970-*
15	09304200	White River above Coal Creek, near Meeker, Colo	648	541	1961-*
16	09304300	Coal Creek near Meeker, Colo	25.1	5.23	1957-68
17	09304480	Coal Creek below Little Beaver Creek, near Meeker, Colo	89.8	.00	1978-*
18	09304500	White River near Meeker, Colo	755	617	1901-06,1909-*
19	09304550	Curtis Creek near Meeker, Colo	23.1	.00	1978-*
20	09304600	White River at Meeker, Colo	808	606	1978-*
21	09304800	White River below Meeker, Colo	1024	614	1961-*
22	09305000	White River at White River, Colo	1131	------	1895
23	09305500	Piceance Creek at Rio Blanco, Colo	8.97	1.40	1952-57
24	09306000	Piceance Creek near Rio Blanco, Colo	147	20.8	1940-43
25	09306007	Piceance Creek below Rio Blanco, Colo	177	11.8	1974-*
26	09306015	Middle Fork Stewart Gulch near Rio Blanco, Colo	24.0	.00	1974-76,1978-*
27	09306022	Stewart Gulch above West Fork, near Rio Blanco, Colo	44.1	1.56	1974-*
28	09306042	Piceance Creek Tributary near Rio Blanco, Colo	1.06	0.31	1974-*
29	09306045	Piceance Creek below Gardenhire Gulch, near Rio Blanco, Colo	258	10.2	1980-82
30	09306052	Scandard Gulch at mouth, near Rio Blanco, Colo	8.00	.01	1974-76,1977-*
31	09306058	Willow Creek near Rio Blanco, Colo	48.4	1.96	1974-*
32	09306061	Piceance Creek above Hunter Creek, near Rio Blanco, Colo	309	16.2	1974-*
33	09306175	Black Sulphur Creek near Rio Blanco, Colo	103	6.24	1974-*
34	09306200	Piceance Creek below Ryan Gulch, near Rio Blanco, Colo	506	19.9	1964-*
35	09306210	Piceance Creek near White River, Colo	553	------	1971-76

Table 12.--*Summary of basin-characteristics stations*--Continued

Site number on figure 12	U.S. Geological Survey station number	Station name	Drainage area (square miles)	Annual mean discharge (cubic feet per second)	Period of streamflow record (water years)
36	09306222	Piceance Creek at White River, Colo	652	24.8	1964-66, 1970-*
37	09306230	Stake Springs Draw near Rangely, Colo	26.1	.03	1974-77
38	09306235	Corral Gulch below Water Gulch, near Rangely, Colo	8.61	.22	1974-*
39	09306242	Corral Gulch near Rangely, Colo	31.6	1.35	1974-*
40	09306244	Corral Gulch at 84 Ranch, Colo	38.5	.10	1975-77
41	09306250	Duck Creek near 84 Ranch, Colo	55.3	.01	1975-77
42	09306255	Yellow Creek near White River, Colo	262	1.90	1972-82
43	09306300	White River above Rangely, Colo	2773	633	1972-82
44	09306380	Douglas Creek at Rangely, Colo	425	7.24	1977-78
45	09306395	White River near Colorado-Utah State line, Utah	3680	634	1976-*
46	09306400	White River above Hell's Hole Canyon, near Watson, Utah	3700	626	1975-76
47	09306405	Hell's Hole Canyon at mouth, near Watson, Utah	24.5	.07	1974-*
48	09306410	Evacuation Creek above Missouri Creek, near Dragon, Utah	100	1.41	1974-*
49	09306415	Evacuation Creek below Park Canyon, near Watson, Utah	246	1.24	1975-76
50	09306417	Thimble Rock Canyon near Watson, Utah	1.70	.00	1975
51	09306420	Evacuation Creek at Watson, Utah	259	1.36	1975-76
52	09306425	Evacuation Creek tributary near Watson, Utah	12.4	.00	1975
53	09306430	Evacuation Creek near mouth, near Watson, Utah	284	2.81	1951-54, 1974-*
54	09306500	White River near Watson, Utah	4020	626	1904-06, 1923-79
55	09306600	White River above Southam Canyon, near Watson, Utah	4030	758	1974-76
56	09306605	Southam Canyon Wash near Watson, Utah	2.50	.00	1976, 1979-80
57	09306610	Southam Canyon Wash at mouth, near Watson, Utah	8.30	.03	1976, 1979-80
58	09306620	Asphalt Wash below Center Fork, near Watson, Utah	94.4	.02	1976
59	09306625	Asphalt Wash near mouth, near Watson, Utah	97.5	.24	1974-*
60	09306700	White River below Asphalt Wash, near Watson, Utah	4130	666	1974-78, 1981-82
61	09306760	Sweetwater Canyon below South Canyon, near Watson, Utah	22.6	.45	1974-78
62	09306780	Sweetwater Canyon near mouth, near Watson, Utah	124	.11	1975-78
63	09306800	Bitter Creek near Bonanza, Utah	324	1.70	1971-*
64	09306850	Bitter Creek at mouth, near Bonanza, Utah	398	1.24	1974-*
65	09306870	Sand Wash near Ouray, Utah	59.7	.04	1974-*
66	09306885	Cottonwood Wash at mouth, near Ouray, Utah	70.6	7.76	1976-*
67	09306900	White River at mouth, near Ouray, Utah	5120	654	1974-*

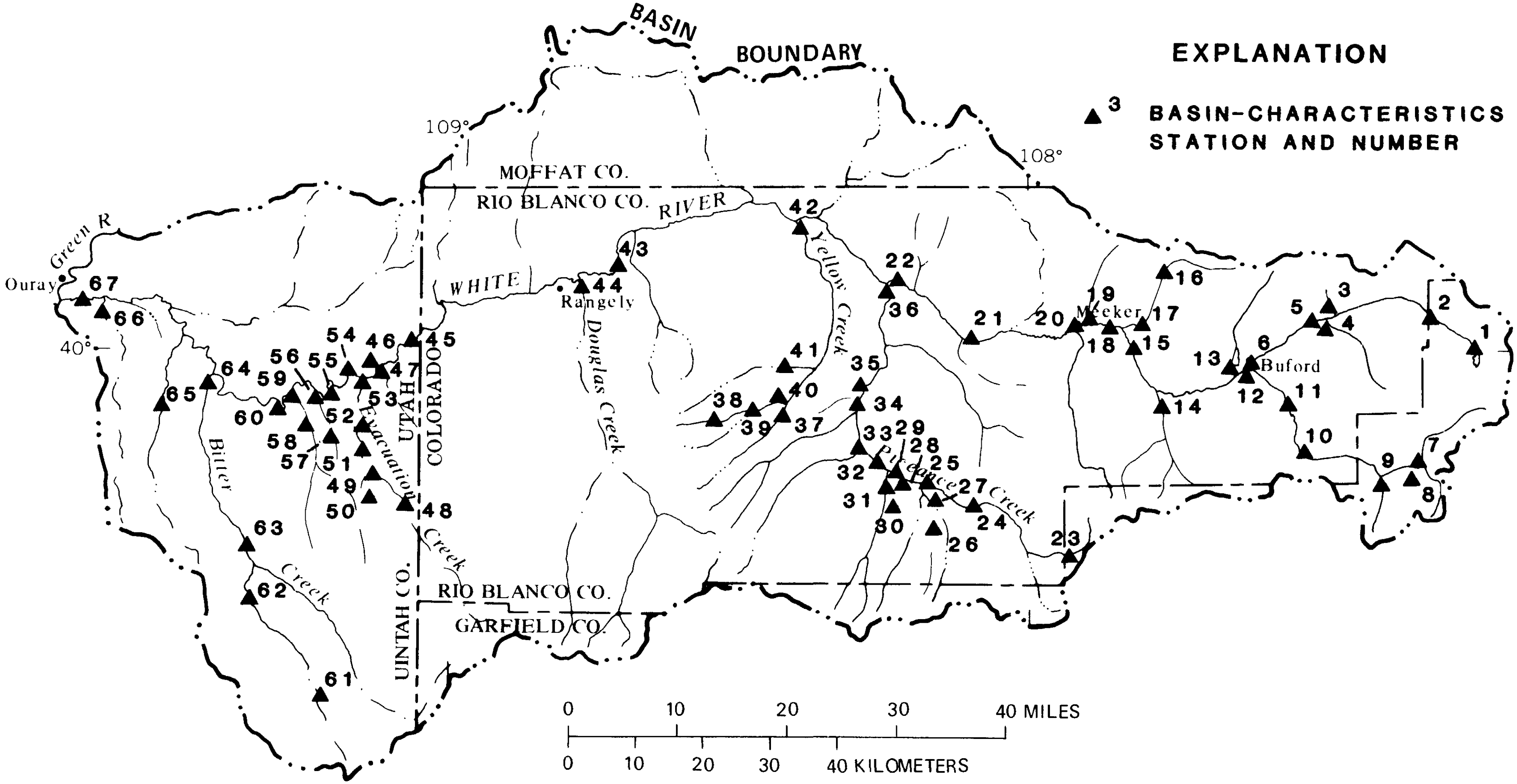

Figure 12.--Location of basin-characteristics stations.

Table 13.--*Summary of basin characteristics measured from U.S. Geological Survey topographic maps*

Site number on figure 12	Mean basin elevation (feet)	Mean annual precipitation (inches)	Main-channel slope (feet per mile)	Slope orientation (degrees)	Forest cover (percent)	Storage area (percent)	Basin relief (feet per square mile)	Relative degree of roughness (feet)	Area above 6,000 feet (percent)	Area above 8,000 feet (percent)
1	10,800	40.0	314	315	75.0	6.37	108	592	100	100
2	10,400	38.3	195	290	72.2	3.03	52.8	643	100	100
3	8,960	27.5	295	170	75.0	.93	140	438	100	100
4	9,780	32.2	214	315	87.8	2.95	70.3	686	100	96.2
5	9,730	31.5	119	285	80.5	6.01	20.5	634	100	96.0
6	9,530	30.9	98.0	275	81.6	5.12	18.8	658	100	91.8
7	10,600	40.0	197	285	68.3	1.76	45.9	487	100	100
8	10,600	40.0	234	380	40.4	2.73	322	340	100	100
9	10,600	40.0	294	5	70.8	3.50	224	405	100	100
10	10,200	40.0	132	285	69.2	1.49	29.7	558	100	98.9
11	10,100	33.6	103	295	74.3	1.26	25.7	568	100	95.3
12	9,800	33.9	88.1	295	72.5	1.27	24.5	598	100	90.4
13	8,320	26.9	177	210	89.7	.91	85.0	514	100	69.7
14	8,600	29.2	150	15	66.7	.00	44.4	517	100	73.6
15	9,140	30.7	67.5	290	76.0	.54	8.59	599	100	80.3
16	7,960	28.4	238	225	75.9	.84	127	516	100	34.5
17	7,460	26.4	124	260	67.9	.23	34.3	544	100	19.3
18	8,940	29.6	67.1	285	72.0	.49	7.15	588	100	71.8
19	7,260	24.1	94.8	195	48.3	1.47	86.5	493	100	8.4
20	8,820	28.9	64.2	280	69.4	.50	7.03	584	100	67.3
21	8,450	27.5	55.9	285	66.9	.51	5.76	557	100	55.2
22	8,280	26.1	47.5	280	67.0	.50	5.39	542	99.0	50.0
23	8,180	30.0	179	215	94.4	.00	245	340	100	53.9
24	7,710	25.8	68.1	280	87.6	.12	20.4	375	100	27.2
25	7,630	24.5	57.3	280	82.8	.10	20.3	362	100	22.7
26	7,710	22.0	118	0	83.7	.00	74.9	298	100	21.8
27	7,620	22.0	106	355	88.9	.00	40.9	309	100	21.9
28	6,670	16.0	220	0	74.3	.00	500	96	100	.0
29	7,570	22.2	54.4	300	87.3	.07	13.2	333	100	20.2
30	7,100	19.0	150	10	75.0	.00	201	178	100	6.3
31	7,500	21.8	99.1	20	86.2	.00	45.4	344	100	26.9
32	7,550	21.2	93.1	315	82.9	.06	11.0	334	100	21.1
33	7,350	21.8	104	30	70.3	.00	23.3	308	100	21.0
34	7,420	20.8	42.7	340	79.6	.03	6.92	317	100	19.5
35	7,350	20.5	65.5	340	78.6	.03	6.51	314	99.6	17.9

Table 13.--*Summary of basin characteristics measured from U.S. Geological Survey topographic maps*--Continued

Site number on figure 12	Mean basin elevation (feet)	Mean annual precipitation (inches)	Main-channel slope (feet per mile)	Slope orientation (degrees)	Forest cover (percent)	Storage area (percent)	Basin relief (feet per square mile)	Relative degree of roughness (feet)	Area above 6,000 feet (percent)	Area above 8,000 feet (percent)
36	7,270	20.0	29.5	340	79.6	0.02	5.83	314	99.2	16.0
37	7,220	19.8	128	40	79.2	.00	62.8	296	100	14.0
38	7,740	20.0	225	70	56.6	.00	192	401	100	30.8
39	7,490	20.0	165	60	51.6	.00	66.6	311	100	23.1
40	7,380	20.0	130	60	75.0	.00	54.6	287	100	12.3
41	7,160	19.4	124	85	82.5	.00	43.4	348	100	7.9
42	6,880	17.3	45.6	50	69.7	.00	11.8	281	98.4	5.3
43	7,410	20.9	31.2	320	74.8	.24	2.38	424	89.2	25.0
44	7,340	19.3	33.7	355	86.9	.00	8.71	410	90.6	11.6
45	7,240	19.8	23.5	320	71.9	.19	1.86	409	82.9	21.0
46	7,230	19.8	22.3	320	71.6	.19	1.86	408	83.0	21.0
47	6,610	12.1	93.2	315	65.0	.00	98.0	408	70.0	.0
48	7,220	17.4	77.6	335	88.9	.03	31.0	470	73.0	10.0
49	6,790	16.7	64.6	315	80.4	.02	13.4	435	85.5	5.2
50	6,340	12.0	215	0	38.5	.00	471	128	100	.0
51	6,780	14.3	58.5	315	59.4	.01	13.5	422	73.3	2.6
52	6,120	12.0	162	290	20.3	.00	129.	345	33.0	.0
53	6,700	13.4	50.0	315	47.2	.00	13.0	412	59.8	.0
54	7,180	19.2	22.2	315	69.2	.18	1.71	408	82.0	20.0
55	7,180	19.1	20.7	315	68.6	.18	1.71	408	82.0	20.0
56	5,930	10.3	281	340	80.0	.00	120	120	.0	.0
57	5,580	10.3	140	315	80.0	.00	120	298	8.5	.0
58	6,120	11.9	71.6	345	68.1	.00	22.2	248	62.0	.0
59	6,100	11.9	70.4	345	68.1	.00	22.6	244	31.0	.0
60	7,140	18.6	19.8	315	68.3	.18	1.67	404	81.0	19.0
61	7,790	16.0	141	0	97.3	.00	66.4	302	96.0	35.0
62	7,300	15.7	82.8	355	93.2	.02	19.4	315	97.5	19.5
63	7,150	16.1	62.5	330	93.5	.02	10.5	316	97.0	14.7
64	6,890	14.8	43.3	330	82.2	.02	9.8	306	89.0	8.8
65	5,980	10.8	66.8	350	50.0	.02	25.1	482	53.0	.0
66	5,490	9.0	55.8	350	17.3	.04	22.7	329	.0	.0
67	6,910	18.1	17.0	310	67.0	.17	1.38	379	73.0	15.6

Basin relief.--Basin relief is the change in elevation per square mile of the land within the basin. This affects the time in which it takes surface runoff to reach the stream channel. Basin relief, in feet per square mile, was computed as the difference between the elevation of the highest point within the basin and the station location, divided by the drainage area.

Relative degree of roughness.--Relative degree of roughness is an indication of the contour of the land surface. A small value for the relative degree of roughness indicates a nearly flat surface, whereas a large value indicates a large variation in elevation. Relative degree of roughness, in feet, was computed as the standard deviation of elevation about the mean basin elevation, which is the summation of the squared difference between the elevations used for the computation and the mean basin elevation, divided by the number of elevations minus one.

Area above 6,000 and 8,000 feet.--The percentages of area above 6,000 and 8,000 feet are characteristics of the basin that can indicate the weather conditions associated with the basin, such as air pressure and air temperature, and possibly indicate the type of stream, such as a mountain or lowland stream. They were computed as the percents of drainage area covered by land above 6,000 and 8,000 feet, respectively, as shown on U.S. Geological Survey topographic maps.

Maximum 24-hour Precipitation

The maximum 24-hour precipitation expected for recurrence intervals of 2, 5, 10, 25, 50, and 100 years was computed for tributary and main-stem stations on the White River using data found in Miller and others (1973). The stations used for this computation were the same as those used to measure basin characteristics and are listed in table 12 and are shown in figure 12. The precipitation values are listed in table 14. The maximum 24-hour precipitation for each recurrence interval generally decreases downstream. This decrease reflects the change in the White River from a mountain-type climate in the headwaters to the semi-arid climate in the lower part of the basin. The White River basin has a strong relationship between precipitation and elevation. Therefore, the decrease in elevation also reflects the change in elevation (see table 13) from upstream to downstream.

Characteristics Measured from Aerial Photographs

On September 11, 1981, low-elevation and thermal-infrared color aerial photographs were taken of the White River. The scale for both types of photographs is about 1:24,000. The average discharge in the White River was about 300 cubic feet per second, which is considered low (about 90-percent flow duration). Percent of pools and riffles, average stream width, and average stream temperature were measured from these photographs. The results of these measurements are discussed in the following sections.

Table 14.--*Maximum 24-hour precipitation for recurrence intervals of 2, 5, 10, 25, 50, and 100 years*

Site number on figure 12	Maximum 24-hour precipition, in tenths of inches					
	Recurrence interval, in years					
	2	5	10	25	50	100
1	17.2	21.7	26.1	30.7	34.5	37.1
2	16.6	19.7	25.2	30.5	33.8	35.8
3	15.7	19.8	22.8	26.7	29.6	33.6
4	16.0	20.3	24.2	28.7	31.9	34.0
5	16.0	19.9	24.0	28.6	31.4	34.6
6	16.0	19.8	23.7	28.3	31.0	34.1
7	18.1	22.0	26.2	30.5	34.2	38.1
8	18.1	22.0	26.2	30.5	34.2	38.1
9	18.3	22.8	27.1	31.6	34.8	39.8
10	18.2	22.2	26.3	30.7	34.3	38.4
11	17.3	21.4	25.3	29.3	32.9	36.2
12	16.5	20.6	24.3	28.0	31.5	34.7
13	14.6	18.8	21.4	25.4	28.0	30.6
14	14.3	18.5	21.6	26.1	28.8	31.0
15	15.4	19.4	23.0	27.1	30.1	33.0
16	13.5	17.4	20.0	24.0	26.0	28.7
17	13.3	17.1	19.5	23.4	25.4	27.8
18	15.1	19.1	22.5	26.6	29.5	32.2
19	12.6	16.2	18.7	22.5	25.6	27.0
20	14.9	18.8	22.2	26.3	29.2	31.9
21	14.3	18.2	21.3	25.5	28.4	30.7
22	14.0	17.8	20.9	25.1	28.0	30.1
23	13.0	18.8	19.6	26.3	28.6	30.0
24	13.0	17.3	19.6	23.7	26.3	27.9
25	12.9	17.0	19.3	23.4	25.9	27.6
26	12.3	16.0	18.4	22.0	24.6	26.7
27	12.3	16.0	18.4	22.1	24.7	26.6
28	11.8	15.7	18.0	21.1	23.0	25.7
29	12.6	16.7	19.0	22.9	25.3	27.2
30	12.0	16.0	18.0	21.6	23.4	26.0
31	12.4	15.7	18.3	21.7	23.8	26.5
32	12.6	16.5	18.9	22.7	25.0	27.0
33	12.2	15.0	18.1	21.0	23.6	25.9
34	12.4	15.9	18.6	22.0	24.5	26.6
35	12.3	15.9	18.5	21.9	24.3	26.4

Table 14.--*Maximum 24-hour precipitation for recurrence intervals of 2, 5, 10, 25, 50, and 100 years*--Continued

Site number on figure 12	Maximum 24-hour precipition, in tenths of inches					
	Recurrence interval, in years					
	2	5	10	25	50	100
36	12.1	15.8	18.3	21.9	24.2	26.3
37	12.2	15.0	18.0	21.0	23.7	25.9
38	12.4	15.0	18.0	21.0	23.9	26.0
39	12.4	15.0	18.0	21.0	23.9	26.0
40	12.4	15.0	18.0	21.0	23.9	26.0
41	12.1	15.0	17.5	21.0	23.0	25.9
42	11.5	14.8	17.3	21.0	23.3	25.3
43	12.6	16.1	18.2	22.9	25.4	27.4
44	11.4	14.8	17.6	21.0	23.5	25.3
45	12.4	16.0	18.3	22.8	25.3	27.2
46	12.4	16.0	18.3	22.8	25.3	27.2
47	11.0	14.0	16.8	20.3	22.5	24.0
48	11.6	14.8	17.6	20.4	23.0	25.6
49	11.4	14.9	17.3	20.5	22.9	25.2
50	10.0	14.0	16.0	20.0	22.0	24.0
51	11.3	14.8	17.3	20.4	22.9	25.1
52	10.9	14.1	16.3	20.0	22.1	24.0
53	11.2	14.8	17.2	20.4	22.8	25.0
54	12.3	15.9	18.2	22.6	25.1	27.0
55	12.3	15.9	18.2	22.6	25.1	27.0
56	10.0	14.0	16.0	19.0	22.0	24.0
57	10.0	13.4	16.0	19.0	22.0	24.0
58	10.2	13.9	16.2	19.6	22.1	24.0
59	10.2	13.9	16.2	19.6	22.1	24.0
60	12.3	15.8	18.1	22.5	25.0	26.9
61	12.0	15.0	17.0	21.0	23.0	26.0
62	11.5	14.8	17.0	20.9	23.0	25.7
63	11.4	14.7	16.5	20.6	22.8	25.5
64	11.1	14.5	16.4	20.4	22.6	25.2
65	9.8	13.8	16.0	19.2	21.8	23.9
66	9.3	13.1	15.6	18.6	21.3	23.4
67	11.9	15.3	17.5	21.7	24.1	26.1

Pools and Riffles

The pools and riffles were defined on the low-elevation photographs using stereoscopes. The stream length of the pools and riffles was then measured and the average length and percent of pools and riffles was computed. These values were computed for the traveltime measurement reaches. The sites defining the reaches are shown on figure 2 and listed in table 1. The results of the measurements are given in table 15. The length of riffles is greater than the length of pools from sites 1 to 13; below site 13, the length of pools and riffles is almost equal. The average pool length generally increases downstream, whereas the average riffle length generally decreases until about site 14, then increases again at about site 34.

Channel Width and Depth

Channel widths were measured from the low-elevation photographs. The average channel widths of the traveltime reaches were computed and are listed in table 16 along with the minimum and maximum measured width in the reach. Channel widths were measured on the photographs at randomly selected points within a reach and averaged. These average widths will probably remain the same over a small range of flows. The measured channel widths ranged from about 45 to 322 feet. The average depth of each reach was also computed using the average width in the following equation:

$$D=Q/(VW), \tag{31}$$

where D=average reach depth, in feet;
Q=average reach discharge, in cubic feet per second;
V=average reach velocity, in feet per second; and
W=average reach width, in feet.

The average reach discharge was estimated using the discharges recorded at streamflow-gaging stations nearest the reach. The average velocity of streamflow in the reaches in Colorado was estimated from the traveltimes using the graphical method, and the velocity of streamflow in the reaches in Utah was estimated from the traveltime simultations using the linear-regression method. These values are also listed in table 16. The slope of each reach is also listed in table 16 because velocity and depth are dependent upon slope. If the slope is increased, the velocity is faster and the depth is shallower.

Stream Temperature

Stream temperatures were estimated from thermal-infrared color aerial photographs of the entire White River. Ranges of temperatures of selected reaches in which there were large changes in temperature are shown in figure 13. Average stream temperatures were 10° Celsius at the headwaters of the South Fork White River and 14° Celsius at the headwaters of the North Fork White River and generally increased downstream to 18° Celsius at the mouth of the White River. Ambient air temperatures also increase from the headwaters downstream to the mouth of the White River which directly affects the water temperatures (Boyle and others, 1984). The stream temperatures varied slightly up and down along the river because of irrigation return flows, tributaries, and springs.

Table 15.--*Average length and percent of pools and riffles in traveltime study reaches*

Reach as defined by site numbers	Pools in reach (percent)	Riffles in reach (percent)	Average pool length (feet)	Average riffle length (feet)
1-2	42	58	220	305
2-3	24	76	174	582
3-7	28	72	217	565
7-8	28	72	194	521
8-9	22	78	163	586
9-11	34	66	282	554
11-12	42	58	270	376
12-13	27	73	281	738
13-14	43	57	267	356
14-15	53	47	322	282
15-16	54	46	295	248
16-17	45	55	250	315
17-18	50	50	394	394
18-19	48	52	362	388
19-20	44	56	353	446
20-22	49	51	418	438
22-23	47	53	315	351
23-24	54	46	394	367
24-25	50	50	285	285
25-26	48	52	314	334
26-27	50	50	294	294
27-30	48	52	364	392
30-31	44	56	261	335
31-32	45	55	214	255
32-33	49	51	232	239
33-34	47	53	266	295
34-35	43	57	420	547
35-36	42	58	373	522
36-37	42	58	396	541
37-38	47	53	429	477
38-39	53	47	498	443
39-40	54	46	524	441
40-41	50	50	502	502

Table 16.--*Average channel width and depth in traveltime study reaches*

Reach as defined by site numbers	Average width (feet)	Minimum width (feet)	Maximum width (feet)	Average velocity (feet per second)	Average depth (feet)	Slope of reach (feet per mile)
1-2	84	54	109	2.54	0.67	48.4
2-3	81	45	112	2.92	.61	42.2
3-7	88	45	146	3.09	1.00	36.8
7-8	81	45	148	2.92	.71	31.4
8-9	114	68	148	2.51	.77	26.1
9-11	105	62	176	2.05	1.26	26.9
11-12	93	62	135	2.51	1.16	20.6
12-13	105	52	218	2.36	1.33	18.7
13-14	97	65	140	2.48	1.37	18.2
14-15	120	79	225	1.94	1.41	11.9
15-16	131	101	180	1.91	1.31	10.0
16-17	106	82	141	1.83	1.65	11.5
17-18	116	60	149	2.28	1.17	8.82
18-19	123	80	159	1.90	1.24	8.22
19-20	131	83	187	1.71	1.20	9.01
20-22	125	96	150	1.59	1.41	7.50
22-23	123	86	171	1.71	1.36	7.84
23-24	108	75	128	2.08	1.31	9.20
24-25	124	96	160	1.91	1.27	5.69
25-26	119	86	182	1.49	1.80	5.88
26-27	119	90	157	1.60	1.78	6.72
27-30	119	101	157	1.32	2.32	5.41
30-31	114	79	146	1.46	2.17	10.0
31-32	106	73	147	1.47	2.29	8.90
32-33	89	63	147	1.36	2.92	8.41
33-34	104	73	157	1.58	2.12	4.32
34-35	118	96	160	1.48	1.96	7.97
35-36	107	86	139	1.41	2.24	5.50
36-37	137	107	223	1.38	1.75	9.14
37-38	141	106	191	1.38	1.65	5.08
38-39	147	117	225	1.38	1.54	2.72
39-40	137	96	172	1.13	1.97	2.89
40-41	171	107	322	1.25	1.42	2.35

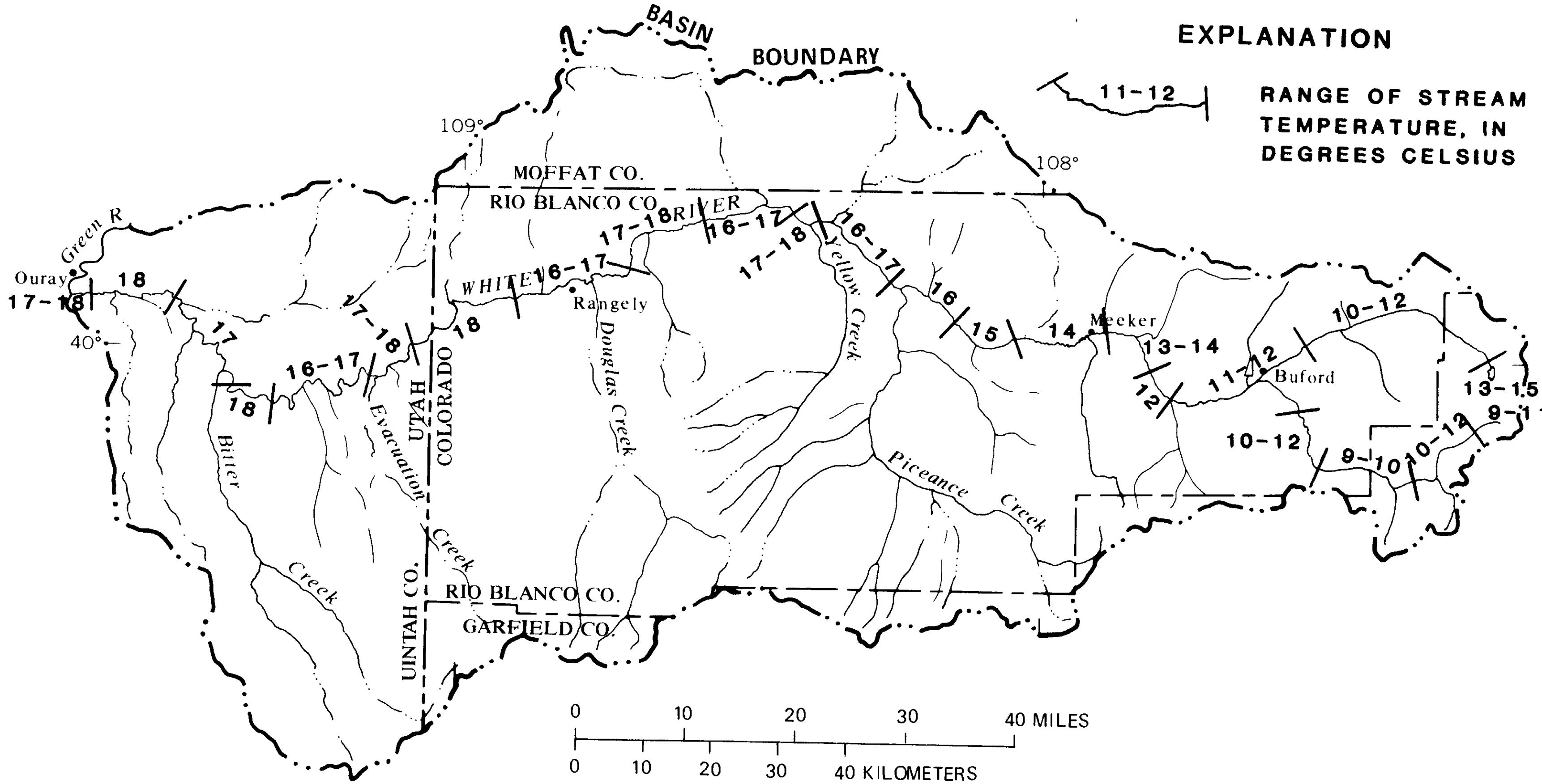

Figure 13.--Changes in average stream temperature of the White River, North Fork White River, and South Fork White River.

SUMMARY

The White River basin contains extensive energy resources which might affect the quantity and quality of the basin's water resources. The purpose of this study was to determine traveltime, longitudinal dispersion, reaeration, and basin characteristics of the White River which can be used in making decisions concerning energy developments.

Traveltime and longitudinal-dispersion characteristics were determined for reaches of the White River. Measurements were made during high and medium flow. The study reaches extended for 7 miles of the North Fork White River and 6 miles of the South Fork White River upstream from their confluence and downstream on the White River for 198 miles to its mouth near Ouray, Utah. For all the traveltime measurements, the discharge ranged from 281 to 1,840 cubic feet per second, and the stream velocity ranged from 1.26 to 3.17 miles per hour.

Traveltimes were determined for discharges other than measured discharges by a graphical method using index-discharge stations. The index-discharge stations used were: (1) Station 09304500 White River near Meeker, Colo.; (2) station 09304800 White River below Meeker, Colo.; (3) station 09306395 White River near Colorado-Utah State line, Utah; and (4) station 09306900 White River at mouth, near Ouray, Utah. Traveltimes also were simulated using a linear-regression method. Linear-regression relationships were developed for each reach in Colorado separately (sites 1-8, 8-15, 14-20, 19-25, and 24-30), for all the reaches in Utah together (sites 27-41), and for all the reaches on the White River together (sites 1-41).

Longitudinal-dispersion coefficients ranged from 284 square feet per second at a discharge of 539 cubic feet per second to 3,560 square feet per second at a discharge of 1,580 cubic feet per second.

Reaeration coefficients were determined for four reaches in the White River during a medium-flow period in August 1982. Measured reaeration coefficients at 20° Celsius for the reaches ranged from 5.3 to 25.3 per day using ethylene as the tracer gas. Measured reaeration coefficients were compared with predicted reaeration coefficients calculated using semi-empirical and empirical equations. Prediction equations by Bennett and Rathbun (1972) and Isaacs and Gaudy (1968) gave the most accurate comparison results.

Basin characteristics were computed from U.S. Geological Survey topographic maps as follows: Mean basin elevation, mean annual precipitation, main-channel slope, slope orientation, forest cover, storage area, basin relief, relative degree of roughness, area above 6,000 feet, and area above 8,000 feet. Basin characteristics were also computed using aerial photographs taken on September 11, 1981. These basin characteristics are pools and riffles, channel width, and stream temperature.

SELECTED REFERENCES

Bansal, M.K., 1973, Atmospheric reaeration in natural streams: Water Research, v. 7, no. 5, p. 769-782.

Bauer, D.P., Rathbun, R.E., and Lowham, H.W., 1979, Traveltime, unit-concentration, longitudinal-dispersion, and reaeration characteristics of upstream reaches of the Yampa and Little Snake Rivers, Colorado and Wyoming: U.S. Geological Survey Water-Resources Investigations 78-122, 66 p.

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

Boyle, J.M., Covay, K.J., and Bauer, D.P., 1984, Quantity and quality of streamflow in the White River basin, Colorado and Utah: U.S. Geological Survey Water-Resources Investigations Report 84-4022, 84 p.

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

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

Dobbins, W.E., 1965, Closure to "BOD and oxygen relationship in streams": American Society of Civil Engineers, Journal of the Sanitary Engineering Division, v. 91, no. SA-5, p. 49-55.

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

Fischer, H.B., 1973, Longitudinal dispersion and turbulent mixing in open-channel flow, *in* Annual review of fluid mechanics: Palo Alto, Calif., Annual Review, Inc., v. 5, p. 59-78.

Hubbard, E.F., Kilpatrick, F.A., Martens, L.A., and Wilson, J.F., Jr., 1982, Measurement of time of travel and dispersion in streams by dye tracing: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, chapter A9, 44 p.

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

Krenkel, P.A., and Orlob, G.T., 1963, Turbulent diffusion and the reaeration coefficient: American Society of Civil Engineers Transactions, v. 128, Paper 3491, p. 293-334.

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

Lau, Y.L., 1972, Prediction equations of reaeration in open-channel flow: American Society of Civil Engineers, Journal of the Sanitary Engineering Division, v. 98, no. SA-6, p. 1063-1068.

Miller, J.F., Frederick, R.H., and Tracey, R.J., 1973, Precipitation-frequency atlas of the Western United States, Volume 3-Colorado: Silver Spring, Md., National Oceanic and Atmospheric Administration Atlas 2, p. 33-43.

National Climatic Data Center, 1980a, Climatological data annual summary, Colorado: Asheville, N.C., v. 87, no. 13.

_____1980b, Climatological data annual summary, Utah: Asheville, N.C., v. 87, no. 13.

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

Nordin, C.F., Jr., and Sabol, G.V., 1974, Empirical data on longitudinal dispersion in rivers: U.S. Geological Survey Water-Resources Investigations 20-74, 334 p.
O'Connor, D.J., and Dobbins, W.E., 1958, Mechanisms of reaeration in natural streams: American Society of Civil Engineers Transactions, v. 123, p. 641-684.
Owens, M., Edwards, R.W., and Gibbs, J.W., 1964, Some reaeration studies in streams: Oxford, England, International Journal of Air and Water Pollution, v. 8, no. 8/9, p. 469-486.
Padden, T.J., and Gloyna, E.F., 1971, Simulation of stream processes in a model river: Austin, University of Texas, Center for Research in Water Resources, Technical Report no. 2, 130 p.
Parkhurst, J.D., and Pomeroy, R.D., 1972, Oxygen absorption in streams: American Society of Civil Engineers, Journal of the Sanitary Engineering Division, v. 98, no. SA-1, p. 101-124.
Rathbun, R.E., 1977, Reaeration coefficients of streams--State-of-the-art: American Society of Civil Engineers, Journal of the Hydraulics Division, v. 103, no. HY-4, p. 409-424.
_____1979, Estimating the dye and gas quantities for modified tracer technique measurements of stream reaeration coefficients: U.S. Geological Survey Water-Resources Investigations 79-27, 52 p.
Rathbun, R.E., and Grant, R.S., 1978, Comparison of the radioactive and modified techniques for measurement of stream reaeration coefficients: U.S. Geological Survey Water-Resources Investigations 78-68, 57 p.
Rathbun, R.E., Shultz, D.J., and Stephens, D.W., 1975, Preliminary experiments with a modified tracer technique for measuring stream reaeration coefficients: U.S. Geological Survey Open-File Report 75-256, 36 p.
Rathbun, R.E., Stephens, D.W., Shultz, D.J., and Tai, D.Y., 1978, Laboratory studies of gas tracers for reaeration: American Society of Civil Engineers, Journal of the Environmental Engineering Division, v. 104, no. EE-2, p. 215-229.
Shultz, D.J., Pankow, J.F., Tai, D.Y., Stephens, D.W., and Rathbun, R.E., 1976, Determination, storage, and preservation of low-molecular weight hydrocarbon gases in aqueous solution: U.S. Geological Survey Journal of Research, v. 4, no. 2, p. 247-251.
Thackston, E.L., and Krenkel, P.A., 1969, Reaeration prediction in natural streams: American Society of Civil Engineers, Journal of the Sanitary Engineering Division, v. 95, no. SA-1, p. 65-94.
Tsivoglou, E.C., 1967, Tracer measurements of stream reaeration: Washington, D.C., Federal Water Pollution Control Administration, 86 p.
Tsivoglou, E. C., and Neal, L. A., 1976, Tracer measurement of reaeration, Part III. Predicting the reaeration capacity of inland streams: Journal of the Water Pollution Control Federation, v. 48, no. 12, p.2669-2689.
Wentz, D.A., and Steele, T.D., 1980, Analysis of stream quality in the Yampa River basin, Colorado and Wyoming: U.S. Geological Survey Water-Resources Investigations 80-8, p. 3.
Wilson, J.F., Jr., 1968, Fluorometric procedures for dye tracing: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, chapter A12, 31 p.

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