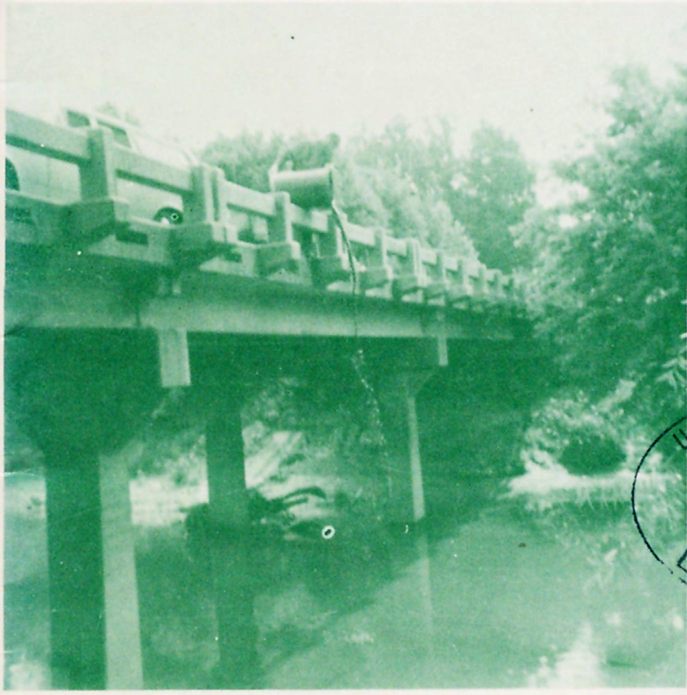
MOVEMENT AND DISPERSION OF SOLUBLE MATERIALS IN SALEM CREEK, MUDDY CREEK AND YADKIN RIVER BETWEEN WINSTON-SALEM AND SALISBURY, NORTH CAROLINA



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By

K. L. Lindskov

U. S. GEOLOGICAL SURVEY Water Res. Div.

Water-Resources Investigation 6-74

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1974

UNITED STATES DEPARTMENT OF THE INTERIOR

ROGERS C. B. MORTON, Secretary

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MOVEMENT AND DISPERSION OF SOLUBLE MATERIALS IN SALEM CREEK, MUDDY CREEK, AND YADKIN RIVER BETWEEN WINSTON-SALEM AND SALISBURY, NORTH CAROLINA

By K. L. Lindskov

ABSTRACT

Wastes entering the Yadkin River from the Winston-Salem area, particularly during heavy rains, resulted in several major fish kills in the late 1960's and early 1970's. The actions undertaken to solve this problem, included the collection of data on the time of travel and dispersion characteristics of the tributaries draining the Winston-Salem area and of the main stem of the Yadkin below their confluence.

Fluorescent dye was used to simulate the movement of waterborne wastes under four different flow conditions over a reach of about 41 miles (66 kilometers) beginning at the sewage-treatment plant on Salem Creek and ending on the Yadkin River at High Rock Lake near Salisbury. Total travel time for the entire reach ranges from about 28 hours during periods of high streamflow to about 47 hours during periods of low flow. A soluble substance released as a slug at the sewage-treatment plant disperses longitudinally and laterally as it moves downstream. Longitudinal dispersion, expressed as the time required for a substance released as a slug at the sewage-treatment plant to pass a downstream point, ranges from about 8 hours at the upper end of High Rock Lake during periods of high flow to about 15 hours during periods of low flow. The rate of lateral dispersion also depends on the rate of flow of the Yadkin. During high-flow conditions wastes entering the Yadkin from Winston-Salem disperse across the river in a few miles. Under low-flow conditions lateral dispersion is still incomplete more than 10 miles (16 kilometers) downstream.

Longitudinal dispersion casues the maximum concentrations resulting from slug injections to decrease significantly as the traveltime increases. A relation is presented so the maximum concentration can be estimated at any location downstream from a point of injection at flow rates between about 80 and 500 cubic feet per second (2 and 14 cubic meters per second) at the Muddy Creek gaging station and between about 1,500 and 10,000 cubic feet per second (42 and 280 cubic meters per second) at the Yadkin College gaging station.

Water entering the Yadkin River from Muddy Creek during low-flow periods does not completely disperse laterally for more than 10 miles (16 kilometers) below the confluence, but, when the Yadkin River discharge is above 5,000 cubic feet per second (140 cubic meters per second), lateral mixing is complete within a few miles below the confluence.

INTRODUCTION

Although the quantity of water in the Yadkin River is abundant when compared to that withdrawn, wastes discharged into the river have at times taxed the ability of the river to disperse and assimilate these materials. Dissolved oxygen concentrations below levels necessary for fish survival have been measured (Shoffner and Wilder, 1973) in the Yadkin River at U.S. Highway 64 during periods of low flow.

The city of Winston-Salem, N. C., discharges treated effluent into Salem Creek which ultimately flows into the Yadkin River. Because of water quality problems in the Yadkin River, city officials recognized a need for information to evaluate the effects of their effluent releases on downstream water quality and to provide a basis for management decisions to minimize any detrimental effects, leading them to request a study to provide insight into the behavior of the effluent as it moves downstream from the point of release at Winston-Salem to High Rock Lake.

An areal investigation of movement and dispersion of waterborne materials in streams began in May 1971 in cooperation with the city of Winston-Salem. As a part of this study, the U.S. Geological Survey developed relationships for the use of the planner to predict the arrival time of contaminated water at points downstream on Salem Creek, Muddy Creek, and the Yadkin River. In addition, a determination was made of the ability of these streams to disperse waterborne materials both longitudinally and laterally as they travel downstream.

To determine how sewage effluent moved from Winston-Salem downstream, fluorescent dye was used to measure the traveltime (time the stream takes to carry waterborne material from one location to another) and the dispersion characteristics of nondegradable soluble substances as they move downstream to High Rock Lake. Dye was introduced at specific locations and concentrations were continuously monitored at other downstream locations, using fluorometers to detect the degree of fluorescence of the water-dye solution at the specified locations.

Four dye studies were made, each under differing flow conditions from July 14, 1971, to March 14, 1973. The study reach included Salem Creek from the outfall of the city of Winston-Salem's Archie Elledge Sewage Treatment Plant through Muddy Creek and down the Yadkin River to High Rock Lake near Salisbury. (See fig. 1.)

Relationships developed from the data can be used to predict when the soluble material reaches downstream locations, how much time is required for the material to pass, and what the maximum-probable concentration will be. Also the effects of an accidental spillage of a contaminant can be evaluated using the data in this report. In addition to the traveltime and dispersion relations, the data can be used in conjunction with dissolved oxygen profiles to define the ability of the stream to reaerate and to assimilate wastes.

It is important to note that the results presented in this report show what will happen if a conservative (nondegradable) soluble material is introduced into the reach. The actual peak concentrations can be much less than those predicted by this study because many pollutants or contaminants are degradable. Also some types of pollutants may move along the bed of the stream with the sediments and can remain in the reach longer than the relations predict.

Explanation of Terms

The following definitions cover most of the technical terms used in this report:

Assimilative capacity is the ability of a stream to receive and transform wastes without causing excessive water-quality deterioration that would limit other beneficial uses.

Centroid is the center of mass of the time-concentration graph representing the passage of dissolved material.

Conservative solute is a dissolved substance of low degradability.

Cubic feet per second (ft^3/s) is a unit expressing the rate of discharge. One ft^3/s is equivalent to the discharge of a stream whose channel is 1 foot square in cross-sectional area and whose average velocity is 1 foot per second.

$1\ ft^3/s = 448.8\ gpm = 0.646\ mgd$

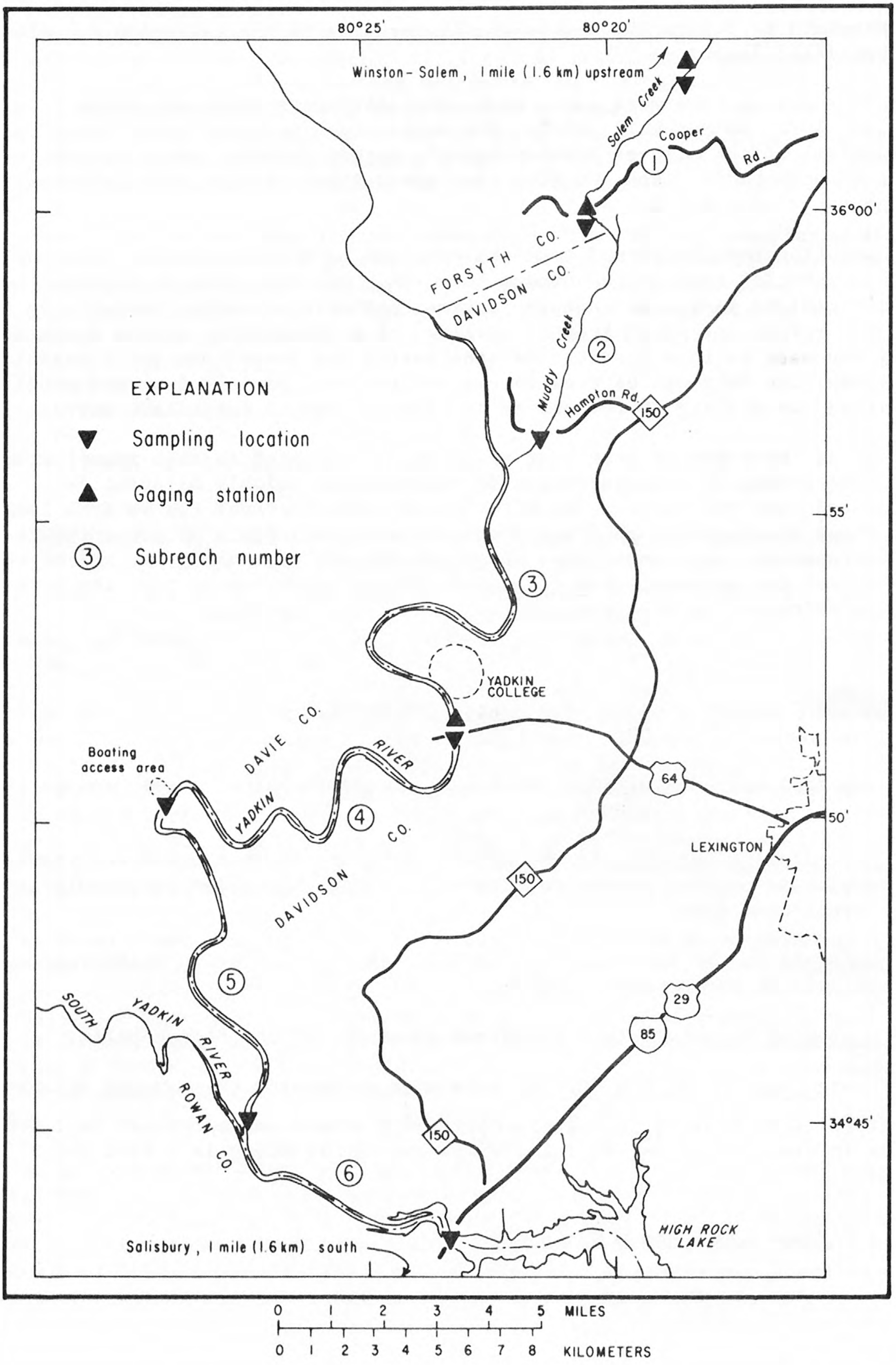

Figure 1.--Location and extent of the study reach.

Degradable substance is one that is readily reduced to a less complex compound when added to a stream.

Dispersion is the mixing action of a substance in a stream. Dispersion takes place in all three dimensions of the channel. Complete mixing normally occurs first in the vertical direction. Lateral mixing is completed later depending upon the width of the stream and variations in velocity. Longitudinal dispersion is mixing in the downstream direction and continues indefinitely. Longitudinal dispersion is usually the dispersion component of primary interest.

Duration is the percentage of time daily discharge at a point on a stream exceeds a certain indicated value. The number of days are not necessarily consecutive. In tabulating the data for a period of record, all the days that exceed the indicated magnitude are counted whether they occur singly or in groups. The word "duration" is also used to designate tables or curves that give the percentages for various magnitudes. Duration in this sense should not be confused with the use of the word to indicate a continuous period of time, as "a contamination of 5 day's duration."

Leading edge is the first point on the time-concentration curve where dye is detected.

Left bank is the streambank on the left when facing downstream.

Micrograms per liter (μg/l) is a unit expressing the weight of a dissolved substance with respect to the volume of the solution. If the liter of solution weighs 1 kilogram, results in micrograms per liter are equivalent to those expressed in parts per billion.

Peak concentration, adjusted is the peak concentration that would occur if there were no dye losses. It is equal to the observed peak concentration divided by the decimal fraction of the dye recovered.

Peak concentration, observed is the maximum concentration on a time-concentration curve defined by observed values. Although it has not been corrected for dye losses, the background fluorescence that would exist if no dye were present has been removed.

Trailing edge is the point on the time concentration curve where the concentration is 10-percent of the peak.

Unit peak concentration is the peak concentration resulting from adding 1 pound of a soluble substance to a discharge of 1 cubic foot per second and assuming there is no loss in the channel.

Conversion Factors

The following factors are for use to convert the English units used in this report to international system (SI) units:

Multiply English units	By	To obtain SI units
	Length	
feet	0.3048	meters
miles	1.609	kilometers
	Area	
square miles	2.590	square kilometers
	Flow	
cubic feet per second	28.32	liters per second
cubic feet per second	0.02832	cubic meters per second
gallons per minute	0.06309	liters per second
million gallons per day	43.81	cubic decimeters per second
	Mass	
pounds	0.4536	kilograms

DESCRIPTION OF THE STUDY REACH

Location and Extent of the Study Reach

The 40.8 mile (65.6 kilometers) study reach, which includes parts of Salem Creek, Muddy Creek, and the Yadkin River, begins on Salem Creek in Forsyth County at Winston-Salem's Archie Elledge Sewage Treatment Plant outfall and ends in Davidson County near Salisbury at the Interstate Highway 85 bridge. To better define traveltimes and dispersion characteristics through the study reach, it was divided into six subreaches. (See fig. 1.) Table 1 shows the cumulative downstream distance and drainage area of the stream segments studied, which includes 2.8 miles (4.5 kilometers) of Salem Creek, 7.2 miles (11.6 kilometers) of Muddy Creek, and 30.8 miles (49.6 kilometers) of the Yadkin River.

Subreach 1 extends from the sewage treatment outfall at Winston-Salem to Cooper Road (State secondary road 2995) where the Muddy Creek gaging station is located. Subreach 2 extends from Cooper Road to Hampton Road (State secondary road 1485). Subreach 3 extends from Hampton Road to U.S. Highway 64 where the Yadkin College gaging station is located. Subreach 4 extends from U.S. Highway 64 to Concord Church boating access area. Subreach 5 extends from the Concord Church boating access area to the water intakes for the city of Salisbury which are about 1,000 feet upstream from the confluence with the South Yadkin River. Subreach 6 extends from the city of Salisbury's water intakes to Interstate Highway 85 near Salisbury.

The entire reach lies in the northwestern and central parts of the Piedmont, and the area is either already heavily developed or rapidly developing. Major water and disposal systems withdrawing from or discharging to the reach are Winston-Salem, North Davidson Water, Inc., and Salisbury. According to Jackson (1972) the Winston-Salem system serves a population of 140,000; the North Davidson Water, Inc. serves a population of 19,200; and the Salisbury system serves a population of 33,500.

Topography and Channel Characteristics

Topography for areas draining into the study reach is characterized by rolling hills with moderate to steep land slopes. Land surface altitudes range from more than 3,000 feet (910 meters) in the headwaters of the Yadkin River to less than 630 feet (190 meters) above mean sea level in the vicinity of High Rock Lake.

The slope of the low-water channel decreases from about 6 feet per mile (1 meter per kilometer) for Salem Creek at the Winston-Salem sewage effluent outfall to less than about 2 feet per mile (0.4 meter per kilometer) in the lower part of the Yadkin River. The channel width at median discharge ranges

Table 1.--Data for dye sampling points and stream-gaging stations used for the study

Location	Miles[1] below Winston-Salem sewage effluent outfall	Approximate drainage area in square miles[2]	Remarks
Salem Creek at Winston-Salem's Archie Elledge Sewage Treatment Plant outfall	0	65	Beginning of subreach 1.
Muddy Creek at Cooper Road (State secondary road 2995)	3.1	178	Stream-gaging station (USGS no. 02-1158.60) is located here. Record began July 1964. End of subreach 1.
Muddy Creek at Hampton Road (State secondary road 1485)	9.0	258	End of subreach 2.
Yadkin River at U.S. Highway 64	18.1	2,280	Stream-gaging station (USGS no. 02-1165.00) is located here, Record began July 1928. End of subreach 3.
Yadkin River at Concord Church boating access area	26.6	2,430	End of subreach 4.
Yadkin River at the City of Salisbury's water intakes	35.8	2,460	About 1,000 feet upstream from the confluence with the South Yadkin River. End of subreach 5.
Yadkin River at Interstate Highway 85	40.8	3,480	End of Subreach 6.

1/ Miles times 1.609 = kilometers.
2/ Square miles times 2.59 = square kilometers.

from about 35 feet (11 meters) for Salem Creek to about 250 feet (76 meters) for the lower part of the Yadkin River. At 5 percent duration (see fig. 2) of flow, the widths are about 60 and 350 feet (18 and 110 meters) respectively while at 90 percent duration the widths are about 20 and 160 feet (6 and 49 meters respectively. The mean depth of the channel at median discharge ranges from about 1.2 feet (0.37 meters) for Salem Creek to about 7 feet (2 meters) for the lower part of the Yadkin River. At 5 percent duration of flow, the mean depths are about 2 and 9 feet (0.6 and 2.7 meters) respectively, while at 90 percent duration the mean depths are about 0.8 and 4.5 feet (0.2 and 1.4 meters), respectively.

DETERMINATION OF TRAVELTIME

Traveltimes were measured by tracing the movement of Rhodamine dyes, stable fluorescent dyes that can be detected in small concentrations, making precise traveltime determinations possible. The techniques involved are described in detail by Kilpatrick, Martens, and Wilson (1970).

Dye Studies

Four separate dye studies were made during the July 1971 to March 1973 period in order to adequately define traveltimes for the desired range in flows. Traveltimes for Salem Creek and Muddy Creek are referenced to the discharge at the Muddy Creek gaging station, and those for the Yadkin River are referenced to the Yadkin College gaging station.

The range in discharge with respect to the daily values that occurred from 1963-71 at Yadkin College and from 1965-71 near Muddy Creek are shown on figure 2. The entire record at Yadkin College was not used due to the increased low flow resulting from the operation of W. Kerr Scott Reservoir, located about 90 miles or 140 km (kilometers) upstream, which began in August 1962. These flow-duration curves are cumulative frequency curves that show the percentage of time specified discharges were equaled or exceeded for the indicated period. A 90-percent duration indicates a low value, one that has been equaled or exceeded 90 percent of the time. Similarly a 10-percent discharge indicates a high value, one that has been equaled or exceeded only 10-percent of the time.

The discharges at the Muddy Creek gaging station during the dye studies were 125, 254, 318, and 349 ft^3/s (cubic feet per second), or 3.5, 7.2, 9.0, and 9.9 m^3/s (cubic meters per second), which correspond to flow durations of approximately 50, 12, 9, and 7 percent. The discharges at the Yadkin College gaging station during the studies were 2,290, 5,390, 7,150, and 8,650 ft^3/s,

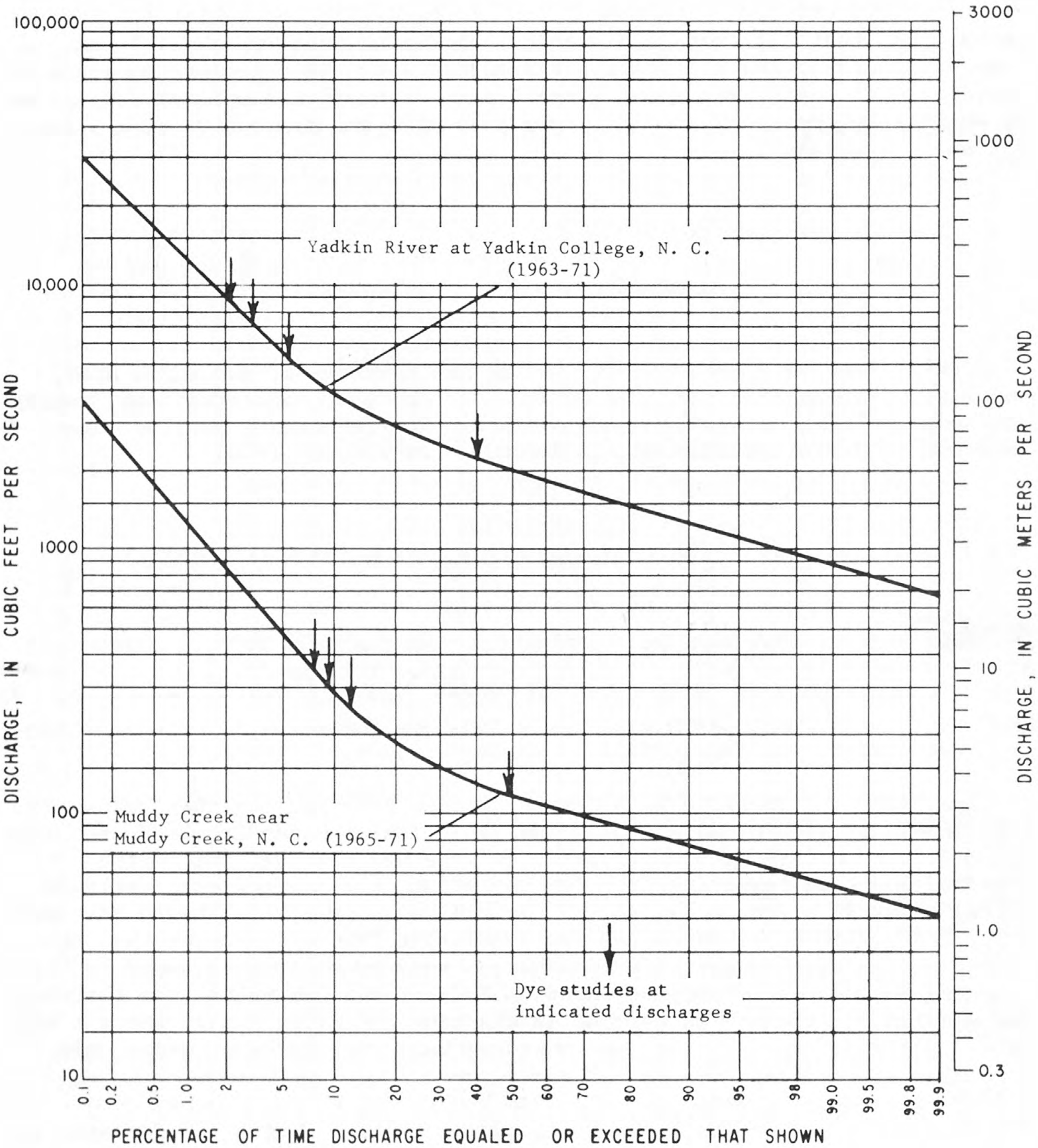

Figure 2.--Duration curves of daily mean flows for Yadkin River at Yadkin College and Muddy Creek near Muddy Creek.

or 64.9, 153, 202, and 245 m^3/s, which correspond to flow durations of approximately 40, 6, 3, and 2 percent. Although the flow during the dye studies generally always increased in the downstream direction, it was essentially steady to gradually varied and did not change appreciably with time.

Table 2 is a summary of the data collected during the four dye studies. Length of subreaches, discharges, traveltimes, and peak concentrations are listed for the six subreaches. Traveltimes are listed for the leading edge, peak, centroid, and the trailing edge. Peak concentrations include observed, those adjusted for dye losses, and unit values. The velocity of the centroid is also tabulated for each subreach for the four dye studies.

The observed peak concentrations defined by the observed time-concentration curves depend on the quantity of dye injected, the stream discharge, the longitudinal dispersion, and dye losses. Adjusting the observed peak concentrations for the dye losses gives concentrations equivalent to what the most conservative (no losses) tracer would produce. The adjusted peak concentration at a sampling site is equal to the observed concentration divided by the decimal fraction of the dye recovered. In addition, reporting peak concentrations in terms of unit values overcomes most of the differences caused by variations in the quantity of dye injected and the stream discharge. The unit concentration is the amount produced in 1 ft^3/s (0.02832 m^3/s) of flow due to the injection of 1 pound of a conservative solute. Longitudinal dispersion and unit-peak concentrations will be discussed in greater detail later.

Time-concentration curves for the sampling sites are shown on figure 3 for the March 13-14, 1973 dye study, when a slug of 150 pounds or 68 kg (kilograms) of dye was injected at the Archie Elledge Sewage Treatment Plant outfall on Salem Creek. The discharge at the Muddy Creek gaging station was 349 ft^3/s (9.9 m^3/s), and the discharge at the Yadkin College gaging station was 5,390 ft^3/s (153 m^3/s). Note the amount of dye lost by various physical, chemical, and biological processes as the dye cloud moved downstream. Only 69 percent of the injected dye was recovered at the most downstream sampling location. Although the logarithmic scale distorts the curves, one can see the increase for the time base and reduction in peak concentrations as the dye moves donwstream. This spreading out effect is caused by longitudinal dispersion. The peak concentration at the first sampling location was 540 $\mu g/l$ (micrograms per liter) whereas the peak concentration at the most downstream sampling point was 3.5 $\mu g/l$. This reduction of more than 100 times represents the general change in magnitude of peak concentrations for any soluble material for one set of flow conditions. A pollutant introduced at the same location in the same quantity for the same set of flow conditions would behave similarly. Any difference would depend mainly upon the degradability of the pollutant.

Table 2.--Summary of data collected for the four dye studies

			Travel time (hours)					Peak concentrations at lower end of subreach		
Subreach number	Length of subreach (miles)1/	Discharge at lower end of subreach (cubic feet per second)2/	Leading edge	Peak	Centroid	Trailing edge	Velocity of Centroid (feet per second)3/	Observed (μg/l)	Adjusted for dye loss (μg/l)	Unit concentration $\frac{\mu g/l \times ft^3/s}{pounds}$
Dye study of July 14-16, 1971										
1	3.1	125	2.8	3.5	3.63	4.5	1.25	272	371	5,440
2	5.9	165	6.2	7.3	7.37	8.5	1.17	90.0	124	2,400
3	9.1	2,290	7.6	8.7	9.02	11.3	1.48	32.0	33.6	2,430
4	8.5	2,450	5.8	6.8	6.98	7.7	2.08	17.2	19.1	1,470
5	9.2	2,480	6.3	7.0	7.20	8.8	1.64	11.7	13.1	1,020
6	5.0	3,000	7.6	8.0	9.40	10.7	0.78	8.70	11.1	1,050
Dye study of October 27-28, 1971										
1	3.1	318	2.7	3.3	3.33	4.1	1.36	51.0	51.4	6,230
2	5.9	430	5.1	5.4	5.57	6.4	1.55	17.5	19.8	3,250
3	9.1	7,150	4.9	6.0	6.13	7.8	2.17	10.0	10.3	3,000
4	8.5	7,600	4.6	4.7	4.77	5.2	2.61	5.80	7.70	2,430
5	9.2	7,700	-	4.8	4.90	6.5	2.75	3.00	6.10	1,930
6	5.0	Only limited data obtained for subreach 6								
Dye study of July 26-27, 1972										
1	3.1	254	2.5	3.8	3.88	4.9	1.17	565	576	4,830
2	5.9	310	6.0	6.6	6.82	8.0	1.27	196	205	2,100
3	9.1	8,650	-	-	-	-	-	-	-	-
4	8.5	No data obtained for subreach 4								
5	9.2	8,000	-	-	-	-	-	380	4.60	1,200
6	5.0	8,500	3.9	4.3	4.50	5.5	1.63	320	3.80	1,100
Dye study of March 13-14, 1973										
1	3.1	349	2.7	3.1	3.25	3.9	1.39	550	582	6,770
2	5.9	483	3.9	4.6	4.67	5.2	1.85	212	225	3,620
3	9.1	5,390	5.7	6.2	6.33	7.3	2.11	11.2	12.2	2,190
4	8.5	5,740	4.5	4.6	4.67	4.9	2.67	8.40	10.2	1,950
5	9.2	5,820	5.0	5.1	5.15	6.0	2.62	6.72	9.20	1,780
6	5.0	8,000	4.3	4.9	5.16	6.1	1.42	3.50	5.10	1,360

1/ Miles times 1.609 = kilometers.
2/ Cubic feet per second times 0.02832 = cubic meters per second.
3/ Feet per second times 0.3048 = meters per second.

Note: Rhodamine WT, 5 percent solution, was used for subreaches 1-3 during the July 1971 study, and Rhodamine BA, 40 percent solution, was used for subreaches 4-6. During all subsequent studies Rhodamine WT, 20 percent solution, was used.

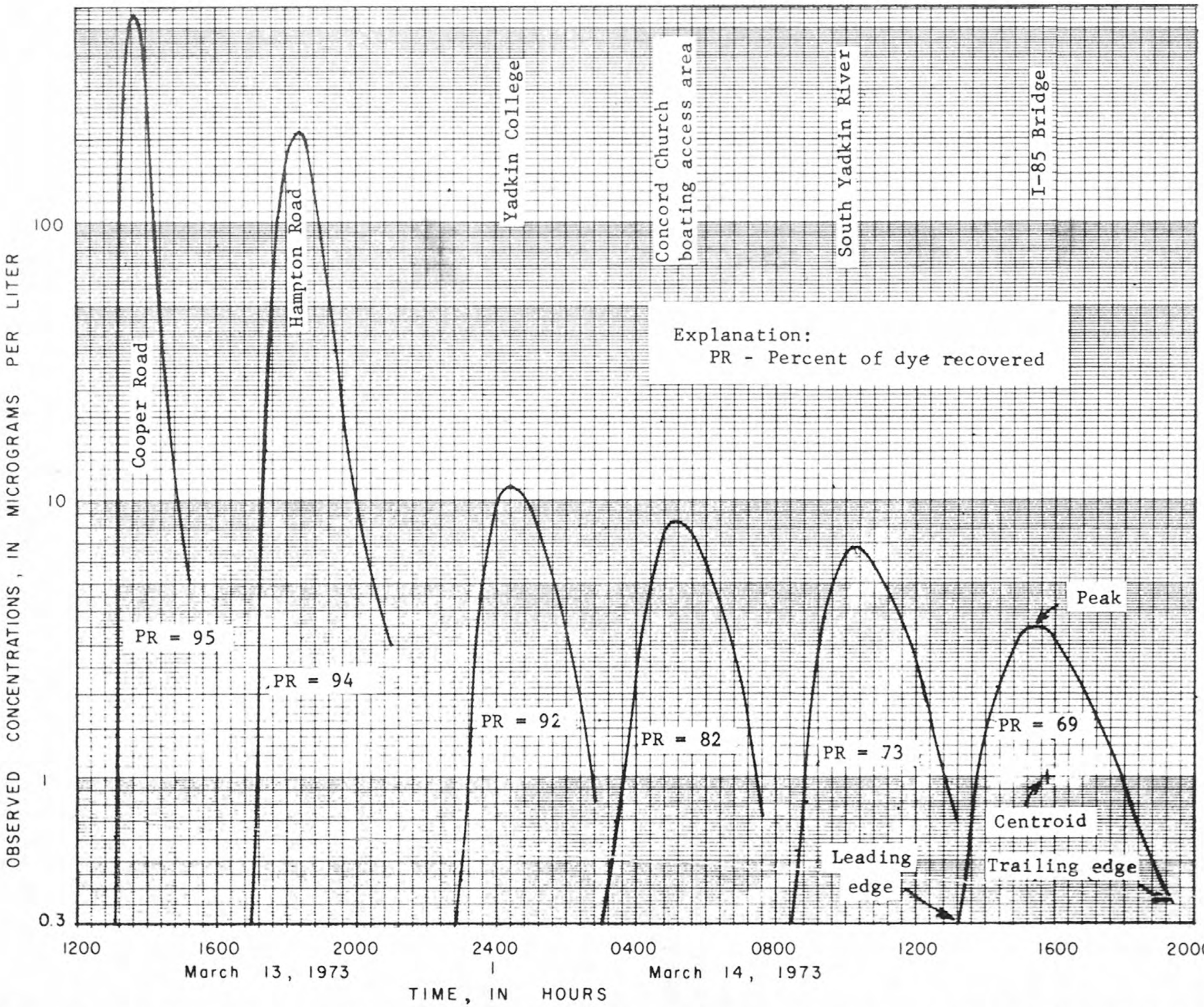

Figure 3.--Observed time-concentration curves for the six sampling sites for the March 1973 dye study showing longitudinal dispersion and travel-time characteristics.

Predictions of Traveltime

Traveltimes measured during the four dye studies can be used to predict the arrival time of water-soluble materials at points along a reach during reasonably steady flow. Graphs of traveltime versus stream discharge are usually shown on logarithmic graph paper. Measured traveltimes plotted against discharge are shown for the six subreaches in figures 4-9. The graphs can be used to estimate traveltime of the leading edge, peak, centroid, and the trailing edge of a soluble substance. Traveltimes for subreaches 1 and 2 are referenced to the discharge at the Muddy Creek gage while the traveltimes for subreaches 3-6 are referenced to the Yadkin River gaging station at Yadkin College. The curves are reasonably well defined for flows from about 5 to 90 percent duration.

One reason for scatter of data for all four curves for subreaches 1 and 2 is the complex situation that exists when the Yadkin River is abnormally high when compared to Muddy Creek, which results in backwater for a considerable distance up Muddy Creek, thus increasing traveltime for Muddy Creek. Another reason for some scatter of data is the Muddy Creek gaging station isn't always a perfect index of the discharge at all locations. Flows from Salem Creek, sewage effluent from the treatment plant, and South Fork Muddy Creek are not always representative. There are many other reasons that can contribute to data scatter, but they are too numerous to discuss. Although the data for subreaches 1 and 2 show considerable scatter about the curves, the relations should provide estimates of traveltime that are accurate to within half an hour. Also, note the abnormal shapes of the curves for subreach 6, which are affected by backwater from High Rock Lake during low discharges on the Yadkin River. Natural flow characteristics exist for subreach 6 when the discharge at Yadkin College is above about 4,000 ft^3/s (110 m^3/s) and High Rock Lake is at normal elevation. Caution should be used when estimating traveltimes for subreach 6 when the discharge is below about 4,000 ft^3/s (110 m^3/s).

One can predict total traveltime for the entire study reach or parts of the study reach by entering figures 4-9 with discharges for Muddy Creek at Muddy Creek (80 to 500 ft^3/s or 2.3 to 14.2 m^3/s) and the Yadkin River at Yadkin College (1,500 to 10,000 ft^3/s or 42.5 to 283 m^3/s) and simply accumulating the traveltimes obtained for the respective subreaches used.

Figure 10 gives two examples of total traveltime accumulated by using figures 4-9 for two hypothetical situations. The lower (dashed) curves on figure 10 represent conditions when the discharge at the Muddy Creek gaging station is 400 ft^3/s (11.3 m^3/s) while the discharge at the Yadkin College gaging station is 8,000 ft^3/s (227 m^3/s). The upper (solid) curves on figure 10 represent conditions when the discharge at the Muddy Creek gaging station is 100 ft^3/s (2.83 m^3/s), and the discharge at the Yadkin College gaging

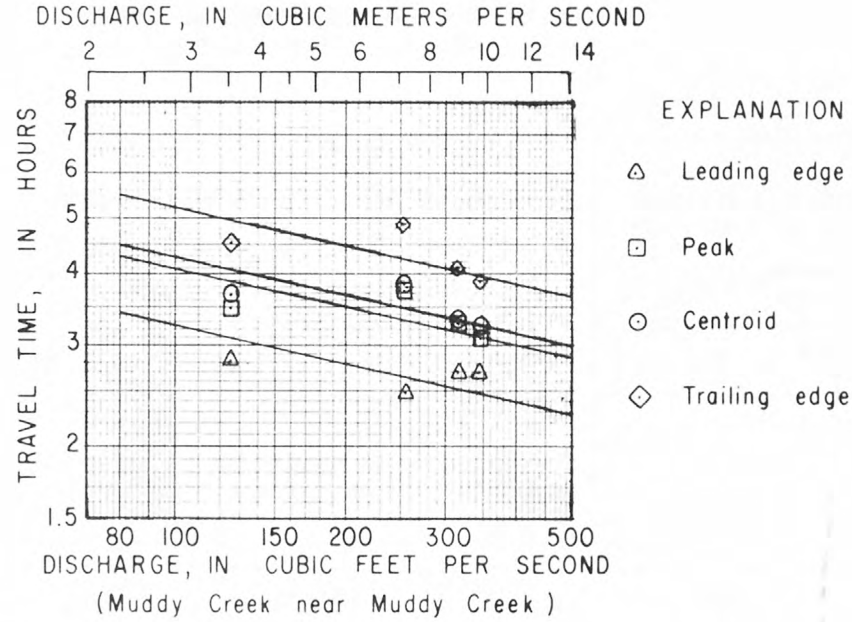

Figure 4.--Relation of discharge at the Muddy Creek gaging station to traveltime of leading edge, peak, centroid, and trailing edge: Winston-Salem sewage effluent outfall to Cooper Road (Subreach 1).

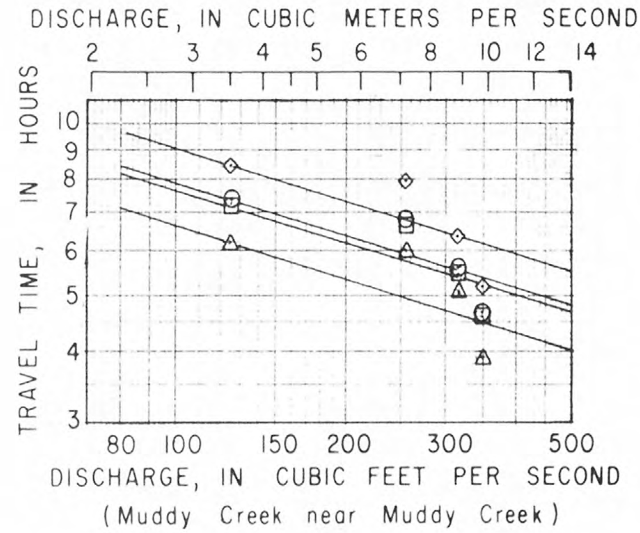

Figure 5.--Relation of discharge at the Muddy Creek gaging station to traveltime of leading edge, peak, centroid, and trailing edge: Cooper Road to Hampton Road (Subreach 2).

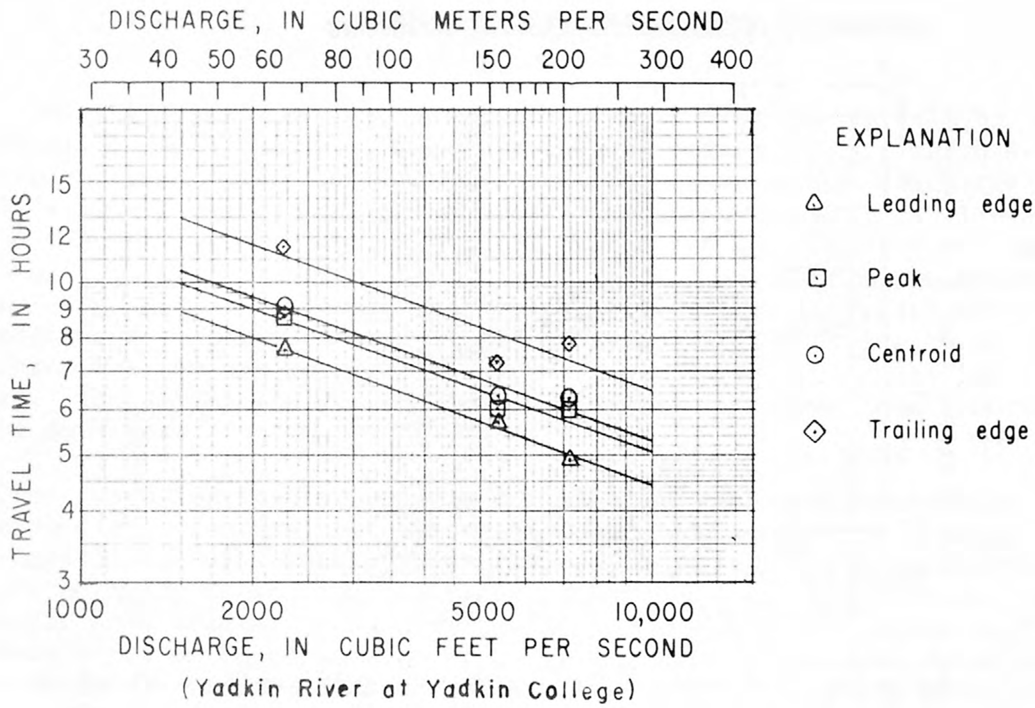

Figure 6.--Relation of discharge at the Yadkin College gaging station to traveltime of leading edge, peak, centroid, and trailing edge: Hampton Road to Yadkin College (Subreach 3).

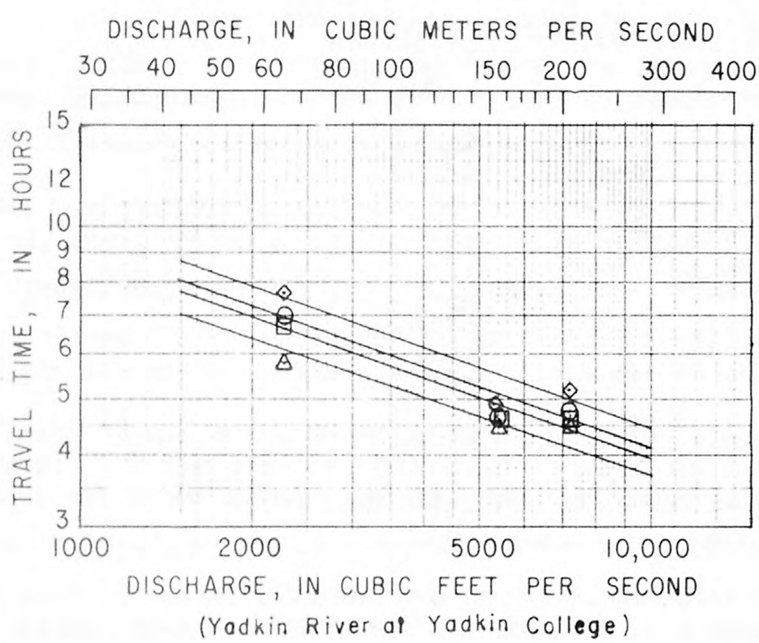

Figure 7.--Relation of discharge at the Yadkin College gaging station to traveltime of leading edge, peak, centroid, and trailing edge: Yadkin College to Concord Church boating access area (Subreach 4).

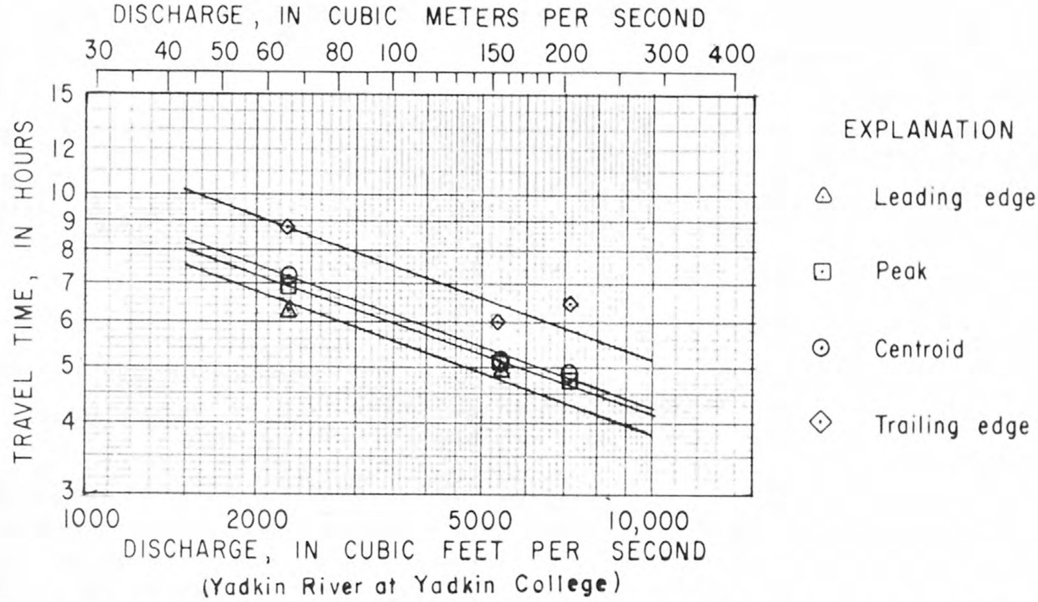

Figure 8.--Relation of discharge at the Yadkin College gaging station to traveltime of leading edge, peak, centroid, and trailing edge: Concord Church boating access area to confluence with South Yadkin River (Subreach 5).

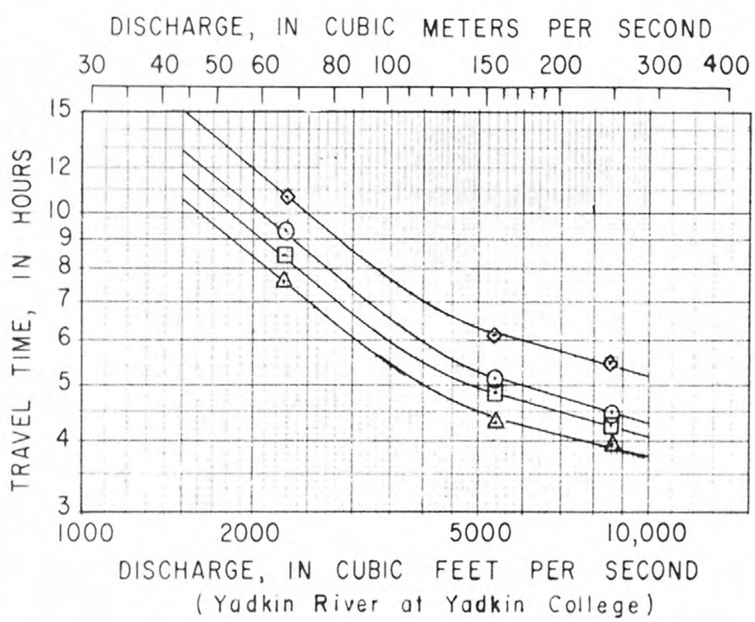

Figure 9.--Relation of discharge at the Yadkin College gaging station to traveltime of leading edge, peak, centroid, and trailing edge: Confluence with South Yadkin River to I-85 bridge (Subreach 6).

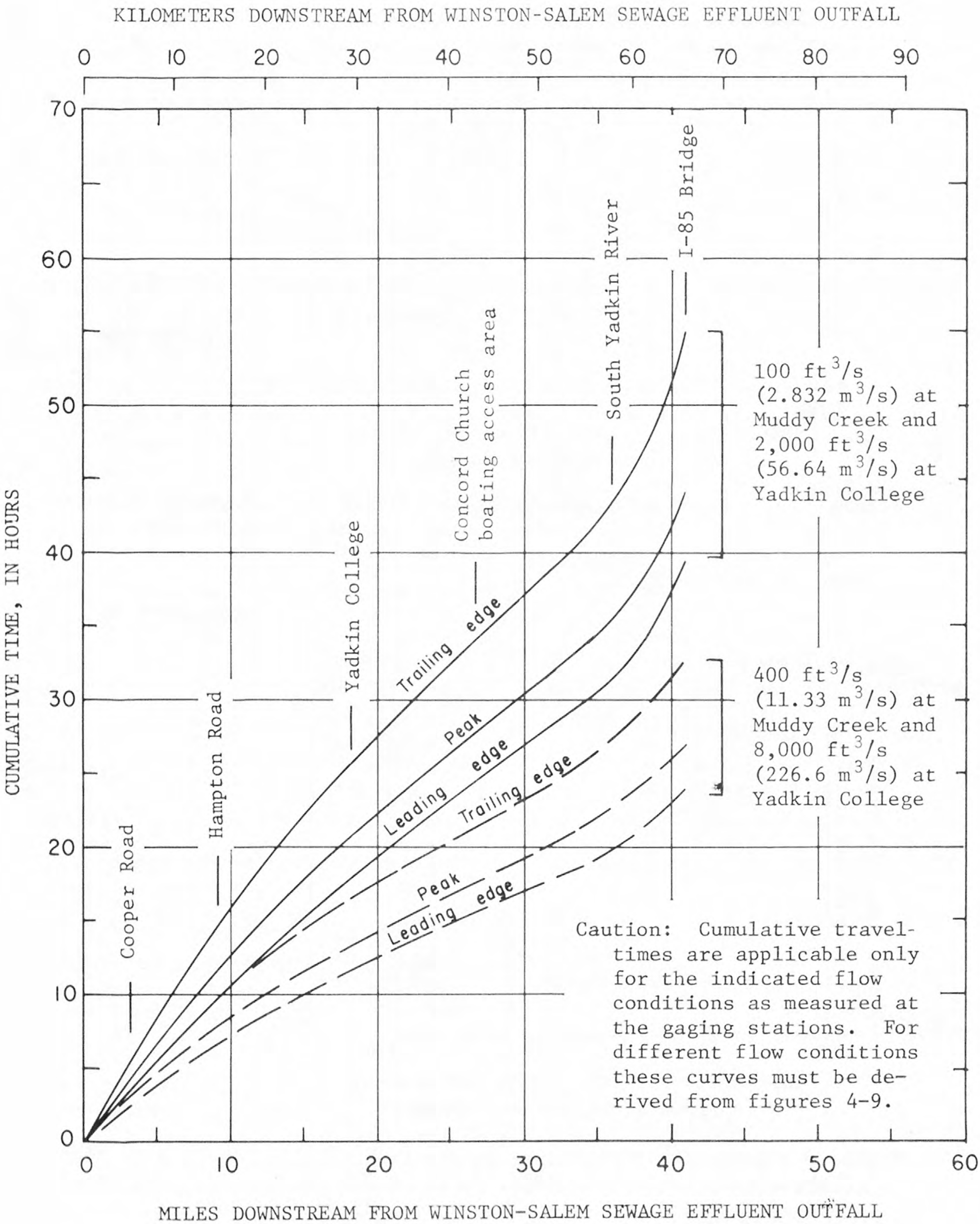

Figure 10.--Cumulative traveltime for waterborne materials: Salem Creek at Winston-Salem to Yadkin River near Salisbury.

station is 2,000 ft^3/s (56.6 m^3/s). The cumulative traveltimes are for a conservative soluble substance dumped at the Winston-Salem sewage treatment plant outfall, although traveltime can be accumulated for any part of the study reach in question. Although the traveltime graphs presented in figures 4-9 were developed from data obtained when the dye was injected near the upper part of the study reach, the nonlinearity of the longitudinal dispersion does not decrease the accuracy when traveltimes are accumulated for conditions where soluble substances are injected at points farther downstream.

DISPERSION CHARACTERISTICS

In addition to predicting when released material will arrive at downstream locations, it is equally important to know how long it will take the material to pass a downstream point and what the maximum concentrations are likely to be. Both of these factors are affected by the dispersion or mixing characteristics of the streams.

Longitudinal Dispersion

Passage time.--The passage time (from leading to trailing edge), one measure of longitudinal dispersion, of a water-soluble substance is inversely related to the discharge because as the discharge increases, velocity increases. As velocity increases, passage time decreases at any downstream location because the soluble substance has had less time to disperse. Passage time varies, especially for long reaches of a stream, but the approximate time can be predicted by using the difference between the arrival time of the leading edge and the time the trailing edge passes. For example, using figure 10 the passage time, in the Yadkin River at its confluence with the South Yadkin River, for a soluble substance released at the Winston-Salem sewage treatment plant for a discharge of 400 ft^3/s (11.3 m^3/s) at the Muddy Creek gaging station and 8,000 ft^3/s (227 m^3/s) at the Yadkin College gaging station would be approximately 7 hours. The leading edge would arrive in about 20 hours, and the trailing edge (at 10 percent of the peak concentration) would pass in about 27 hours, hence the 7 hours passage time.

Maximum-probable concentration.--Another measure of longitudinal dispersion is maximum-probable concentration, which is more useful when reported in terms of unit concentration. The unit concentration provides a technique for determining the maximum-probable concentration at any location downstream resulting from a dye injection, waste spill, or any substantial release of polluted water. The unit concentration is the peak concentration resulting from 1 pound (.454 kg) of a conservative soluble substance in 1 ft^3/s (0.02832 m^3/s) of water.

$$\text{Unit concentration} \left(\frac{\mu g/l \times ft^3/s}{\text{pounds}} \right) = \frac{\text{Peak concentration } (\mu g/l) \times \text{discharge } (ft^3/s)}{\text{Weight of injected solute (pounds)}}$$

The data in table 2 for the four dye studies were used to develop a relationship to determine the maximum-probable or extreme unit-peak concentration. (See fig. 11.) This relationship can be used to predict the maximum probable concentration at any location downstream resulting from injecting a conservative soluble substance.

An example is given below to show how the extreme unit-peak curve can be used to predict the maximum probable concentration for a conservative soluble substance:

1. Assume that 500 pounds of a nondegradable soluble substance is discharged instantaneously at the Winston-Salem sewage treatment plant outfall.

2. Assume the discharge at the Muddy Creek gaging station is 400 ft^3/s and the discharge at the Yadkin College gaging station is 8,000 ft^3/s.

3. Determine the maximum-probable concentration expected at the confluence of the Yadkin River with the South Yadkin River.

4. Figure 10 shows the traveltime of the peak as 22.5 hours. Note: Figures 4-9 can be used to cumulate traveltimes of peaks for other discharges.

5. Figure 11 gives a unit-peak concentration of 1,750 $\frac{\mu g/l \times ft^3/s}{\text{pounds}}$ for the cumulative traveltime of 22.5 hours.

6. Convert the unit-peak concentration to the maximum-probable concentration by using the following formula:

$$\text{Maximum probable concentration } (\mu g/l) = \text{unit-peak concentration} \left(\frac{\mu g/l \times ft^3/s}{\text{pounds}} \right) \times \frac{\text{Weight of soluble substance (pounds)}}{\text{discharge } (ft^3/s) \text{ at confluence}}$$

Unit-peak concentration = 1,750 $\frac{\mu g/l \times ft^3/s}{\text{pounds}}$

Weight of soluble substance = 500 pounds

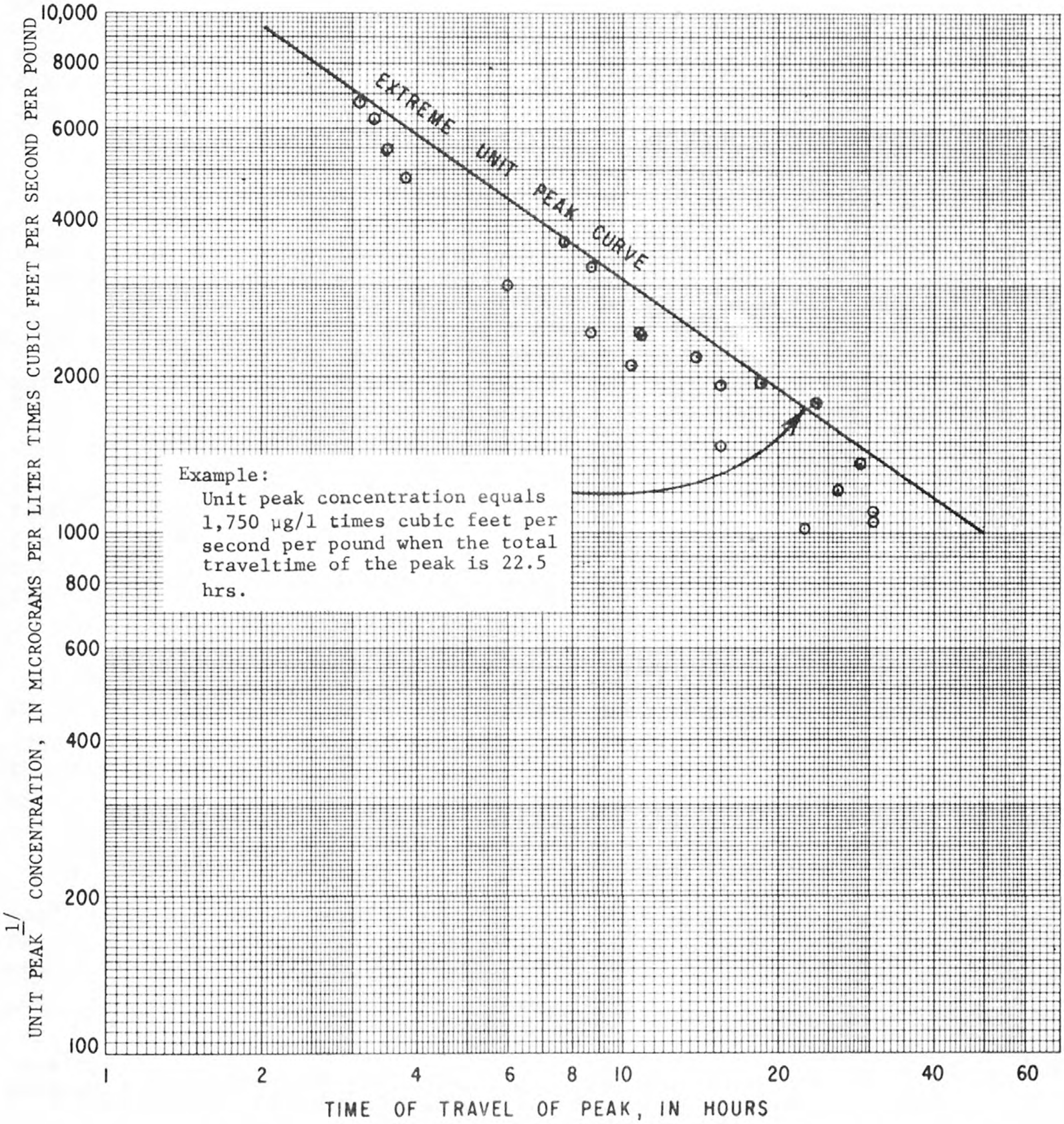

Figure 11.--Unit-peak concentration curve for entire study reach.

The discharge at the confluence of the Yadkin River with the South Yadkin River can be approximated by multiplying the 8,000 ft^3/s at the Yadkin College gaging station by the drainage area ratio.

$$\text{Discharge} = 8000\ ft^3/s \times \frac{2460\ (\text{drainage area at site})}{2280\ (\text{drainage area at Yadkin College})} = 8630\ ft^3/s$$

$$\text{Maximum probable concentration} = \frac{1{,}750 \times 500}{8{,}630} = 100\ \mu g/l$$

Caution should be used when the soluble substance enters the stream at any manner other than as a slug. A continuous injection of a conservative soluble substance could result in a much higher peak concentration at a point downstream. For example, the maximum concentration at the confluence with the South Yadkin River for a constant injection of 500 pounds per hour for the same conditions given above can be approximated as follows:

$$\text{Maximum concentration at confluence} = \frac{\text{Concentration of injected substance } (\mu g/l) \times \text{rate of flow of injected solution } (ft^3/s)}{\text{Discharge at confluence } (ft^3/s)}$$

Assume rate of flow of injected soluble substance equals 10 ft^3/s

Then the concentration of injected soluble substance equals:

$$\frac{500\ \text{pounds/hour} \times 4.54 \times 10^8\ \text{micrograms/pounds} \times \frac{1}{3600} \times \frac{hr}{sec}}{10\ ft^3/s \times 28.3\ \text{liters}/ft^3}$$

$$= 500 \times 4.54 \times 10^8 \times \frac{1}{3600} \times \frac{1}{10} \times \frac{1}{28.3}$$

$$= 2.2 \times 10^5\ \mu g/l$$

Therefore the maximum concentration would be:

$$\frac{10 \times 2.2 \times 10^5}{8630} = 260\ \mu g/l$$

Lateral Dispersion

Upon entering a stream, a soluble substance immediately begins to disperse not only longitudinally but also laterally. Complete lateral mixing may not take place under certain flow conditions for a considerable distance below the point of injection. Also poor lateral mixing may cause waterborne materials entering into a larger stream from a tributary to remain concentrated along one bank of the larger stream for a considerable distance downstream. Such is the case when water from Muddy Creek enters the Yadkin River.

The degree of lateral mixing was measured in detail at Yadkin College (end of subreach 3) and at the Concord Church boating access area (end of subreach 4) for different flow conditions. Figure 12 shows the variations in peak concentrations observed across the channel at Yadkin College when the discharges were 2,290 and 5,390 ft^3/s (64.9 and 153 m^3/s). No significant variations in peak concentrations across the channel were measured at the Concord Church boating access area for the flow conditions experienced during the four dye studies.

Lateral mixing depends upon width and velocity variations. The degree of lateral mixing increases with velocity and decreases with width. Velocity increases in the Yadkin River are more pronounced than width increases as the discharge becomes larger. Therefore, complete lateral mixing occurs within a shorter distance when the discharge in the Yadkin River is high. Lateral mixing is not complete for water entering the Yadkin River from Muddy Creek for discharges below about 3,000 ft^3/s (85 m^3/s) until the water reaches a point beyond the end of subreach 3 (8.2 miles or 13 km below confluence of Muddy Creek and the Yadkin River). For discharges above about 5,000 ft^3/s (140 m^3/s) lateral mixing is complete within a few miles below the confluence. For all discharges experienced during the dye studies lateral mixing was complete by the time the water reached the end of subreach 4 (16.7 miles or 26.9 km below confluence).

Waterborne material introduced into the Yadkin River by Muddy Creek generally remains concentrated along the left bank of the river during low-flow periods. Shoffner and Wilder (1973) observed this phenomenon by measuring DO concentrations across the section near the gage at the Yadkin College bridge, when the discharge was 2,520 ft^3/s (71.4 m^3/s). They said, "A continuous DO recorder showed that, even 10 miles (16 km) downstream from its point of entry into the river, the polluted slug was still sharply defined, and hand samples indicated it had not mixed laterally across the river."

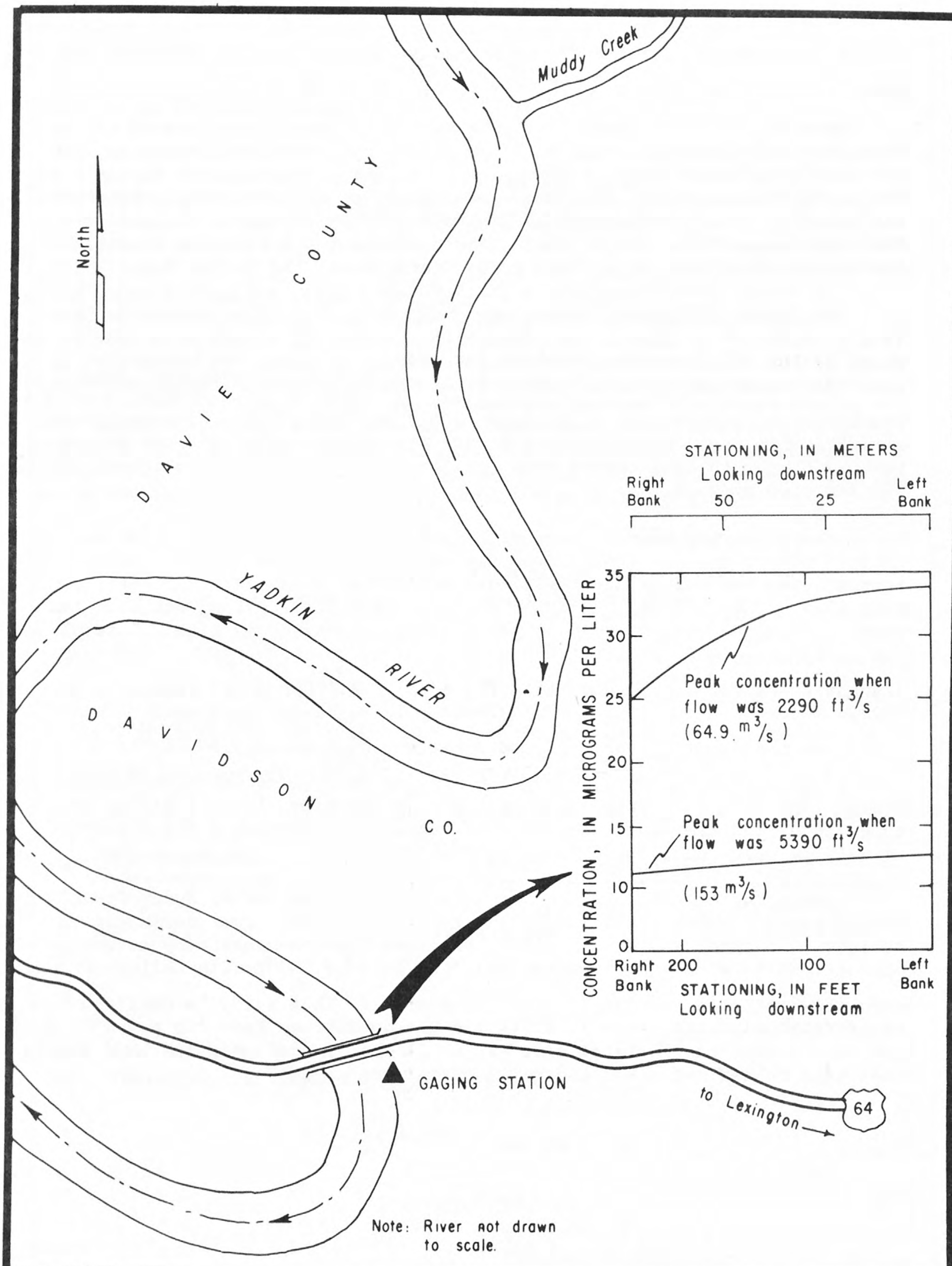

Figure 12.--Lateral dispersion for polluted water entering on the left side from Muddy Creek.

SUMMARY

Data collected during the four dye studies were used to develop relationships that can be used to predict traveltime to any location within the study reach. The traveltime can be computed by summing up the incremental traveltimes obtained for each subreach. One only needs the current discharges at the gaging stations Muddy Creek near Muddy Creek and Yadkin River at Yadkin College and the location where the soluble substance was injected to compute the cumulative traveltime of the leading edge, peak, centroid, and the trailing edge at any location downstream. The traveltime relationships are defined for discharges ranging from about 80 to 500 ft^3/s (2 to 14 m^3/s) for the Muddy Creek gaging station and from about 1,500 to 10,000 ft^3/s (42 to 280 m^3/s) for the Yadkin College gaging station. The incremental traveltimes obtained from the relationships for the subreaches are considered accurate to within half an hour.

Examples computed using the traveltime relationships show that the passage time, from arrival of leading edge to trailing edge, is significantly higher for low-flow periods. The passage time when a soluble substance is released at the Winston-Salem treatment plant is 7 hours at the City of Salisbury's water intakes when the discharges are 400 ft^3/s (11.3 m^3/s) at the Muddy Creek gaging station and 8,000 ft^3/s (227 m^3/s) at the Yadkin College gaging station. In contrast, the passage time is 12 hours when the discharges at the two gaging stations are 100 and 2,000 ft^3/s (2.8 and 56.6 m^3/s) respectively.

A method is presented that can be used to predict the maximum-probable peak concentration of a conservative-soluble substance at any location downstream of a slug injection. The extreme-unit peak concentration is obtained by entering a graph with the total traveltime from the injection location estimated from the traveltime relations. The maximum-probable peak concentration is the product of the number of pounds of soluble substance injected and the extreme-unit peak concentration divided by the discharge at the location in question. The peak concentration obtained is for a conservative or nondegradable substance and actual results may be lower if considerable degradation takes place in the channel.

Complete lateral mixing of the water entering the Yadkin River from Muddy Creek does not occur until more than about 10 miles (16 km) below the confluence during low-flow periods. Higher concentrations are measured on the left bank as far downstream as Yadkin College under these conditions. Complete lateral mixing takes place much more rapidly during high-flow periods.

SELECTED REFERENCES

Cobb, E. D., and Bailey, J. F., 1965, Measurement of discharge by dye dilution methods: U.S. Geol. Survey Tech. Water Res. Inv., Book 1, chap. 14, 27 p.

Fischer, H. B., 1968, Dispersion predictions in natural streams: Am. Soc. Civil Engineers Proc.; Jour. Sanitary Engr. Div. V. 5, p. 927-943.

Godfrey, R. G., and Frederick, B. J., 1963, Dispersion in natural streams: U.S. Geol. Survey open-file report, 75 p.

Harleman, D. R. F., Lee, Chok-Hung, and Hall, L. C., 1968, Numerical studies of unsteady dispersion in estuaries: Am. Soc. Civil Engineers Proc.; Jour. Sanitary Engr. Div. V. 5, p. 897-911.

Hubbard, E. F., and Stamper, W. G., 1972, Movement and dispersion of soluble pollutants in the Northeast Cape Fear estuary, North Carolina: U.S. Geol. Survey Water-Supply Paper 1873-E, 31 p.

Jackson, N. M., Jr., 1972, Public water supplies of North Carolina, Part 1, Northern Piedmont: North Carolina Dept. Natural and Economic Resources, 277 p., 4 figs.

Kilpatrick, F. A., Martens, L. A., and Wilson, J. F., 1970, Measurement of time of travel and dispersion by dye tracing: U.S. Geol. Survey Water Res. Inv., Book 3, chap A9, 25 p.

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

Shoffner, J. E., and Wilder, H. B., 1973, Dissolved oxygen variations in a large river: U.S. Geol. Survey Prof. Paper 850-A.

Taylor, K. R., 1970, Traveltime and concentration attenuation of a soluble dye in the Monocacy River, Maryland: Maryland State Geol. Survey Circ. 9, 23 p.

Thackston, E. L., Schnelle, K. B., Jr., 1968, Prediction of effect of dead zones on mixing in open channel flow: Chattanooga Tennessee Meeting on Envir. Engr., Am. Soc. Civil Engineers Meeting Preprint 686, 21 p.

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