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The findings of a problem-oriented, river-system investigation of the water quality and streamflow characteristics of the Raritan River, N.J. are described. Information on streamflow duration, time-of-travel measurements, and analyses of chemical, biochemical and physical-water quality are summarized and used to define relations existing between water quality, streamflow, geology, and environmental development in the basin's hydrologic system.

Stream quality, particularly in the lower urban areas of the basin, is shown to be deteriorating with time at most of the sampling sites reported. For example, average dissolved-oxygen concentration is reported to be undersaturated at all sampling sites and is decreasing with time at most sites. Biochemical-oxygen demand is increasing at most sites, as are the dissolved-solids content.

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WATER QUALITY AND STREAMFLOW CHARACTERISTICS, RARITAN RIVER BASIN, NEW JERSEY

by Peter W. Anderson and Samuel D. Faust

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Water-Resources Investigations 14-74

Prepared in cooperation with the State of New Jersey, Department of Environmental Protection

June 1974

UNITED STATES DEPARTMENT OF THE INTERIOR

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The following factors may be used to convert the English units published herein to the International System of Units (SI).

Multiply English units	By	To obtain SI units
	Length	
inches (in)	2.54	centimeters (cm)
feet (ft)	30.48	centimeters (cm)
miles (mi)	1.609	kilometers (km)
	Area	
square miles (mi^2)	2.590	square kilometers (km^2)
	Flow	
cubic feet per second (ft^3/s)	.02832	cubic meters per second (m^3/s)
million gallons per day (mgd)	.04381	cubic meters per second (m^3/s)

WATER QUALITY AND STREAMFLOW CHARACTERISTICS, RARITAN RIVER BASIN, NEW JERSEY

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ABSTRACT

The findings of a problem-oriented river-system investigation of the stream-quality and streamflow characteristics of the Raritan River basin (1,105 square miles or 2,862 square kilometers drainage area) are described. The investigation covers mainly the period 1955-72.

Precipitation in the basin is classified as ample and averages 47 inches or 120 centimeters per year (3-5 inches or 8-12 centimeters per month). During the study period four general precipitation trends were noted: less than normal in 1955-61 and 1966-70; extreme drought in 1962-66; and above normal in 1971-72.

Analyses of streamflow measurements at eight gaging stations indicate a general trend toward lower flows during the study period, which is attributed to generally lower than normal precipitation. Highest flows were observed in 1958, concurrent with maximum annual precipitation; whereas lowest flows were observed in 1965 during extreme drought conditions.

Non-tidal streams in the basin are grouped into three general regions of similar chemical quality based upon predominant constituents and dissolved-solids concentration during low-flow conditions. The predominant cations in solution in all regions are calcium and magnesium (usually exceeding 60 percent of total cation content). In headwater streams of the North and South Branch Raritan Rivers, bicarbonate is the predominant anion; a combination of sulfate, chloride, and nitrate are the predominant anions in the other two regions. The dissolved-solids concentration of streams in areas little influenced by man's activities generally range from 40 to 200 mg/l. Those in areas influenced by man often range much higher sometimes exceeding 800 mg/l. Suspended-sediment yields in the basin range from 25 to 500 tons per square mile annually.

The water quality of the Raritan River and most tributaries above Manville (784 square miles or 2,030 square kilometers drainage area) generally is good for most industrial, domestic, and recreational uses, although pollution has been reported locally in some areas. A comparison of chemical analyses of water collected at several sampling sites in the 1920's with more recent data, however, indicate that there has been a significant increase in sulfate, chloride, and nitrate ions transported per unit of streamflow. These increases reflect increased waste-water discharges and nutrients in agricultural runoff in the upper basin.

Trends in the dissolved-solids and dissolved-oxygen concentration of water in the Raritan and Millstone Rivers above their confluence at Manville are described. The dissolved solids of the Millstone River are shown to increase, particularly at low streamflows. For example, at a flow of 100 cubic feet per second (2.83 cubic meters per second) this river transported 13 percent more dissolved solids in 1969-70 than it did in 1957-58. A similar trend, however, was not apparent on the Raritan River. This phenomenon is attributed to dilution provided since 1964 by upstream reservoir releases during low flows.

With the exception of low-flow periods on the Raritan River, dissolved-oxygen concentrations showed little or no significant time trends at Manville on either the Raritan or Millstone River. An improvement in dissolved-oxygen content at flows lower than 100 cubic feet per second (2.83 cubic meters per second) is observed with time on the Raritan River. This improvement is attributed to generally better quality water and dilution of nonconservative pollutants by upstream reservoir releases during low flows.

The Raritan River between Manville and Perth Amboy flows through a large urban and industrial complex. Much of this reach is tidal. Detrimental activities of man are reflected in higher concentrations of most constituents below Manville than those observed upstream. For example, between Manville and the head of tide near South Bound Brook, the maximum concentration of dissolved solids observed during the study period increased from 464 to 1,520 mg/l; orthophosphates from 0.93 to 2.3 mg/l; phenolic materials from 22 to 312 ug/l; and coliform bacteria from 13,300 to 100,000 colonies per 100 milliliters. A general deterioration in water quality with time in the river below Manville is demonstrated through comparisons of dissolved-oxygen and biochemical-oxygen demand data collected between the late 1920's and early 1970's.

Several time-of-travel measurements within the basin are reported. These data provide reasonable estimates of the time required for soluble contaminants to pass through particular parts of the river system. For example, the peak concentration of a contaminant injected into the river system at Clinton at a flow of 100 cubic feet per second (2.83 cubic meters per second) would be expected to travel to the head of tide near South Bound Brook, about 34 miles (55 kilometers), in about 70 hours; but at a flow of 50 cubic feet per second (1.42 cubic meters per second) the traveltime would increase to about 125 hours.

INTRODUCTION

The State of New Jersey, through its Department of Environmental Protection, and the U.S. Geological Survey, began a cooperative program in 1962 to appraise the quality of the State's surface waters. Representing New Jersey in this program are the State Divisions of Water Resources and of Fish, Game, and Shellfisheries. The initial effort in this program was a reconnaissance (Anderson and George, 1966) of the water quality of the State's stream systems. This reconnaissance was used by the cooperating agencies in improving the design of sample collection and in determining the need for further work on specific problem-oriented river systems. Results of the cooperative stream-quality sampling network, which followed the reconnaissance, have been reported by the U.S. Geological Survey since 1964 in an annual basic-data release titled "Water Resources Data for New Jersey, Part 2. Water Quality Records". The Passaic River basin was selected as the initial river-system to be investigated. Results of this effort were reported by Anderson and Faust (1973).

The Raritan River basin was selected in 1965 to be the second river system for investigation. The project consisted of: (1) collecting data to define relations between stream quality and streamflow, precipitation, geology, and urban and industrial development in the river system; (2) appraising the existence, nature, and magnitude of long-term trends in stream quality and streamflow; and (3) providing information on traveltimes required for soluble contaminants to pass through parts of the river system.

This report describes the results of this investigation, and summarizes the data collected. Also included are the summarized results of three previous studies of stream sedimentation, which were conducted in cooperation with the State Departments of Agriculture and of Environmental Protection, and the U.S. Army, Corps of Engineers.

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Acknowledgment is made also to Messrs. Jerry Caden and Al Lewis of the Elizabethtown Water Company, Mr. C. N. Durfor of the U.S. Environmental Protection Agency, and Mr. Richard Delgado of the State Division of Water Resources for their valued assistance in providing much of the basic stream-quality data upon which this report is based. The authors are exceedingly grateful also to Mr. A. Bruce Pyle of the State Division of Fish, Game, and Shellfisheries for the kind loan of analytical equipment necessary for the time-of-travel measurements; Brig. Gen. (ret'd.) William Whipple, Jr., director of the New Jersey Water Resources Research Institute, Rutgers University, for financial support as well as manpower for conducting several of these measurements; and several members of the staffs of the State Division of Water Resources and Water Resources Research Institute, who assisted in the collection of samples during these measurements.

THE BASIN

The Raritan River in central New Jersey (fig. 1) drains approximately 1,105 mi^2 (2,862 km^2), the second largest basin within the

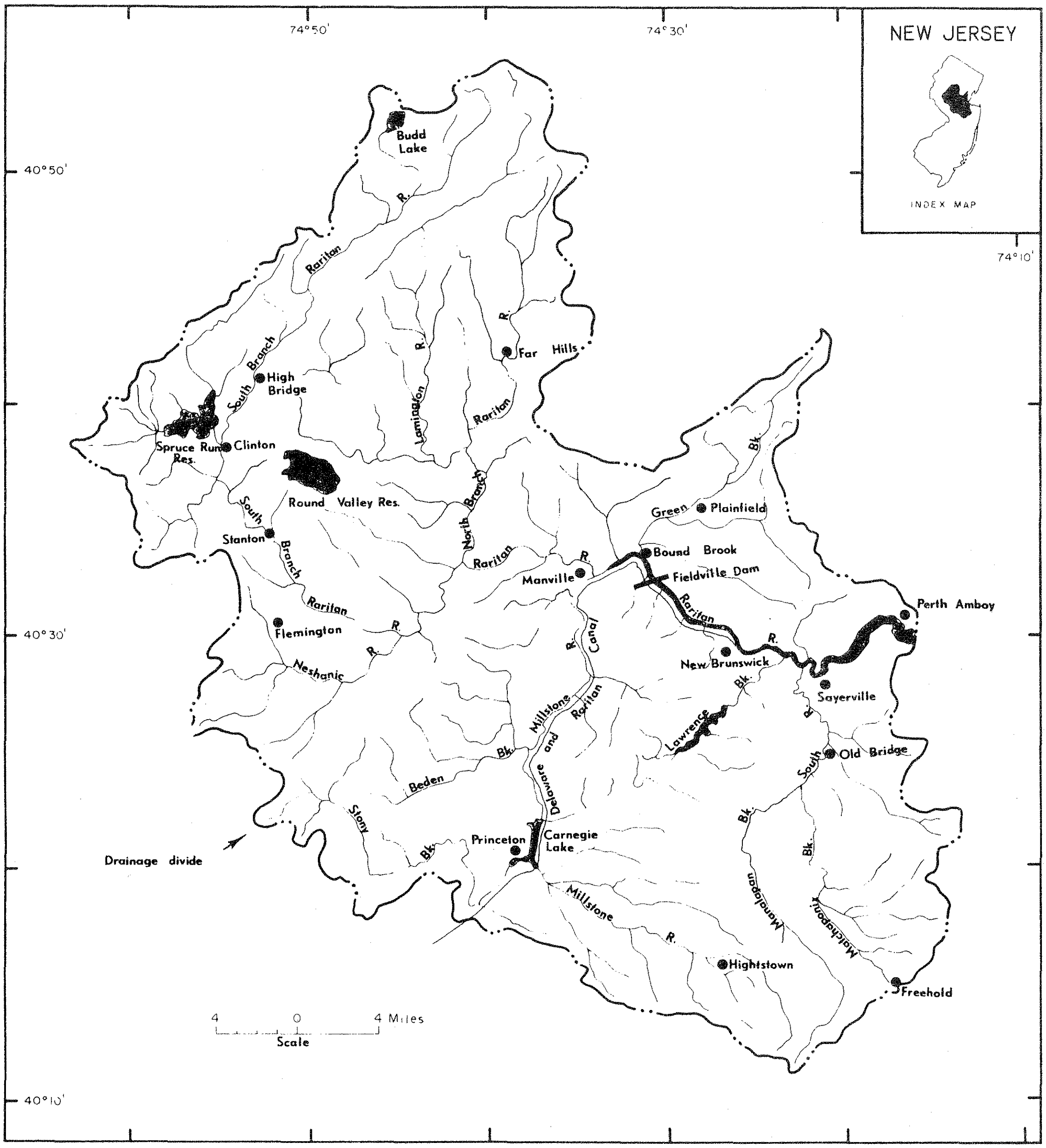

Figure 1.--Map of the Raritan River basin.

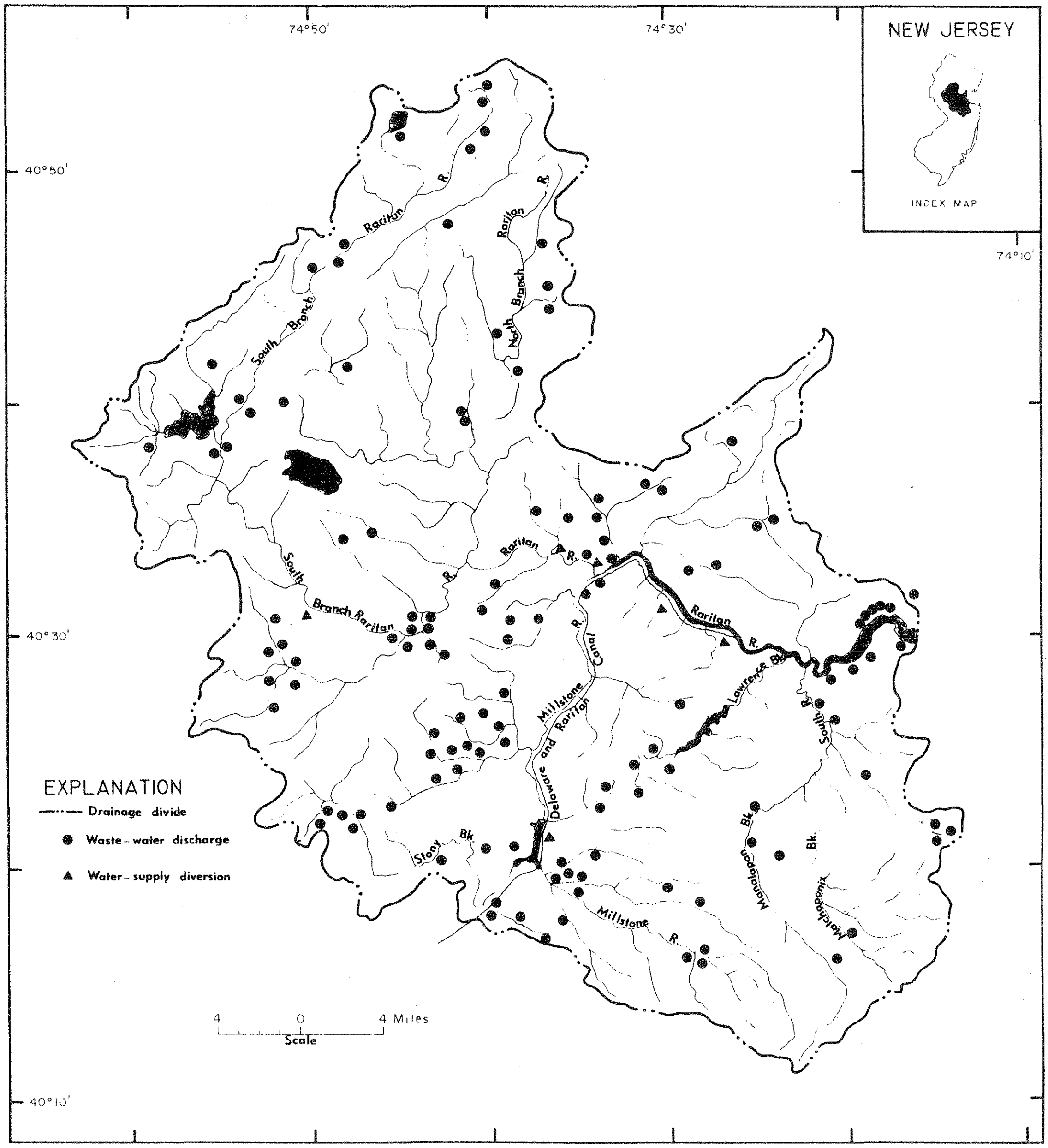

Figure 2.--Location of principal water-supply diversions and of waste-water discharge sites.

State, exceeded only by the Delaware River basin, with 2,345 mi^2 (6,074 km^2) within the State's boundary. Major tributary systems and their respective drainage areas are the North Branch Raritan River (190 mi^2 or 492 km^2), South Branch Raritan River (279 mi^2 or 722 km^2), Millstone River (287 mi^2 or 743 km^2), Green Brook (65.2 mi^2 or 169 km^2), and South River (133 mi^2 or 344 km^2). The Raritan River and most of its tributaries are tidal below Fieldville Dam, about 14 mi (23 km) above the river's mouth at Raritan Bay.

The Raritan River basin is traversed by the Delaware and Raritan Canal. This canal is a watercourse created by diversion of the Delaware River. It is about 65 mi (105 km) long, parallels the Delaware River from its diversion point at Raven Rock to Trenton, turns northeast to Princeton, parallels the Millstone and Raritan Rivers, and eventually flows into the Raritan River at the head of navigation in New Brunswick. Originally used for navigation, the canal is used now as a source of industrial- and public-water supply.

Water Use

The basin is highly urbanized in its lower reaches and its water resources are utilized extensively. Although some of the water is used for recreational and agricultural purposes, particularly in the headwater areas of the North and South Branch Raritan and Millstone Rivers, the main use is as a source for both public and industrial supply and for the disposal of municipal and industrial waste waters. The location of six points of diversion of water for sources of potable water and 126 points of discharge of municipal and industrial wastes are shown in figure 2.

Diversion for potable-water supply, including water from the Delaware and Raritan Canal, amounted to about 120 mgd (5.26 m^3/s) in 1972 (R. A. Webster, N.J. Div. of Water Resources, oral commun., 1972). Almost 30 percent of this amount is drawn from the Canal. Three of the six water-supply purveyors withdraw about 95 percent of the total water diverted from basin streams or the adjacent canal at or below Manville.

Treated industrial and municipal waste-water effluents discharged into the basin streams in 1972 amounted to about 150 mgd (6.57 m^3/s) (R. Delgado, N.J. Div. of Water Resources, oral commun., 1972). Thirty-seven of the 126 treatment plants basinwide used streams at or below Manville as a receptor for their effluents. About 80 percent of the total discharged basinwide originates from these 37 plants. Slightly over 60 percent of the total discharges, primarily by the Middlesex County Sewerage Authority in Sayreville (76 mgd or 3.3 m^3/s), are made in tidal areas below New Brunswick.

Water requirements are related to the number of people living in an area or using its water resources. According to the 1970 Census (U.S. Bureau of the Census, 1971), the basin's population was slightly over 900,000. This compares with about 650,000 in 1960, 390,000 in 1950, and 300,000 in 1940 (U.S. Bureau of the Census, 1961). Much of this population is centered in the tidal reach of the basin. Comparatively, total population in the State was about 7.1 million in 1970, 6.1 million in 1960, 4.8 million in 1950, and 4.2 million in 1940. Therefore, about 13 percent of the State's population lived within the basin's boundaries in 1970, as compared with about 11 percent in 1960. Projected population increases suggest a continued expansion in the demands upon the basin's water resources.

STREAMFLOW CHARACTERISTICS

The ultimate source of water in the Raritan River and its tributaries is precipitation. However, not all of the 47 in (120 cm) of precipitation on the basin becomes streamflow. Hely and others (1961, p. 6-7) estimates that water loss in the basin is 25 to 26 in (63-66 cm) per year in the headwater areas, decreasing to 23 to 24 in (58-61 cm) per year in the lower reaches. Evapotranspiration accounts for most of this water loss.

Precipitation

Climatologic data for most of the basin are presented as part of the State's northern climatologic division by the National Weather Service. It is reasonable, on the basis of data presented by Hely and others (1961), to assume that variations in precipitation, as computed for the northern division, probably are representative of those for the basin. Average annual precipitation in the northern division, based on the standard reference period, 1931-60, (World Meteorological Organization, 1956) is 46.96 in (119 cm) (U.S. Weather Bureau, 1963). The lowest monthly average, 2.9 in (7.4 cm), normally occurs in February and the highest, 4.9 in (12.4 cm), in August.

Because much of the following discussion on streamflow and stream quality is based on records collected from 1955 to 1972, a general understanding of the magnitude and extend of variations in precipitation during this period is important. Variations from 1945 are illustrated on a cumulative-departure curve (fig. 3).

This curve is useful in defining precipitation trends. After 1955, four general trends (dashed lines) are apparent, as are several minor trends. After 1955, the slope of the departure curve recedes gently until late 1961, indicating a slow change to less than normal precipitation. The change to a sharply negative slope in late 1961 marks the beginning of 5 consecutive years of severe drought (Barksdale and others, 1966). The Palmer Index of Meteorologic Drought (Palmer, 1965) indicated that meteorologic drought in the basin began in August 1961 and ended in September 1966 (D. V. Dunlap, National Weather Service, written commun., 1968). From 1966 to 1970, the slight downward slope of the departure curve indicates a continuation of less than normal precipitation, but not the deficiency observed during the preceding drought years. A recovery to above normal precipitation is evident after 1970.

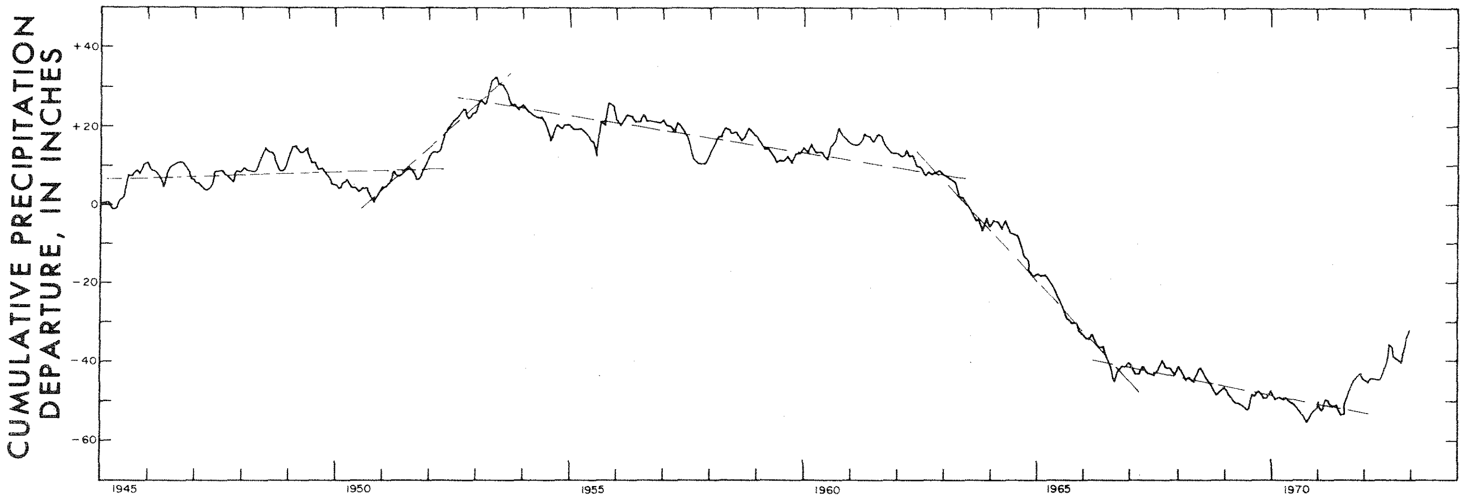

Figure 3.--Cumulative departure from normal of monthly precipitation for New Jersey's northern climatologic division, 1945-72. Dashed lines represent apparent trends. (Based on Natl. Weather Service recs.)

Streamflow

Streamflow data in the Raritan River basin have been collected in the U.S. Geological Survey's cooperative program with the State and other government agencies at 30 continuous-recording gaging stations, 23 (fig. 4) of which are operated currently (1972). In addition, reservoir content is measured at two sites and water diversion at three sites. These data are augmented by random streamflow measurements at an additional 59 low-flow and 22 crest-stage partial-record stations. Basic streamflow records collected in the basin from 1903-1965 are reported in compilation form (U.S. Geological Survey, 1960, p. 173-191; 1964, p. 132-147; and 1970, p. 424-476). In addition, since 1961 streamflow records are published in annual basic-data releases titled "Water Resources Data for New Jersey, Part 1. Surface Water Records."

Two techniques are used herein for the presentation and analysis of streamflow data: flow-duration and moving-average analysis. Flow-duration analysis (Searcy, 1959) involves the computation, based on daily mean discharge values, of the percentage of time during a given period in which specified discharges are equaled or exceeded at a particular measuring site.

Flow-duration curves for the Raritan River at Manville (fig. 4, site 9) during four different time periods are presented in figure 5. Changes in streamflow patterns with time can be observed by comparing curves for different time periods. For example, the flow in the Raritan River at Manville during the recent drought, 1962-66, can be compared with the other time periods plotted. Curves for the period of record, 1904-06, 1922-72; for the standard reference period, 1931-60; and for the study period, 1955-72 are similar. In fact, that for the period of record is identical to that for the standard reference period. However, streamflows were significantly lower during the drought at all percentages of time.

A summary of the data obtained from a computer analyses of discharge information at gaging stations in the basin is included in table 1. Data for 1931-60 were obtained from Miller (1966, p. 46-51). Comparison of flow-duration data for gaging stations other than Manville also indicates little variation in streamflow values for the different time periods tabulated. Values in table 1 can be used to construct curves similar to those in figure 5 for these stations.

The second technique used to analyze streamflow data, moving averages, involves the sequential calculation and graphing of values obtained by averaging data for successive time periods. Moving averages tend to dampen the extremes of short-term fluctuations in the chronological sequence of the parameter that is analyzed. Although such curves can be used to indicate large general trends with time, they are seldom used for the determination of small variations, nor should they be used for quantitative results without an additional serial-correlation analyses. Thus, significant predictions or projections cannot be made with this technique.

Table 1.--Descriptive material on streamflow and stream-quality stations operated by the U.S. Geological Survey.

Map no. (fig. 4)	Stream and location	Drainage area (mi^2)	Data type	Period of discharge record	Long-term average flow (ft^3/s)	Discharge, in cfs, equaled or exceeded the indicated percentage of time: Period	1	10	25	50	75	90	99
1	So. Br. Raritan R. nr. High Bridge	65.3	QCTS	1918-72	114	1919-70	600	221	135	79	47	33	22
						1931-60	620	228	140	81	48	34	23
2	Spruce Run at Clinton	41.3	QCTS	1959-72	48.1	--	--	--	--	--	--	--	--
3	So. Br. Raritan R. at Stanton	147	QCTS	1903-06, 1919-72	229	1904-06, 1920-70	1350	455	267	150	82	55	33
						1931-60	1480	480	280	162	86	55	32
4	Walnut Brk. nr. Flemington	2.24	Q	1936-60	3.20	--	--	--	--	--	--	--	--
5	Neshanic R. at Reaville	25.7	Q	1930-72	33.7	--	--	--	--	--	--	--	--
6	No. Br. Raritan R. nr. Far Hills	26.2	QCS	1921-72	45.4	1922-70	262	92	55	31	16	9.2	3.8
						1931-60	270	97	54	33	18	9.9	3.8
7	Lamington R. nr. Pottersville	32.8	Q	1921-72	53.1	--	--	--	--	--	--	--	--
8	No. Br. Raritan R. nr. Raritan	190	QCS	1923-72	286	1924-70	2200	560	310	168	81	49	21
						1931-60	2300	590	325	180	87	50	23
9	Raritan R. at Manville	490	QCS	1903-07, 1921-72	722	1904-06 1922-70	5500	1470	770	400	195	110	50
						1931-60	5700	1580	820	425	191	105	48
10	Raritan R. nr. Manville	497	CT	--	--	--	--	--	--	--	--	--	--
11	Millstone R. at Plainsboro	65.8	Q	1964-72	81.7	--	--	--	--	--	--	--	--
12	Baldwin Ck. at Baldwin L., nr. Pennington	2.52	QCTS	1962-70	2.73	--	--	--	--	--	--	--	--
13	Honey Branch nr. Pennington	.70	QS	1967-72	--	--	--	--	--	--	--	--	--
14	Stony Brk. at Princeton	44.5	QCTS	1953-72	56.7	--	--	--	--	--	--	--	--
15	Millstone R. nr. Kingston	117	Q	1933-49	239	--	--	--	--	--	--	--	--
16	Delaware and Raritan Canal at Kingston	--	Q	1947-72	--	--	--	--	--	--	--	--	--
17	Millstone R. at Blackwells Mills	258	QCS	1921-72	358	1922-70	2750	770	375	192	99	57	20
						1931-60	2750	790	400	196	100	59	19
18	Royce Brk. Trib. at Frankford	.29	Q	1968-72	--	--	--	--	--	--	--	--	--
19	Royce Brk. Trib. nr. Belle Mead	1.20	Q	1966-72	2.36	--	--	--	--	--	--	--	--

Table 1.--Descriptive material on streamflow and stream-quality stations operated by the U.S. Geological Survey--Continued.

Map no. (fig. 4)	Stream and location	Drainage area (mi^2)	Data type	Period of discharge record	Long-term average flow (ft^3/s)	Discharge, in cfs, equaled or exceeded the indicated percentage of time: Period	1	10	25	50	75	90	99
20	Millstone R. nr. Manville	287	CT	--	--	--	--	--	--	--	--	--	--
21	Raritan R. bel. Calco Dam, at Bound Brook	785	Q	1903-09, 1944-72	1,177	1904-08, 1945-70	8900	2450	1250	620	300	158	68
						1931-60	8600	2460	1250	610	298	176	58
22	Raritan R. at Queens Br., at Bound Brook	--	CS	--	--	--	--	--	--	--	--	--	--
23	Green Brk. at Plainfield	9.75	Q	1938-72	11.8	--	--	--	--	--	--	--	--
24	Green Brk. at Middlesex	--	Q	1972	--	--	--	--	--	--	--	--	--
25	Green Brk. at Bound Brook	50.2	Q	1923-30	73.7	--	--	--	--	--	--	--	--
26	Raritan R. nr. So. Bound Brook	862	CT	--	--	--	--	--	--	--	--	--	--
27	Lawrence Brk. at Patricks Corner	29	Q	1922-26	--	--	--	--	--	--	--	--	--
28	Lawrence Brk. at Farrington Dam	34.4	Q	1927-72	37.3	--	--	--	--	--	--	--	--
29	Manalapan Brk. at Spotswood	40.7	QC	1957-72	61.2	--	--	--	--	--	--	--	--
30	Matchaponix Brk. at Spotswood	43.9	QC	1957-67	62.5	--	--	--	--	--	--	--	--
31	South R. at Old Bridge	94.6	QC	1939-72	131	--	--	--	--	--	--	--	--
32	Deep Run nr. Browntown	8.07	Q	1932-40	14.0	--	--	--	--	--	--	--	--
33	Tennent Brk. nr. Browntown	5.25	Q	1932-41	--	--	--	--	--	--	--	--	--
34	Raritan R. at Perth Amboy	1,101	QS	1966-72	--	--	--	--	--	--	--	--	--

Q - daily discharge
C - chemical analyses
T - daily temperature records
S - sediment records

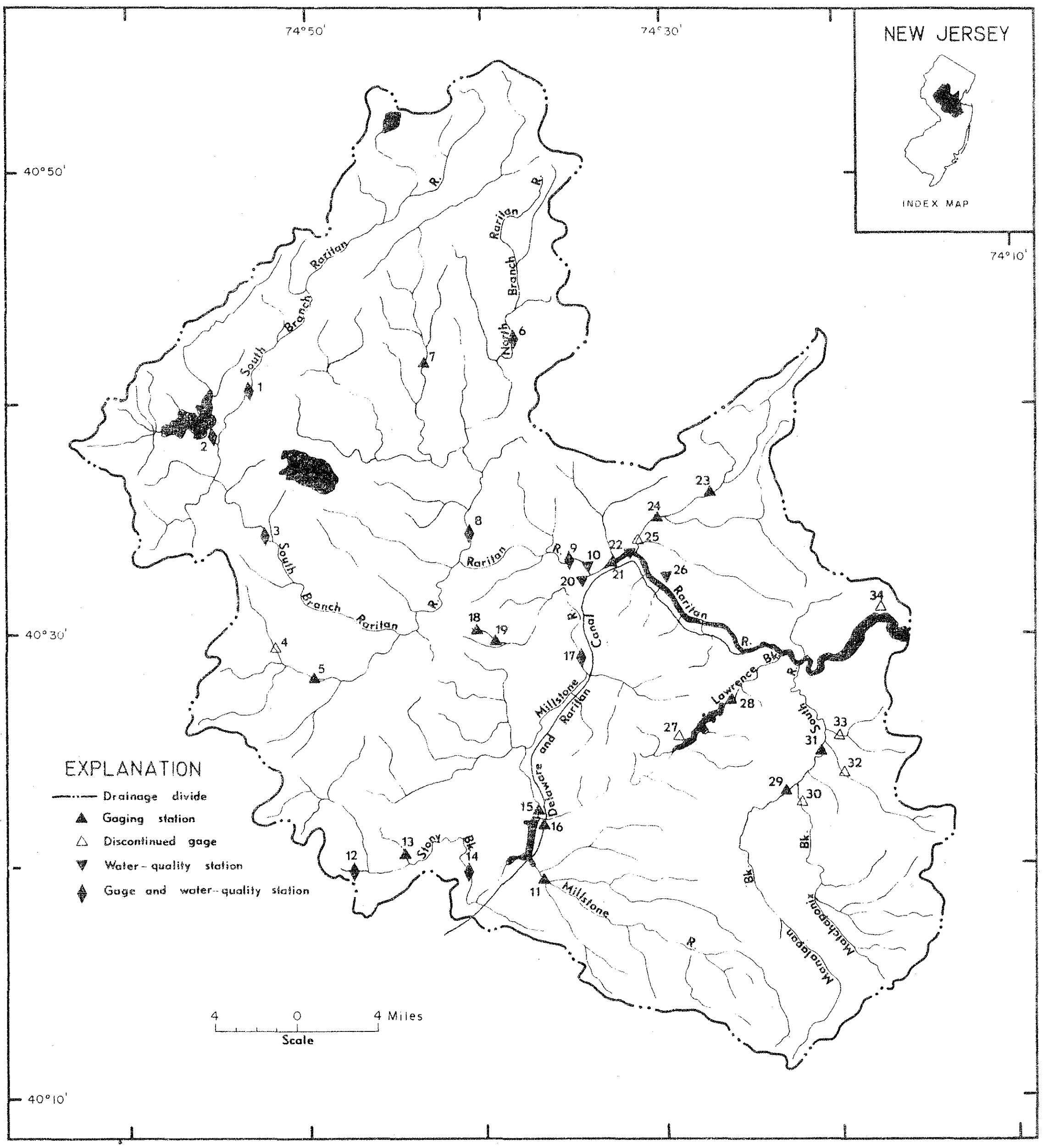

Figure 4.--Location of streamflow and stream-quality measurement sites. Numbers refer to station descriptions given in table 1.

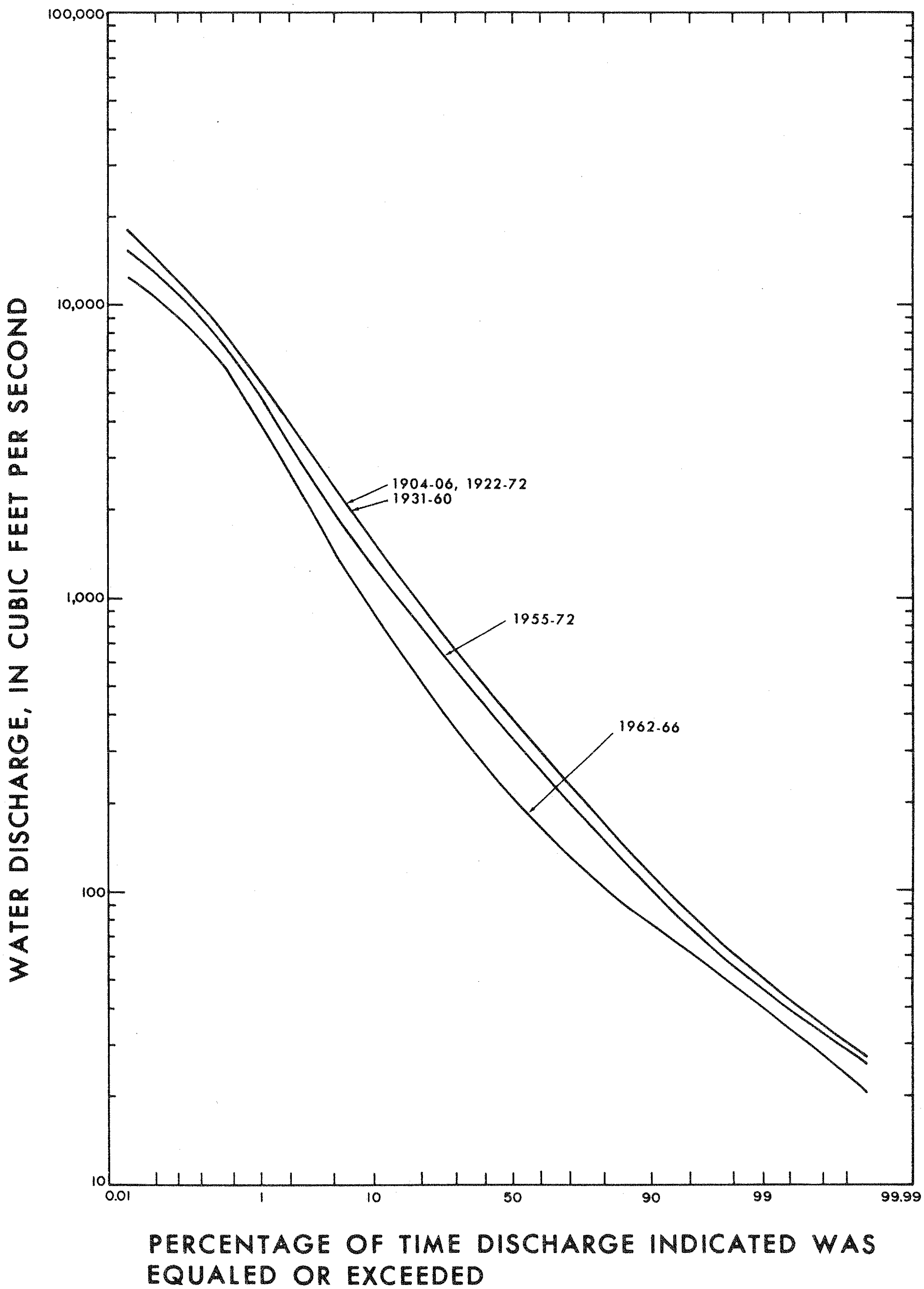

Figure 5.--Flow-duration curves, Raritan River at Manville.

As used in this report, the moving average is on a 12-month cycle; data points represent the preceding 12-month average. Examples of curves produced by such analyses of mean monthly streamflow at two gaging stations on the Raritan River main stem, at two stations in the Millstone River system, and at two stations each in the North and South Branch Raritan River systems are illustrated in figure 6.

A comparison of long-term average streamflow (dashed lines) with the moving averages indicates that after 1955 streamflow generally exceeded the long-term average in 1956, 1958, 1960-61, 1967-68, and 1970-72. Likewise, streamflows generally were less than the long-term average in 1955, 1959, 1962-66, and 1969. In general, the highest flows were observed in 1952, whereas the lowest were observed in 1965.

The plots of moving averages indicate a general trend toward decreasing streamflow between 1955 and 1972. These downward trends are most apparent at the most downstream gaging stations when the moving average plot is compared with long-term average flows (dashed lines). Similar trends toward decreasing flows can be observed at the other gaging stations illustrated, although they are not as apparent due to lower discharge values and their plotting scale.

However, any interpretation that this apparent trend represents the long term, and not just the time period illustrated, may be inaccurate in that abnormally high streamflows occurred during the early part of the period illustrated and abnormally low flows during the later part.

The influence of the 1962-66 drought in reducing flows in the river system is evident. Interestingly, the average annual flows after the drought at the gaging stations illustrated did not exceed the recorded long-term average discharge (dashed lines) until 1970, except for a short period in 1967.

Time-of-Travel Measurements

River systems, particularly those near metropolitan areas, transport, dilute, and assimilate waste waters discharged by industries and municipalities. Many contaminants introduced into river systems either are dissolved or are dispersed in a fine suspension and generally are assumed to travel at the same rate as the water particle that transports them. Water-pollution control and abatement work has demonstrated a need for more accurate knowledge of the movement of such materials in streams.

No truly satisfactory method for determining the rate of movement of a water mass through a river system existed before the use of soluble dye tracers. Use of these dyes, technical aspects of their measurement and application, and interpretation of results have been reported previously by many authors, among whom are Pritchard and Carpenter (1960), Buchanan (1964), Wilson (1968), and Kilpatrick and others (in press).

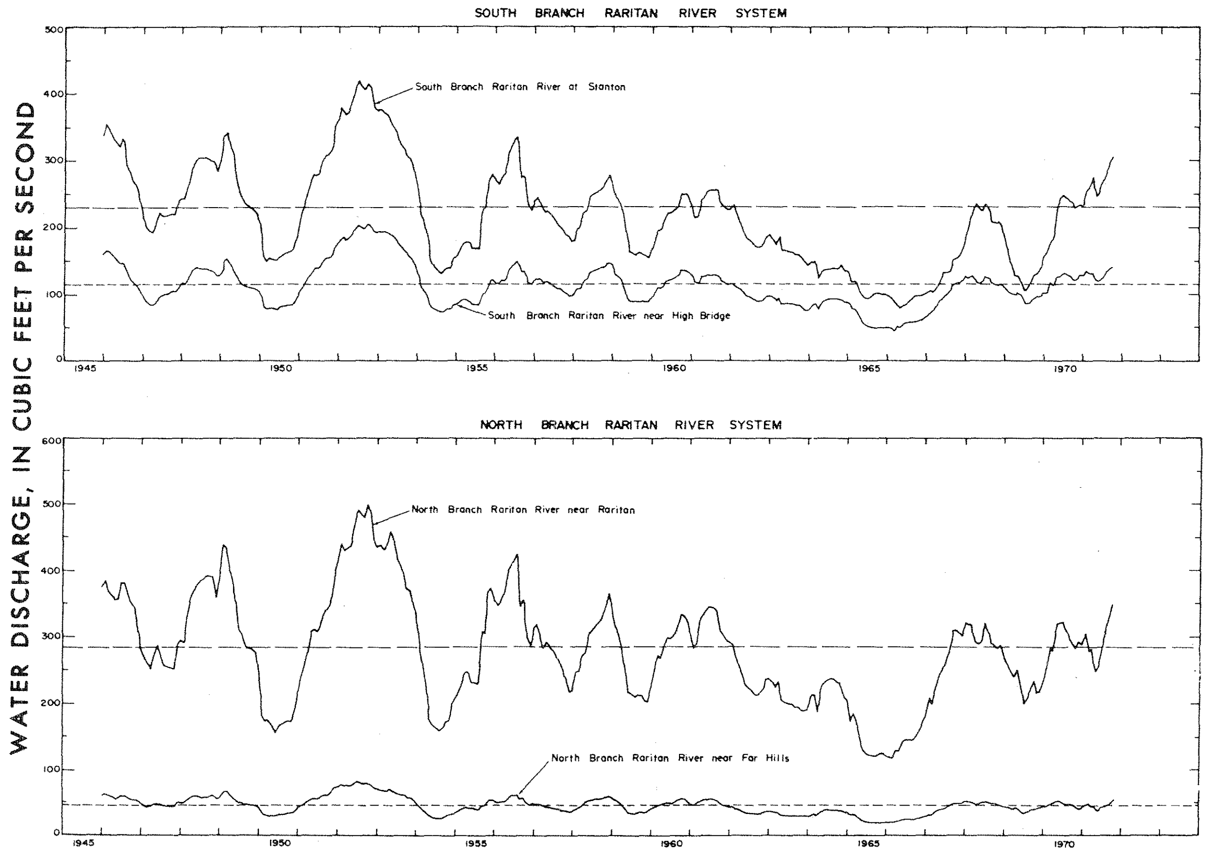

Figure 6.--Trend analysis, based on 12 month moving averages, of streamflow records at selected gaging stations. Horizontal dashed line represents long-term average flow at gaging station.

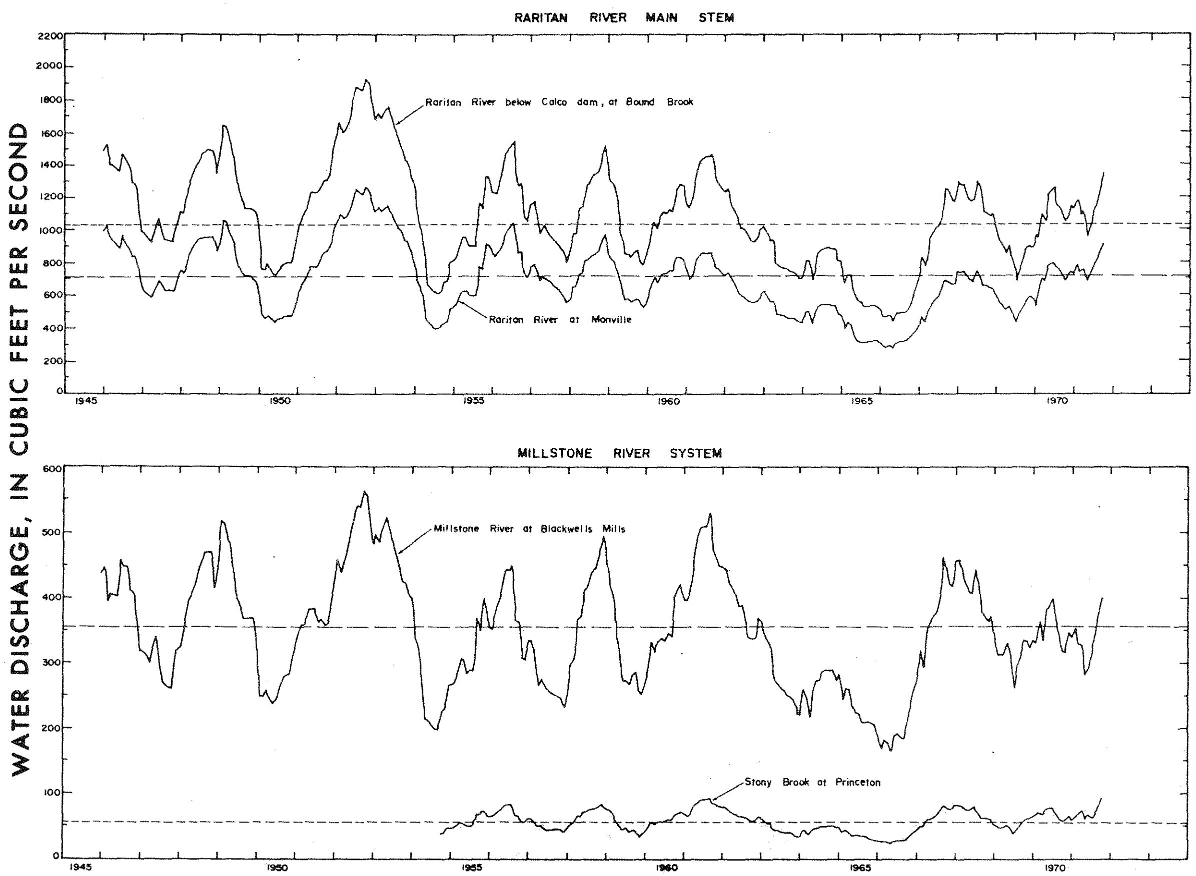

Figure 6.--Continued

As mentioned in the introduction of this report, one of the project's objectives was to provide information necessary to predict accurately the amount of time required for a soluble contaminant to pass through finite lengths of the Raritan River system. Data were collected on 76 mi (122 km) of stream channel: 12 mi (19 km) on the Raritan River; 25 mi (40 km) on the Millstone River; 14 mi (23 km) on the North Branch Raritan; 22 mi (35 km) on the South Branch Raritan River; and 3 mi (5 km) on Matchaponix Brook, a tributary of South River. Results of these measurements are summarized on table 2.

An effort was made during each measurement to achieve vertical and lateral dispersion of the dye (Rhodamine BA or WT) within a short distance of its introduction into the water. The effect of longitudinal dispersion on the dye was studied during the June 1969 measurement in each of the stream reaches. For example, the successive diminution at four downstream sites of the peak concentration with time and distance of a dye cloud produced by a single injection in the South Branch Raritan River at Clinton is illustrated in figure 7. Note on this graph that the concentration curve flattens and becomes more skewed as the dye moves downstream. The reduction in dye concentration at each successive site is not entirely due to dispersion characteristics, as indicated by the decrease in area under each curve. Some is due to dilution effects from tributary inflow, some to the loss of dye on streambed materials and vegetation, and some to photochemical decay.

The data presented in table 2 indicate the variability of traveltime within the Raritan River basin. For example, mean velocities of the dye peak ranged from 1.62 ft/s (49.4 cm/s) on the main stem and North Branch during the March 1971 measurement to 0.062 ft/s (1.9 cm/s) through Carnegie Lake during May 1968. In all measurements, velocities in the measured reach related directly with streamflow; that is, as flows increased, velocities increased. In general, velocities observed at intermediate sampling sites were highest in the headwater areas of the North and South Branches and the Millstone River, reflecting the steeper channel gradients in these areas. Observations at intermediate sampling sites also indicate a general decrease in velocity in a downstream direction. This phenomenon reflects also the lesser channel gradients, and, in addition, the broadening and deepening of the channel, and, in some parts of a reach, the ponding of water by several small dams. Velocities in the North and South Branch Raritan Rivers are higher than those in the Millstone River, reflecting the lesser channel gradient and relatively deeper and wider channel of the Millstone River.

Variations in the traveltime of the peak dye concentration during different streamflow conditions are shown in figure 8 for selected reaches in the Raritan River system. Because each curve is based on only two measurements (table 2), interpolation must be made with caution. A more reliable definition would require additional data, particularly during lower streamflow patterns. This, however, should not hinder the use of these graphs to provide the best available estimate of traveltimes except for extreme discharge rates.

Table 2.--Summarized results of time-of-travel measurements.

Channel reach (see fig. 1)	Length (mi)	Channel fall (ft/mi)	Date of study	Streamflow (ft^3/s)	Streamflow (duration)	Leading edge traveltime (hr)	Leading edge velocity (ft/s)	Peak concentration traveltime (hr)	Peak concentration velocity (ft/s)
				SOUTH BRANCH RARITAN RIVER[1]					
Clinton to North Branch confluence	21.8	5.7	06-18-69	91	72	46.2	0.69	53.9	0.59
			03-23-71	414	13	17.6	1.82	20.5	1.56
				NORTH BRANCH RARITAN RIVER[2]					
Far Hills to South Branch confluence	14.4	10.1	06-18-69	114	61	26.1	.81	31.6	.67
			03-23-71	477	12	11.3	1.87	13.0	1.62
				MILLSTONE RIVER[3]					
Hightstown to Carnegie Lake inflow	8.4	3.0	05-06-68	182	55	13.4	.92	15.2	.81
Carnegie Lake	2.6	--	05-05-68	189	56	60.8	.063	62.0	.062
Carnegie Lake outflow to Weston	13.9	1.8	06-18-69	179	52	34.1	.60	42.6	.48
			03-23-71	458	21	18.8	1.08	22.6	.90
				RARITAN RIVER[4]					
North-South Branch confluence to Fieldville dam	12.4	3.2	06-18-69	344	62	28.4	.64	34.3	.53
			03-23-71	1,700	16	9.8	1.86	11.2	1.62
				MATCHAPONIX BROOK[5]					
Englishtown to Redshaw Corner	2.8	10.7	03-17-71	47	53	6.0	.68	6.8	.60

[1] Streamflow based on Stanton gage (fig. 4, site 3).
[2] Streamflow based on Raritan gage (site 8).
[3] Streamflow based on Blackwells Mills gage (site 17).
[4] Streamflow based on Bound Brook gage (site 21).
[5] Streamflow based on Manalapan Brook gage (site 29).

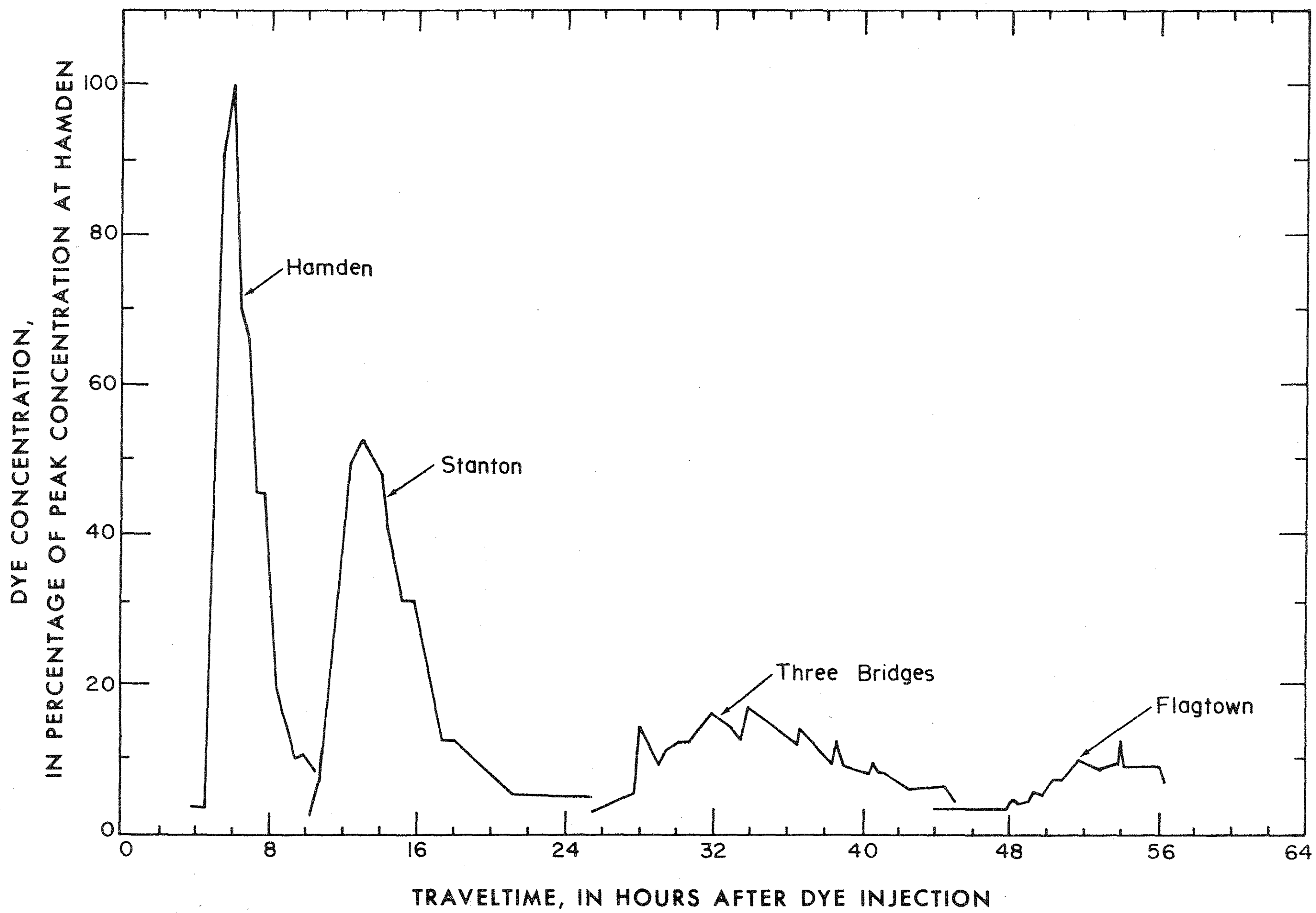

Figure 7.--Dye-cloud dispersion with both time and distance, South Branch Raritan River.

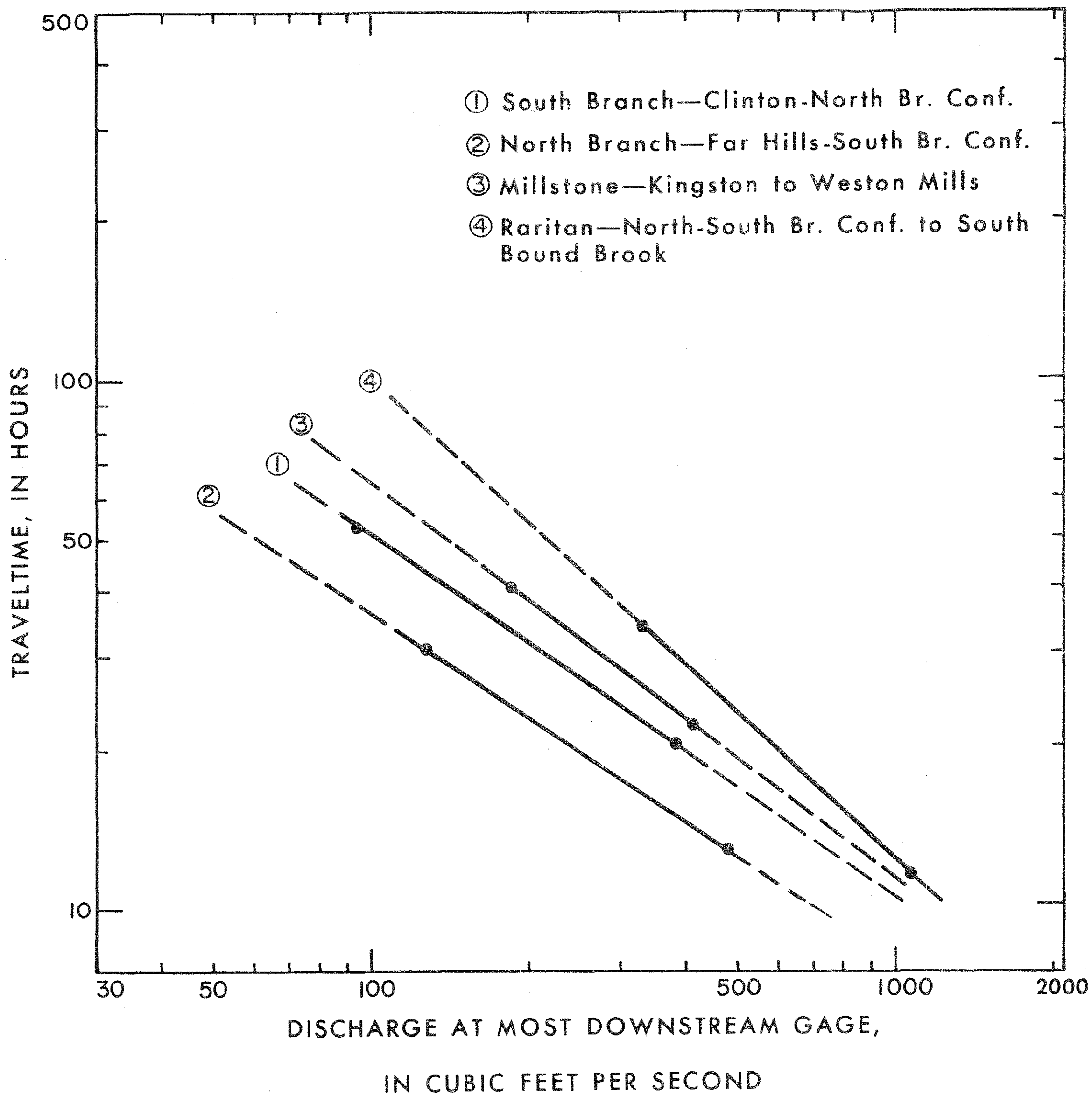

Figure 8.--Variations in dye-peak traveltime during different streamflow conditions.

This particular type of plot, over a range of discharge rates, can be of particular interest to water user. Consider, for example, that a spill of some toxic material occurs on the South Branch Raritan River at Clinton (fig. 1). Assuming a discharge of 100 ft^3/s (2.83 m^3/s) in the South Branch Raritan River reach, the traveltime between Clinton and the confluence with the North Branch Raritan River would be 51 hr. Likewise, assuming a discharge of 550 ft^3/s (15.6 m^3/s) (based on increased drainage area) on the main stem, the traveltime between the North-South Branch confluence and Fieldville dam on the Raritan River would be 22 hr. Thus, the expected traveltime of the peak concentration of the spill from Clinton to the head of tide near South Bound Brook, a distance of 34 mi (55 km), is 73 hr. A simple calculation predicts that the mean velocity of the peak concentration would be 0.68 ft/s (21 cm/s) at the assumed streamflow condition. At 50 ft^3/s (1.42 m^3/s) in the South Branch and 250 ft^3/s (7.08 m^3/s) in the main stem, the estimated traveltime would be 126 hr or a mean velocity of 0.40 ft/s (12 cm/s).

An additional time-of-travel measurement made in the basin was not included in table 2, as it was conducted during non-steady-state conditions. Buchanan (1968) compared flood-wave and water-particle traveltimes from Spruce Run Reservoir (fig. 1) to the Elizabethtown Water Company's intake at Manville, a distance of about 30 mi (48 km). The flood wave's traveltime was determined by increasing the reservoir release by 135 ft^3/s (3.82 m^3/s) and observing changes in water stage at selected points downstream. Traveltime of the water particles was measured by injecting Rhodamine B dye in the reservoir outfall and tracing its passage at downstream sampling points.

The flood wave moved 1.1 to 2.2 times faster than the peak dye concentration. Thus, additional quantities of water were available downstream from the reservoir before the arrival of the reservoir's water. Buchanan noted that the mean velocity of the water particles traveling through the pools behind six small dams in the reach were much slower than that in natural channels, but that the velocity of the flood wave tended to increase behind these dams.

In addition to slower traveltimes through a pooled area, other factors can produce a sizable fluctuations in the passage time of a dye cloud. The curve plotted in figure 9 represents the measurement of a dye cloud on the Millstone River between Penns Neck and Kingston. This 2.65 mi (4.26 km) reach is through a manmade lake, Carnegie Lake. The leading edge of the dye cloud was detected 60.8 hr (0.063 ft/s or 2.0 cm/s), and the peak, 62.0 hr (0.062 ft/s or 1.9 cm/s) after injection. However, seven additional dye peaks were observed for at least 14 hr (when sampling was discontinued) after that of the peak concentration. These fluctuations probably reflect differences in traveltime through the lake due to current variations resulting from depth, density, or temperature patterns.

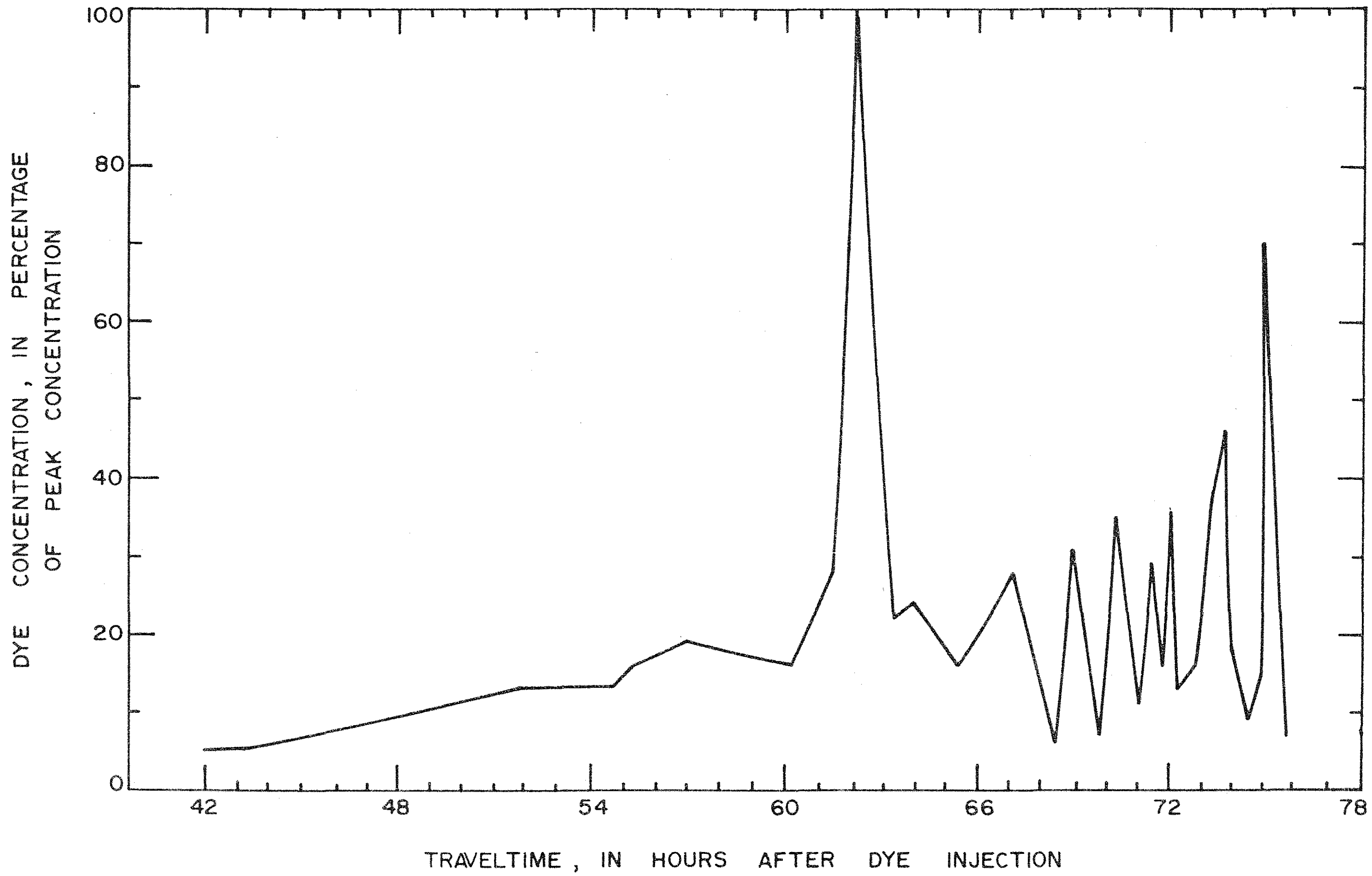

Figure 9.--Traveltime of a dye cloud through Carnegie Lake, May 1968.

STREAM-QUALITY CHARACTERISTICS

Basic records (1928-42, 1958 to present) of the quality of the basin's streams have been collected by several State agencies. Generally, these records are unpublished, but are available for inspection from the State Division of Water Resources. In addition, some information is available from the State Division of Fish, Game, and Shellfisheries, and from various research laboratories at Rutgers-The State University.

Stream-quality records collected by the State are augmented and supplemented by those of water-supply agencies, conservation groups, sewage authorities, and industrial-water users. For example, extensive sampling programs are conducted by the Middlesex County Sewerage Authority, Elizabethtown Water Company, American Cyanamid Corp., Johns-Manville Corp., Upper Raritan Watershed Association, South Branch Raritan River Watershed Association, and Stony Brook-Millstone Watersheds Association, to mention a few. These records generally are unpublished, but are available in local offices.

In addition, some basic stream-quality records have been collected by Federal agencies; mainly, the U.S. Environmental Protection Agency and the U.S. Geological Survey.

Records collected by the U.S. Environmental Protection Agency also generally are unpublished; however, such records can be obtained readily upon request. Summary tabulations and graphical profiles of water-quality parameters are found in the proceedings of enforcement conferences, mainly pertaining to pollution in the tidal Raritan Bay and adjacent interstate waters, held by this agency under the provisions of the Federal Water Pollution Control Act.

The U.S. Geological Survey has reported its water-quality studies within the basin in five interpretive reports: Leighton (1902), Collins and Howard (1927), George (1963), (Mansue and Anderson, in press), and Anderson and George (1966).

In addition to these five interpretive reports, basic water-quality data collected as a part of its cooperative programs with State and other governmental agencies are published annually in water-supply paper titled "Quality of Surface Waters of the United States." Beginning with the 1964 water year, water-quality data also are published in annual basic-data released titled "Water Resources Data for New Jersey, Part 2. Water Quality Records."

Results of an analysis of regional, long-term, seasonal, and diurnal variations in the water quality of streams in the basin are described in this section. Emphasis is placed on chemical and biochemical water quality, because of the greater amounts of data available on these parameters. However, discussions are presented on physical water quality, where significant data are available.

Regional Variations

Water contains varying amounts of dissolved and particulate matter throughout the hydrologic cycle. As moisture condenses and falls through the atmosphere, it absorbs gases and dust particles, bacteria, spores, and other matter. Consequently, as precipitation reaches the earth, it carries small quantities of dissolved and suspended matter. Although the dissolved-solids content of precipitation is variable (based on unpublished random chemical analyses of rainfall), in New Jersey it probably does not exceed 30 mg/l except during an intense storm, such as a hurricane.

Most water flowing in a New Jersey stream during periods of high flow is from direct overland runoff. Because this water has had little contact time with soluble materials, its dissolved solids generally reflect the concentration and composition of precipitation. Consequently, the dissolved-solids content of New Jersey streams during high flows is usually, but not always, at minimum values (Anderson and George, 1966, p. G7-G8).

Conversely, the dissolved-solids content of most streams during periods of low flow is generally at maximum values. During low flow the natural flow in a stream channel is maintained almost entirely by ground-water inflow. Consequently, dissolved solids at low flows reflect the concentration and composition of the ground-water inflow. Because of its longer contact with soluble materials, ground water generally has as higher dissolved-solids content than does surface runoff.

Under normal conditions, the dissolved-solids content of a stream during intermediate flow is a composite of both the quality of ground-water inflow and the quality of direct runoff and is regulated by the amount of streamflow contributed from each source.

The generalized relation between the dissolved-solids content and streamflow at five sampling locations are plotted in figure 10 to illustrate their variation with flow. An inverse relation between dissolved-solids content and streamflow is shown. The concentrations of calcium, magnesium, sodium, potassium, bicarbonate or alkalinity, sulfate, chloride, and hardness show similar relations.

The relation between dissolved-solids content and streamflow in a New Jersey stream unaffected by man's activities should remain fairly constant with time at a particular sampling site. Any changes in the relation are caused by relatively slow changes in weathering processes. The greater scatter in the dissolved solids-streamflow relation at Bound Brook (fig. 10) in relation to other stations illustrated may reflect man's activities, as this reach of the main stem receives large volumes of treated municipal and industrial waste-waters.

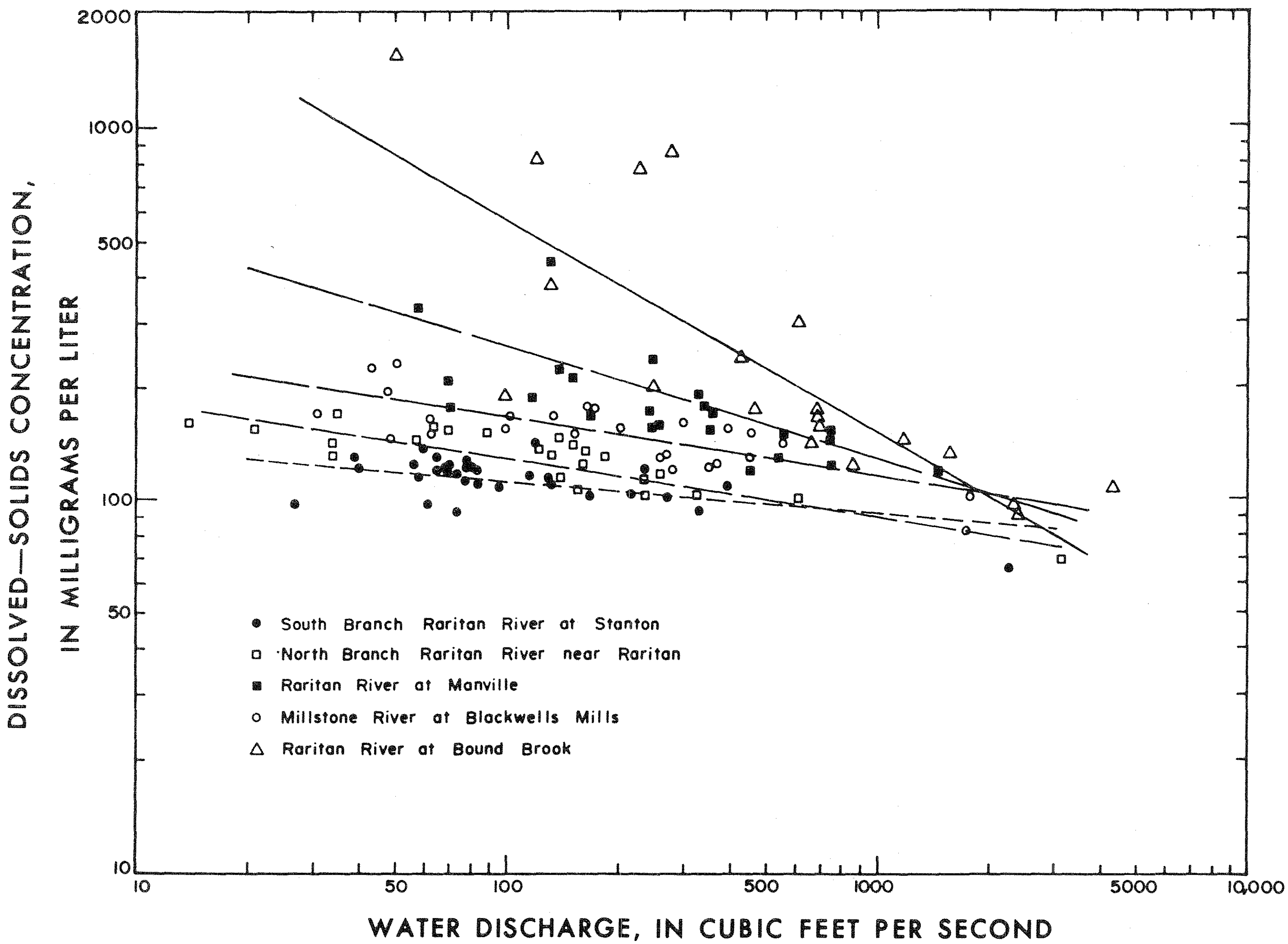

Figure 10.--Generalized relation between dissolved-solids concentration and streamflow at five sampling sites.

The chemical character and dissolved-solids content of basin streams above the influence of tide were mapped by regions of similar quality and compared with physiography. The boundaries of both the regions of similar stream quality and physiographic provinces are shown in figure 11.

The map was compiled from an analysis of stream-quality data collected during low-streamflow conditions at over 50 sampling sites. Consequently, the regions generally reflect the chemical quality of influent ground waters, which maintain the river system's base flows.

Streams draining region 1, which are largely in and include most of the New England Upland physiographic province, are low in dissolved-solids content, generally less than 200 mg/l. The stream waters range from soft to moderately hard (generally less than 100 mg/l calcium, magnesium hardness as $CaCO_3$) and are neutral to slightly alkaline (pH 6.8-7.9). The predominant cations are calcium plus magnesium (70-90 percent), whereas the predominant anion is bicarbonate (60-80 percent), but occasionally samples with higher than normal pH's contain some carbonate. The high percentage of calcium and magnesium bicarbonate is attributed in part to the presence of the Kittatinny Limestone of Cambrian-Ordovician age.

Streams in region 2, which includes most of the Piedmont Lowland, are slightly higher in dissolved-solids content (100-250 mg/l) than those draining region 1. The predominant cations are also calcium plus magnesium (70-90 percent), but the predominant anions (50-70 percent) are sulfate and chloride plus nitrate. Stream waters are neutral to slightly alkaline (pH 6.7-8.1) and range from moderately hard to very hard (75-200 mg/l calcium, magnesium hardness as $CaCO_3$). The high percentages of calcium and magnesium sulfate are attributed in part to the presence of gypsum and red shales in the underlying geologic units.

The remaining region of similar quality, region 3, corresponds with the Inner Coastal Plain. The virtual lack of solutes in the underlying geologic units, mainly unconsolidated deposits of sand and clay, is reflected in the lowest dissolved-solids content (50-150 mg/l) and hardness (40-75 mg/l) of the three regions. The predominant cations are calcium plus magnesium (60-80 percent), whereas predominant anions are sulfate and chloride, plus nitrate (80-100 percent). The high percentage of sulfate in streams draining this region is attributed to the oxidation of pyrite commonly found in glauconitic sediments underlying this area. The high percentage of calcium and magnesium is attributed to fossil shell beds present in the marine deposits.

A few streams in each of the three regions may not fall within these general limitations. Also, as stream quality in the main stem is extremely variable, particularly below Manville, due to man's activities, the water type assigned on figure 11 may or may not represent the normal.

High, low and mean values of major chemical and biochemical quality parameters observed at major sampling sites (fig. 4) are given in table 3. A comparison with analyses reported earlier by Collins and Howard (table 4) indicates that the concentrations of many constituents have changed, particularly

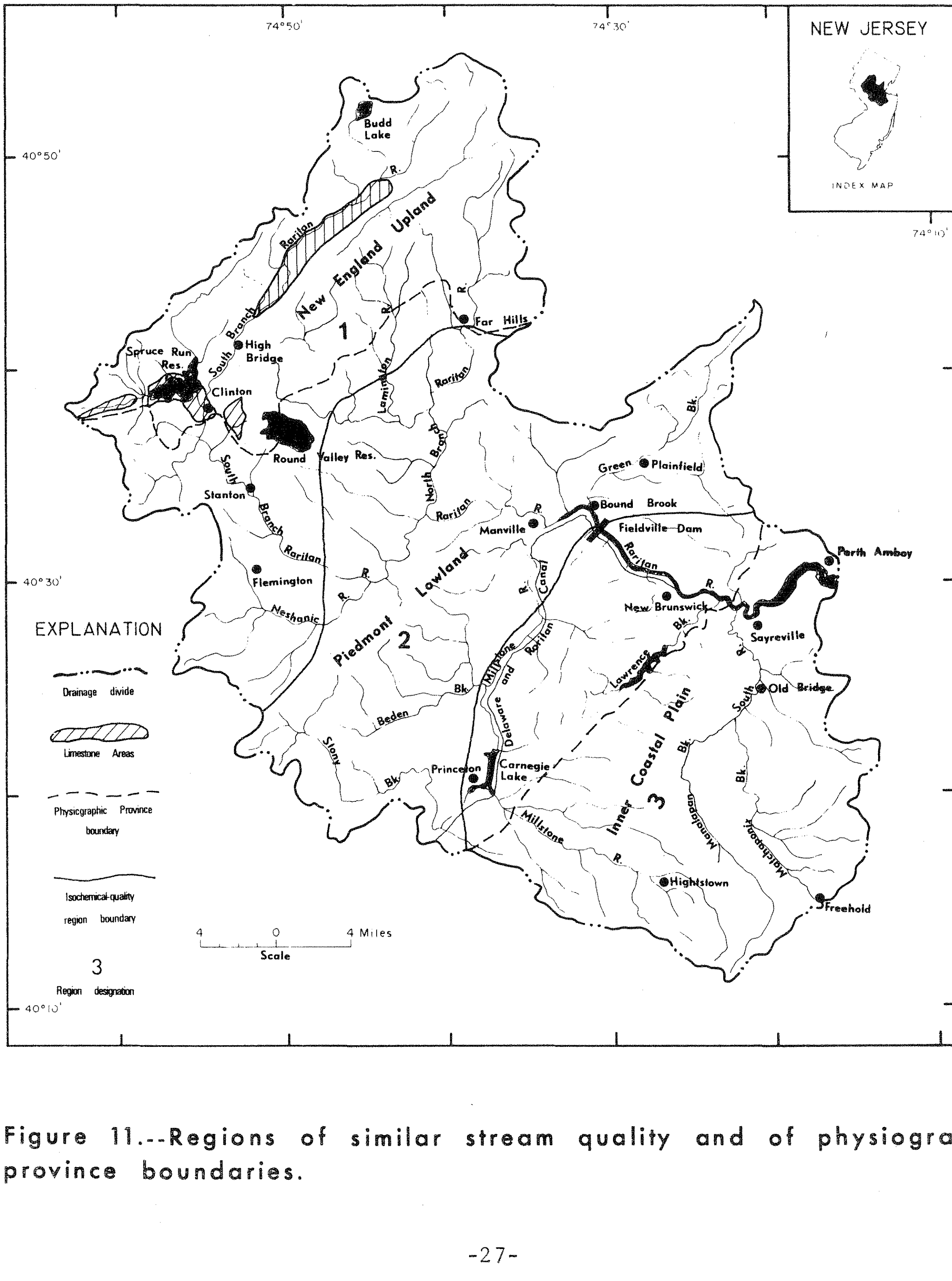

Figure 11.--Regions of similar stream quality and of physiographic province boundaries.

at main stem sampling sites. In general, concentrations of major ions during the earlier period are similar to the minimum concentration during the later period. Consequently, the chemical quality of the earlier samples, which represent a wide range of streamflow conditions, is comparable to that of recent samples only during high streamflow. Note that at sites in the North and South Branch Raritan Rivers and in the Millstone River subbasin, the concentration of sulfate, chloride, and nitrate increased between the 1920's and the present, probably reflecting increased municipal waste-water discharges and increased nutrient levels in agricultural runoff. The increases in concentrations are undoubtedly significant and not totally related to changes in analytical procedures between the two observation periods.

In addition to major ions, the concentration of trace elements, that is, those which generally do not exceed 1000 ug/l in waters, were measured at 11 sampling sites. A summary of observed concentrations of the individual trace elements is given in table 5. The samples were analyzed by spectrographic methods as described by Barnett and Mallory (1971).

Bismuth, beryllium, cadmium, germamium, tin, and zinc were mostly below analytical sensitivity. The analytical sensitivity for zinc using spectrographic methods (Barnett and Mallory, 1971) is poor. Thus, the values given do not indicate the actual zinc content.

Iron and manganese, which normally meet the criterion of trace elements, were in concentrations that allowed normal methods of analysis (Brown and others, 1970). Observed concentrations of these elements also are included in table 3.

A comparison of data collected within this basin (table 5) with those collected in other parts of the State (Anderson, 1970) indicates the prevalence of higher concentrations of trace elements within the basin, particularly in the main stem, than normally found in other New Jersey streams. For example, observation at 35 non-tidal sampling sites statewide showed maximum concentrations of the following trace elements: barium (180 ug/l), boron (570 ug/l), chromium (350 ug/l), copper (340 ug/l), lithium (27 ug/l), molybdenum (14 ug/l), rubidium (16 ug/l), and strontium (1,100 ug/l). Thus, maximum or near maximum concentrations of the elements listed were observed in the basin. This could be related either to the discharge of industrial and municipal waste waters or to variations in surficial geology. However, because of the density of industrial plants along the main stem, it seems reasonable to assume that waste-water discharges are their prinicpal source.

Because streams in the basin are receiving and transporting increasing amounts of agricultural, domestic and industrial waste waters, orthophosphate (table 3), methylene blue active substances (table 3), phenolic materials (table 6), and pesticides (tables 7) were included in the analytical determinations of some water samples. Significant amounts of these four parameters are not normally found in unpolluted waters. They can be used, therefore, as indicators of waste-water discharges.

Table 3.--Maximum, minimum and mean observations of major water-quality parameters at selected sampling sites in the Raritan River basin, 1959-72. Analyses in milligrams per liter except as noted.

	South Branch Raritan River near High Bridge			Spruce Run at Clinton (reservoir outlet)			South Branch Raritan River at Stanton		
	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean
Number of samples	82			68			98		
Silica (SiO_2)	15	6.2	11	25	1.7	12	15	4.6	10
Iron (Fe) µg/l	850	50	274	1800	55	406	5900	35	445
Manganese (Mn) µg/l	482	0	57	980	0	240	420	0	66
Calcium (Ca)	21	6.5	16	34	9.0	17	22	8.2	17
Magnesium (Mg)	13	2.8	7.8	18	4.0	6.8	12	2.8	7.4
Sodium (Na)	8.1	2.2	5.6	24	2.2	6.5	7.5	2.8	5.7
Potassium (K)	4.4	.5	1.5	5.0	1.0	1.7	3.5	.8	1.8
Bicarbonate (HCO_3)	118	16	71	155	20	59	114	21	66
Carbonate (CO_3)	15	0	0	4	0	0	2	0	0
Sulfate (SO_4)	23	8.2	15	33	15	22	26	12	19
Chloride (Cl)	24	1.4	8.0	24	3.0	8.3	20	1.6	8.2
Fluoride (F)	1.1	.0	.1	1.0	.0	.2	.3	.0	.1
Nitrate (NO_3)	11	1.3	3.9	22	.5	3.6	11	.8	4.1
Orthophosphate (PO_4)	.81	.00	.20	5.4	.00	.29	.85	.00	.16
Dissolved solids	128	70	107	192	82	114	139	65	110
Hardness as $CaCO_3$	99	28	72	159	40	68	102	32	73
Noncarbonate hardness as $CaCO_3$	31	0	14	35	5	20	39	4	19
Specific conductance - micromhos at 25°C	245	78	176	327	103	174	235	96	180
pH - units	9.0	6.4	--	8.8	6.4	--	8.6	6.0	--
Color - Pt-Co units	30	0	5	60	0	7	32	0	5
MBAS (detergents)	.05	.01	--	.16	.00	--	.06	.01	--
Dissolved oxygen	14.6	5.6	--	14.4	5.5	--	15.6	5.2	--
Biochemical-oxygen demand	5.9	.5	--	8.3	.8	--	7.2	.3	--
Coliform bacteria - colonies per 100 ml	2000	60	--	6000	12	--	4300	66	--

Table 3.--Maximum, minimum and mean observations of major water-quality parameters at selected sampling sites in the Raritan River basin, 1959-72. Analyses in milligrams per liter except as noted--Continued.

	North Branch Raritan River near Far Hills			North Branch Raritan River near Raritan			Raritan River at Manville		
	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean
Number of samples	73			75			34		
Silica (SiO_2)	16	6.7	12	16	5.1	10	13	4.0	8.2
Iron (Fe) μg/l	1100	50	334	960	28	251	790	20	250
Manganese (Mn) μg/l	290	0	75	150	0	57	280	0	63
Calcium (Ca)	16	4.6	13	26	6.8	18	94	10	35
Magnesium (Mg)	12	1.7	4.9	11	2.9	6.8	14	3.4	9.3
Sodium (Na)	9.0	4.4	6.0	16	3.3	11	50	4.5	15
Potassium (K)	3.0	.2	1.4	3.0	.2	1.7	5.0	.0	1.8
Bicarbonate (HCO_3)	88	22	44	108	13	64	115	18	65
Carbonate (CO_3)	6	0	0	0	0	0	0	0	0
Sulfate (SO_4)	25	13	19	47	18	29	244	22	66
Chloride (Cl)	14	4.6	8.3	21	5.0	12	24	7.1	13
Fluoride (F)	1.2	.0	.2	1.0	.0	.3	.4	.0	.2
Nitrate (NO_3)	11	.7	3.3	8.7	.5	3.8	12	.6	4.7
Orthophosphate (PO_4)	.72	.00	.20	.80	.00	.31	.93	.00	.29
Dissolved solids	119	67	95	169	68	128	464	90	214
Hardness as $CaCO_3$	90	19	54	113	29	75	333	39	112
Noncarbonate hardness as $CaCO_3$	29	0	18	43	0	22	236	20	59
Specific conductance - micromhos at 25°C	195	113	147	289	96	209	746	130	291
pH - units	9.8	6.0	--	9.2	6.1	--	9.1	6.1	--
Color - Pt-Co units	10	0	5	25	1	7	27	1	9
MBAS (detergents)	.05	.00	--	.31	.01	--	.88	.01	--
Dissolved oxygen	14.2	5.6	--	16.4	6.0	--	--	--	--
Biochemical-oxygen demand	7.1	.7	--	7.4	1.0	--	--	--	--
Coliform bacteria - colonies per 100 ml	5000	20	--	27000	170	--	--	--	--

Table 3.--Maximum, minimum and mean observations of major water-quality parameters at selected sampling sites in the Raritan River basin, 1959-72. Analyses in milligrams per liter except as noted--Continued.

	Raritan River near Manville			Stony Brook at Princeton			Millstone River at Blackwells Mills		
	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean
Number of samples	77			85			43		
Silica (SiO_2)	14	3.4	9.0	21	0.9	9.0	12	3.5	7.9
Iron (Fe) μg/l	530	10	148	4800	42	348	1400	35	452
Manganese (Mn) μg/l	180	0	54	140	0	42	470	44	184
Calcium (Ca)	30	10	21	25	6.5	16	21	5.6	16
Magnesium (Mg)	9.2	5.1	7.2	11	2.6	7.4	8.3	3.9	6.8
Sodium (Na)	14	7.7	11	24	4.0	12	34	4.8	16
Potassium (K)	3.6	1.7	2.5	4.3	1.2	2.4	5.8	1.7	3.5
Bicarbonate (HCO_3)	87	15	57	105	6	47	58	3	25
Carbonate (CO_3)	10	0	0	5	0	0	0	0	0
Sulfate (SO_4)	51	23	37	54	20	37	67	24	45
Chloride (Cl)	36	10	15	34	4.0	16	54	8.0	22
Fluoride (F)	.2	.0	.1	.7	.0	.2	.5	.0	.2
Nitrate (NO_3)	11	.2	5.6	10	.0	3.3	23	3.1	9.7
Orthophosphate (PO_4)	.68	.00	.27	.98	.00	.15	5.4	.39	1.7
Dissolved solids	176	107	144	181	76	132	231	82	153
Hardness as $CaCO_3$	113	49	83	108	27	72	90	30	70
Noncarbonate hardness as $CaCO_3$	54	13	36	59	9	33	76	29	49
Specific conductance - micromhos at 25°C	306	175	235	336	92	219	404	120	240
pH - units	8.7	6.0	--	9.2	5.9	--	9.0	5.3	--
Color - Pt-Co units	15	0	5	35	0	7	22	1	8
MBAS (detergents)	.05	.01	--	.07	.00	--	.55	.01	--
Dissolved oxygen	14.8	6.2	--	15.0	3.9	--	--	--	--
Biochemical-oxygen demand	7.4	.4	--	7.6	.2	--	--	--	--
Coliform bacteria - colonies per 100 ml	13300	6	--	2700	52	--	--	--	--

Table 3.--Maximum, minimum and mean observations of major water-quality parameters at selected sampling sites in the Raritan River basin, 1959-72. Analyses in milligrams per liter except as noted--Continued.

	Millstone River near Manville			Raritan River at Queens Bridge at Bound Brook			Raritan River at South Bound Brook		
	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean
Number of samples	78			45			27		
Silica (SiO_2)	14	3.6	9.1	13	3.2	7.8	12	4.9	7.8
Iron (Fe) µg/l	1300	50	357	1100	51	490	2200	40	395
Manganese (Mn) µg/l	370	5	137	900	40	285	660	67	252
Calcium (Ca)	27	10	17	126	11	33	70	5.8	30
Magnesium (Mg)	11	4.4	6.7	31	4.7	10	18	5.0	8.8
Sodium (Na)	24	6.8	13	273	7.8	59	145	11	49
Potassium (K)	5.6	2.2	3.5	20	1.4	5.7	8.8	1.2	4.1
Bicarbonate (HCO_3)	108	8	34	140	3	28	40	2	21
Carbonate (CO_3)	0	0	0	30	0	1	0	0	0
Sulfate (SO_4)	57	32	41	583	34	130	325	34	112
Chloride (Cl)	39	10	20	285	10	62	160	15	55
Fluoride (F)	.6	.0	.3	.4	.0	.2	1.1	.1	.3
Nitrate (NO_3)	24	2.4	10	44	.4	14	45	3.8	23
Orthophosphate (PO_4)	2.7	.08	.97	2.3	.00	.64	1.7	.28	.81
Dissolved solids	190	85	145	1520	107	378	808	144	327
Hardness as $CaCO_3$	113	43	71	442	47	125	249	62	116
Noncarbonate hardness as $CaCO_3$	64	24	43	327	37	102	247	30	98
Specific conductance - micromhos at 25°C	320	149	234	2450	159	562	1250	212	499
pH - units	8.3	5.8	--	9.2	5.1	--	7.9	4.9	--
Color - Pt-Co units	15	1	6	100	1	25	90	4	25
MBAS (detergents)	.02	.01	--	1.0	.01	--	--	--	--
Dissolved oxygen	13.4	3.6	--	13.4	5.0	--	13.8	2.8	--
Biochemical-oxygen demand	7.8	1.3	--	8.0	3.5	--	7.8	.3	--
Coliform bacteria - colonies per 100 ml	40000	25	--	100000	1100	--	57000	38	--

Table 3.--Maximum, minimum and mean observations of major water-quality parameters at selected sampling sites in the Raritan River basin, 1959-72. Analyses in milligrams per liter except as noted--Continued.

	South River at Old Bridge		
	Maximum	Minimum	Mean
Number of samples	33		
Silica (SiO_2)	9.6	2.8	6.0
Iron (Fe) µg/l	2400	60	596
Manganese (Mn) µg/l	240	10	148
Calcium (Ca)	14	5.8	8.7
Magnesium (Mg)	3.9	1.0	3.0
Sodium (Na)	8.5	3.3	5.2
Potassium (K)	12	2.0	3.3
Bicarbonate (HCO_3)	4	0	1
Carbonate (CO_3)	0	0	0
Sulfate (SO_4)	56	23	36
Chloride (Cl)	20	6.5	10
Fluoride (F)	.3	.0	.1
Nitrate (NO_3)	9.3	1.3	3.6
Orthophosphate (PO_4)	.24	.00	
Dissolved solids	118	66	81
Hardness as $CaCO_3$	43	21	35
Noncarbonate hardness as $CaCO_3$	42	21	34
Specific conductance - micromhos at 25°C	205	101	141
pH - units	7.4	4.0	--
Color - Pt-Co units	8	0	4
MBAS (detergents)	.02	.01	--
Dissolved oxygen	9.5	6.8	--
Biochemical-oxygen demand	1.9	1.0	--
Coliform bacteria - colonies per 100 ml	680	250	--

Table 4.--Chemical analyses of selected surface waters in the Raritan River basin, 1923-25.

[N, trace. Data after Collins and Howard (1927)]

DATE	DIS-CHARGE (CFS)	DIS-SOLVED SILICA (SIO2) (MG/L)	TOTAL IRON (FE) (UG/L)	DIS-SOLVED IRON (FE) (UG/L)	DIS-SOLVED CAL-CIUM (CA) (MG/L)	DIS-SOLVED MAG-NE-SIUM (MG) (MG/L)	DIS-SOLVED SODIUM (NA) (MG/L)	DIS-SOLVED SODIUM PLUS POTAS-SIUM (MG/L)	DIS-SOLVED PO-TAS-SIUM (K) (MG/L)
01396500 - S BR RARITAN R NR HIGH BRIDGE NJ (LAT 40 40 40 LONG 074 52 45)									
AUG., 1923 29...	31	14	280	30	16	4.8	--	8.8	--
OCT., 1924 16...	47	13	60	0	14	7.3	--	5.8	--
MAR., 1925 21...	227	4.3	150	30	--	--	--	4.4	--
01397000 - S BR RARITAN R AT STANTON NJ (LAT 40 34 21 LONG 074 52 10)									
AUG., 1923 29...	50	15	320	80	16	5.1	--	8.4	--
JULY, 1924 16...	106	8.0	130	30	15	6.0	--	5.2	--
OCT. 16...	80	9.3	--	80	15	6.9	--	6.3	--
MAR., 1925 24...	422	15	180	40	11	4.0	--	7.1	--
01398500 - N BR RARITAN R NR FAR HILLS NJ (LAT 40 42 30 LONG 074 38 11)									
AUG., 1923 16...	5.0	14	190	30	10	4.2	--	4.1	--
FEB., 1924 05...	134	14	--	20	8.2	3.0	5.4	--	1.0
JULY 16...	17	9.7	100	20	14	7.9	--	4.2	--
AUG. 13...	19	15	170	30	10	3.9	--	5.8	--

DATE	BICAR-BONATE (HCO3) (MG/L)	CAR-BONATE (CO3) (MG/L)	DIS-SOLVED SULFATE (SO4) (MG/L)	DIS-SOLVED CHLO-RIDE (CL) (MG/L)	DIS-SOLVED NITRATE (NO3) (MG/L)	DIS-SOLVED SOLIDS (RESI-DUE AT 180 C) (MG/L)	HARD-NESS (CA,MG) (MG/L)	NON-CAR-BONATE HARD-NESS (MG/L)
01396500 - S BR RARITAN R NR HIGH BRIDGE NJ (LAT 40 40 40 LONG 074 52 45)								
AUG., 1923 29...	89	0	5.1	2.9	.9	94	60	0
OCT., 1924 16...	71	4	7.7	3.0	.7	89	65	0
MAR., 1925 21...	34	0	8.4	2.3	.4	67	34	6
01397000 - S BR RARITAN R AT STANTON NJ (LAT 40 34 21 LONG 074 52 10)								
AUG., 1923 29...	82	0	8.2	3.1	.7	101	61	0
JULY, 1924 16...	68	0	11	2.9	.7	90	62	6
OCT. 16...	78	0	10	4.4	1.5	90	66	2
MAR., 1925 24...	40	0	16	3.0	1.2	80	44	11
01398500 - N BR RARITAN R NR FAR HILLS NJ (LAT 40 42 30 LONG 074 38 11)								
AUG., 1923 16...	46	0	8.0	3.9	N.0	74	42	4
FEB., 1924 05...	33	0	12	2.9	.6	68	33	6
JULY 16...	74	0	8.9	2.5	.5	90	67	6
AUG. 13...	46	0	9.5	3.3	1.1	72	41	3

Table 4.--Chemical analyses of selected surface waters in the Raritan River basin, 1923-25--Continued.

[N, trace. Data after Collins and Howard (1927)]

DATE	DIS-CHARGE (CFS)	DIS-SOLVED SILICA (SIO2) (MG/L)	TOTAL IRON (FE) (UG/L)	DIS-SOLVED IRON (FE) (UG/L)	DIS-SOLVED CAL-CIUM (CA) (MG/L)	DIS-SOLVED MAG-NE-SIUM (MG) (MG/L)	DIS-SOLVED SODIUM (NA) (MG/L)	DIS-SOLVED SODIUM PLUS POTAS-SIUM (MG/L)	DIS-SOLVED PO-TAS-SIUM (K) (MG/L)
01400000 - N BR RARITAN R NR RARITAN NJ (LAT 40 34 10 LONG 074 40 45)									
AUG., 1923									
29...	102	14	1400	100	18	5.6[1]	--	8.6	--
FEB., 1924									
05...	480	9.9	850	30	12	4.5	4.8	--	2.9
APR.									
08...	1290	11	430	30	9.0	5.3	--	3.3	--
MAR., 1925									
24...	390	22	150	30	13	4.2	--	7.1	--
01400500 - RARITAN R AT MANVILLE NJ (LAT 40 33 18 LONG 074 35 02)									
AUG., 1923									
12...	62	7.0	330	30	18	6.8	--	9.5	--
FEB., 1924									
04...	610	12	50	50	12	3.2	12	--	1.4
OCT.									
14...	158	8.0	130	0	17	6.7	--	9.3	--
MAR., 1925									
21...	1600	14	360	110	19	3.1	--	2.8	--
01401000 - STONY BR AT PRINCETON NJ (LAT 40 19 59 LONG 074 40 56)									
AUG., 1925									
12...	--	5.5	210	130	15	4.2	--	11	--

DATE	BICAR-BONATE (HCO3) (MG/L)	CAR-BONATE (CO3) (MG/L)	DIS-SOLVED SULFATE (SO4) (MG/L)	DIS-SOLVED CHLO-RIDE (CL) (MG/L)	DIS-SOLVED NITRATE (NO3) (MG/L)	DIS-SOLVED SOLIDS (RESI-DUE AT 180 C) (MG/L)	HARD-NESS (CA,MG) (MG/L)	NON-CAR-BONATE HARD-NESS (MG/L)
01400000 - N BR RARITAN R NR RARITAN NJ (LAT 40 34 10 LONG 074 40 45)								
AUG., 1923								
29...	67	0	23	4.5	1.0	115	68	13
FEB., 1924								
05...	27	0	30	3.5	3.6	86	48	26
APR.								
08...	22	0	19	2.8	4.8	71	44	26
MAR., 1925								
24...	35	0	26	4.5	.7	84	50	21
01400500 - RARITAN R AT MANVILLE NJ (LAT 40 33 18 LONG 074 35 02)								
AUG., 1923								
12...	59	6	19	5.8	.8	105	73	15
FEB., 1924								
04...	44	0	27	3.0	2.1	88	43	7
OCT.								
14...	68	0	24	3.6	.5	107	70	14
MAR., 1925								
21...	28	0	28	3.5	2.1	84	60	37
01401000 - STONY BR AT PRINCETON NJ (LAT 40 19 59 LONG 074 40 56)								
AUG., 1925								
12...	48	0	22	8.8	N.0	97	55	16

Table 5.--Summary of observations of trace elements, 1963-71.

Stream and Location	Analyses		Aluminium (Al)	Barium (Ba)	Boron (B)	Chromium (Cr)	Cobalt (Co)	Copper (Cu)	Iron (Fe)	Lead (Pb)	Lithium (Li)	Manganese (Mn)	Molybdenum (Mo)	Nickel (Ni)	Rubidium (Rb)	Silver (Ag)	Strontium (Sr)	Titanium (Ti)	Vanadium (V)	Zinc (Zn)
S B Raritan	1	<S	19	18	35	--	--	1.0	90	2.0	1.0	11	--	--	1.0	--	30	--	--	--
R. nr High			0	0	0	1	1	0	0	0	0	0	1	1	0	1	0	1	1	1
Bridge																				
Spruce Run	1	<S	14	33	40	--	--	1.0	510	4.0	0.3	640	--	1.0	0.6	--	60	--	--	--
at Clinton			0	0	0	1	1	0	0	0	0	0	1	0	0	1	0	1	1	1
S B Raritan	9	<S	150	41	60	0.5	0.9	340	500	10	2.0	420	1.0	16	2.0	0.4	80	8.0	2.0	--
R. at Stanton			6.7	14	11	ND	ND	.8	35	1.6	.3	9.0	ND	ND	1.0	ND	8.2	2.0	ND	ND
			0	0	0	7	6	0	0	1	1	0	5	1	1	5	0	4	4	8
N B Raritan	2	<S	50	29	50	--	--	18	180	6.0	0.7	110	1.0	12	0.2	--	63	3.0	1.0	--
R. nr Far			20	16	20	--	--	2.0	110	1.0	--	95	0.2	1.0	--	--	35	1.0	--	--
Hills			0	0	0	2	2	0	0	0	1	0	0	0	0	2	0	0	1	2
N B Raritan	9	<S	600	52	120	0.8	1.0	14	240	8.0	5.0	72	1.0	47	3.0	0.7	220	16	5.0	--
R. nr			19	21	33	.4	ND	2.0	28	2.0	.8	12	ND	1.0	.9	ND	36	.6	ND	ND
Raritan			0	0	0	7	5	0	0	1	1	0	3	1	1	7	0	1	3	7
Raritan R.	9	<S	510	100	570	320	--	23	200	7.0	27	95	14	16	5.0	0.3	1100	18	6.0	--
(nr) Man-			27	26	27	1.0	ND	3.0	20	2.0	2.0	26	.6	3.0	.9	ND	100	2.0	ND	ND
ville			0	0	0	3	7	0	0	3	1	0	0	3	2	7	0	4	2	7
Baldwin Cr	1	<S	70	26	44	--	--	4.0	160	3.0	2.0	450	--	7.0	2.0	--	95	2.0	--	--
nr Penn-			0	0	0	1	1	0	0	0	0	0	1	0	0	1	0	0	1	1
ington																				
Stony Brk. at	8	<S	900	79	90	4.0	--	28	470	7.0	5.0	140	3.0	7.0	7.0	--	320	19	6.0	--
Princeton			15	25	29	.3	ND	2.0	42	.7	.4	13	ND	3.0	1.0	ND	60	1.0	ND	ND
			0	0	0	5	7	5	0	2	1	0	1	1	1	7	0	3	2	7
Millstone R.	5	<S	460	60	120	2.0	0.7	46	350	6.0	4.0	250	4.0	7.0	12	0.6	160	14	3.0	--
at Blackwells			21	38	24	.2	ND	5.0	35	2.0	.7	44	ND	4.0	3.0	ND	25	.6	ND	ND
Mills			0	0	0	1	2	0	0	0	0	0	0	0	1	1	0	1	1	4
Millstone R.	4	<S	230	45	110	5.0	--	13	450	5.0	5.0	140	6.0	25	6.0	--	160	10	3.0	--
nr Manville			17	41	51	--	--	3.0	55	2.0	2.0	70	1.0	3.0	.4	--	130	2.0	1.0	ND
			0	0	0	3	4	0	0	1	1	0	0	0	0	4	0	1	0	3
Raritan R. at	3	<S	70	50	110	8.0	--	11	120	2.0	8.0	440	10	13	13	--	310	1.0	3.0	--
Bound Brook			23	49	70	2.0	--	3.0	51	--	4.0	150	3.0	7.0	5.0	--	140	--	1.0	--
			0	0	0	1	3	0	0	2	0	0	0	0	0	3	0	2	1	3
Raritan R. at	3	<S	50	62	170	2.0	--	8	250	3.0	8.0	660	12	13	7.0	--	360	7.0	--	--
S Bound Brook			40	31	46	--	--	6	55	--	3.0	67	2.0	5.0	7.0	--	110	3.0	--	--
			0	0	0	2	3	0	0	2	1	0	0	0	0	3	0	1	3	3

<S - less than sensitivity
ND - sought but not detected

Table 6.--Summary of phenolic-material content of water samples collected at sampling sites in the Raritan River basin.

Stream and location	Map no. (fig. 4)	Number of samples	Samples above lower limit of detection Number	Range (ug/1)	Average (ug/1)
Raritan River near Manville	10	27	15	2.5-22	8.0
Raritan River below Calco Dam, at Bound Brook	21	11	11	5.0-340	101
Raritan River at Bound Brook	22	30	26	6.0-184	42
Raritan River near South Bound Brook	26	102	102	3.0-312	58
Honey Branch at Princeton	13	1	0	--	--
Stony Brook at Princeton	14	10	6	2.0-13	5.1
Millstone River at Blackwells Mills	17	7	2	9.3-9.5	9.4
Millstone River near Manville	20	6	2	5.0-20	12
Green Brook at Bound Brook	25	20	14	2.5-112	14
Lawrence Brook at Farrington Dam	28	1	1	1.3	1.3
South River at Old Bridge	31	5	2	2.0-3.5	2.8

A review of the phenolic-material content of water at 45 stream-sampling sites were reported recently (Faust and others, 1971). Of these sampling sites, 11 were in the Raritan River basin (table 6). Results indicate higher concentrations of phenols in the basin than were found in unpolluted streams in other parts of the State.

Of the 43 samples collected from the Millstone River at Blackwells Mills (fig. 4, site 17) and near Manville (site 20), and on the Raritan River near Manville (site 10), 19 contained phenolic materials in excess of the lower limit of detection of 1.3 ug/l. The maximum concentration observed was 22 ug/l.

As the Raritan River moves downstream from its confluence with the Millstone River near Manville, it passes through an urban, industrial complex, where substantial volumes of waste waters are discharged. At the Calco Dam station (site 21), phenols were detected in all 11 samples, with a maximum concentration of 340 ug/l. At the Bound Brook station (site 22), concentrations in 26 of 30 samples exceeded the lower limit of detection, with a maximum of 184 ug/l. The maximum phenol content of 102 samples collected about 1.6 mi (2.6 km) farther downstream near South Bound Brook (site 26) was 312 ug/l.

Samples were collected also from several tributaries; Green Brook (site 25), South River (site 31), Lawrence Brook (site 28), Honey Branch (site 13), and Stony Brook (site 14). Concentrations of phenolic materials in 23 of the 37 samples collected on these tributary stations exceeded the lower limt of detection.

Because of the consistently high phenol concentrations observed at South Bound Brook (site 26), 69 samples were collected at this site to determine the cross-channel distribution of phenolic material. The average concentrations were: right side (facing downstream), 57 ug/l; center, 51 ug/l; and left, 66 ug/l. On the basis of individual samples, it would appear that some channeling effects are present, as samples collected from the right and left sides of the river generally yielded higher phenol contents than those collected at the center.

The results of a 24-hr survey of samples collected at the center of the river on October 7-8, 1968 to determine variations in phenol content during a small storm are plotted in figure 12. Maximum concentrations occurred between 0845 and 1645. Streamflow variations during the sampling period also are plotted. An increase in phenol content is evident as flow increased between the hours of 1100 and 1400. Subsequently, the phenol content decreased, as flow continued to increase.

Because phosphate is one of the nutrients that stimulates and supports excessive and undersirable growth of aquatic plants, it is receiving greater attention in most water-resources management programs. Also, at relatively high concentrations it is known to interface with coagulation processes in water-supply treatment (Stumm, 1964).

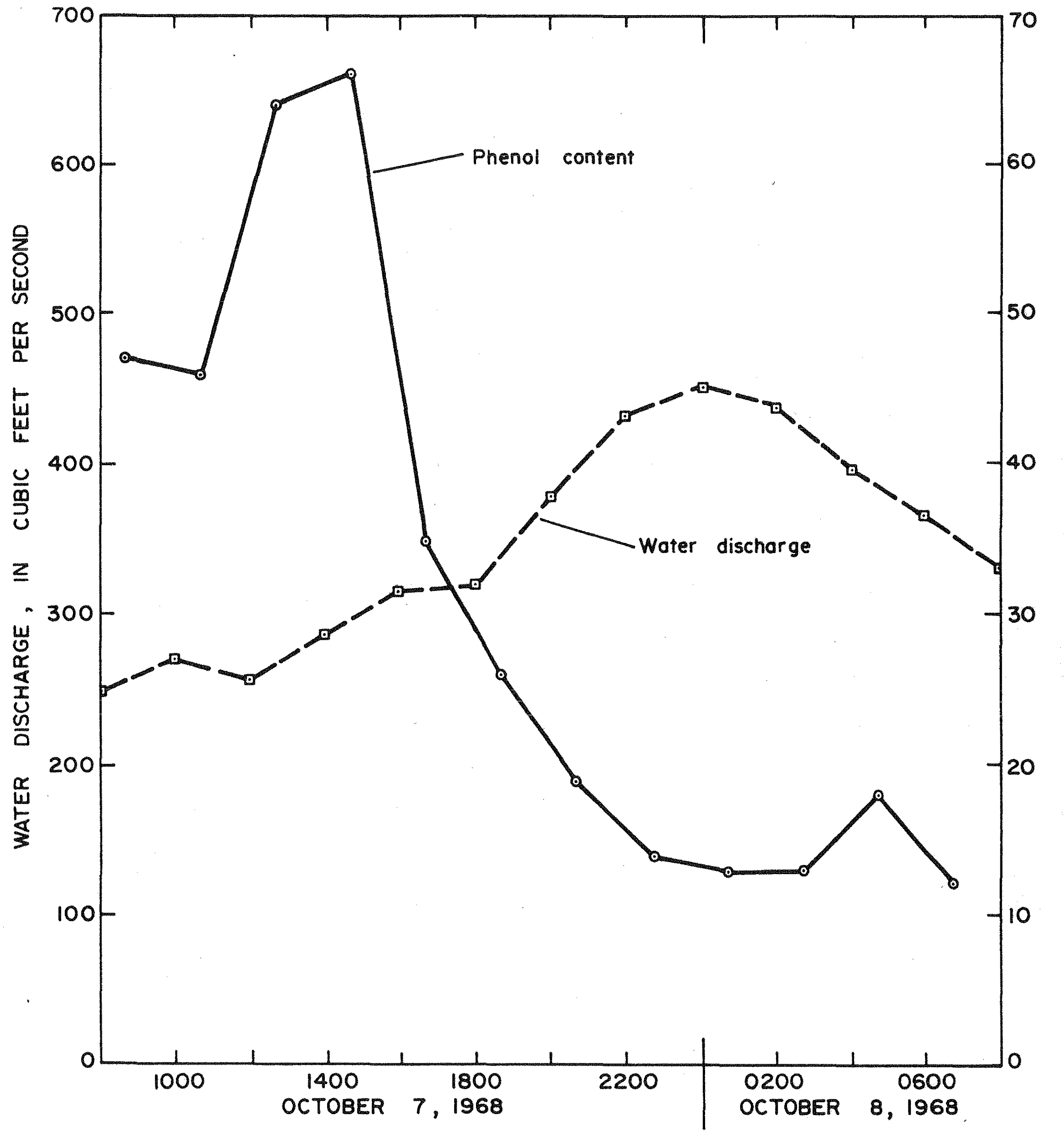

Figure 12.--Variations in phenolic-material content and streamflow during 24-hour surveillance, Raritan River at South Bound Brook.

With the exception of observations at Old Bridge, data presented in table 3 indicate that artifical sources, and not weathering processes (Stumm, 1964; Hem, 1970), probably are the controlling factor in phosphate content at sampling sites in the basin. Land use in the North Branch Raritan, South Branch Raritan, and upper Millstone River subbasins is mostly agricultural, hence the sources of phosphate, other than those of natural contamination, presumably are related to factors associated with agricultural and farm-community runoff. High concentrations found in the main stem Raritan and lower Millstone Rivers most probably are associated with the large amounts of municipal and industrial waste-water discharges in that area.

Detergents (MBAS, table 3), usually associated with municipal waste-water effluents, have decreased in concentrations since 1966, probably owing to the advent of biodegradable compounds.

A special pesticide sampling program was conducted in 1967-68. Water and bed-material samples were collected at six stream-sampling stations and at three sites in Carnegie Lake (fig. 1). The results for samples analyzed for 10 chlorinated-hydrocarbon pesticides are summarized on table 7.

The water-phase data indicate the presence of DDT and its metabolities, DDD and DDE, and some dieldrin and lindane in the Stony Brook and Carnegie Lake samples. Concentrations were slightly higher in samples collected in the spring than those collected in the fall, perhaps indicating an input from agricultural usage.

The bed-material data indicate only the presence of the DDT family. The concentration of DDT and related compounds in bed materials collected at the Carnegie Lake boathouse was greater in samples collected in the spring, although at other sites in the area the concentration was greater in samples collected in the fall. The reason for this is unclear, but may be related to sampling techniques or bed movement. It also may represent recent higher pesticide inputs from Stony Brook than from the Millstone River. The concentration of DDT and DDD in Carnegie Lake bed-material samples are 1000 times greater than those observed in the water phase. The high concentrations of DDD may result from the degradation of DDT. These data may indicate a situation where DDT entered the water medium at a time in the past, and was incorporated in the sediments as a persistent residue. There undoubtably has been a buildup over a period of time, but the lack of previous data precludes any quantitative conclusion.

Stream sedimentation has been important to agricultural experts for many years. It is a significant factor to be considered in any investigation of soil-conservation practices. More recently--perhaps within the last 10-20 years--the significance of a basic knowledge of stream sedimentation to public-water supply superintendents, engineers who design reservoirs or maintain navigable channels, fishery biologists, and water-pollution control officials has increased tremendously.

Anderson and George (1966, p. G38) estimated on the basis of stream sedimentation and turbidity data that annual sediment yields in the Raritan River basin ranges from 10 to 500 tons/mi^2 (3-200 tons/km^2). Although the data were scant, Anderson and George believed that their estimated values were at least in the correct order of magnitude.

Table 7.--Pesticide analyses of water and bed-material samples collected in the Raritan River basin.

DATE	ALDRIN (UG/L)	DDD (UG/L)	DDE (UG/L)	DDT (UG/L)	DI-ELDRIN (UG/L)	ENDRIN (UG/L)	HEPTA-CHLOR (UG/L)	LINDANE (UG/L)	2,4-D (UG/L)	2,4,5-T (UG/L)
01396500 - S BR RARITAN R NR HIGH BRIDGE NJ (LAT 40 40 40 LONG 074 52 45)										
OCT., 1968										
24...	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
01397000 - SO BR RARITAN R AT STANTON NJ (LAT 40 34 21 LONG 074 52 10)										
OCT., 1968										
24...	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
01398500 - NO BR RARITAN R NR FAR HILLS NJ (LAT 40 42 30 LONG 074 38 11)										
OCT., 1968										
25...	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
01400000 - NO BR RARITAN R NR RARITAN NJ (LAT 40 34 10 LONG 074 40 45)										
OCT., 1968										
25...	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
01401000 - STONY BR AT PRINCETON NJ (LAT 40 19 59 LONG 074 40 56)										
SEP., 1967										
15...	.00	.00	.00	.00	.00	.00	.00	<.01	--	--
MAY , 1968										
20...	.00	.01	.01	.03	.01	.00	.00	.01	--	--
01401240 - CARNEGIE LK AT BOATHOUSE AT PRINCETON NJ (LAT 40 20 22 LONG 074 38 59)										
SEP., 1967										
15...	.00	.02	.00	.02	.01	.00	.00	<.01	--	--
MAY , 1968										
20...	.00	.04	.08	.25	.00	.00	.00	<.01	--	--
01401260 - CARNEGIE LK BEL MILLSTONE AT PRINCETON NJ (LAT 40 20 48 LONG 074 37 42)										
SEP., 1967										
15...	.00	.01	.00	.00	.03	.00	.00	<.01	--	--
MAY , 1968										
20...	.00	.03	.05	.01	.20	.00	.00	<.01	--	--
01401290 - CARNEGIE LK .25 MI AB DAM AT PRINCETON NJ (LAT 40 21 58 LONG 074 37 30)										
SEP., 1967										
15...	.00	.01	.00	.01	.03	.00	.00	<.01	--	--
MAY , 1968										
20...	.00	.01	.02	.01	.10	.00	.00	.01	--	--
01402000 - MILLSTONE RIVER AT BLACKWELLS MILLS, N.J. (LAT 40 28 30 LONG 074 34 34)										
OCT., 1968										
25...	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00

Table 7.--Pesticide analyses of water and bed-material samples collected in the Raritan River basin--Continued.

DATE	SILVEX (UG/L)	ALDRIN IN BOTTOM DE-POSITS (UG/KG)	DDD IN BOTTOM DE-POSITS (UG/KG)	DDE IN BOTTOM DE-POSITS (UG/KG)	DDT IN BOTTOM DE-POSITS (UG/KG)	DI-ELDRIN IN BOTTOM DE-POSITS (UG/KG)	ENDRIN IN BOTTOM DE-POSITS (UG/KG)	HEPTA-CHLOR IN BOTTOM DE-POSITS (UG/KG)	LINDANE IN BOTTOM DE-POSITS (UG/KG)
01396500 - S BR RARITAN R NR HIGH BRIDGE NJ (LAT 40 40 40 LONG 074 52 45)									
OCT., 1968 24...	.00	.0	.0	.0	2.5	.0	.0	.0	.0
01397000 - SO BR RARITAN R AT STANTON NJ (LAT 40 34 21 LONG 074 52 10)									
OCT., 1968 24...	.00	.0	.0	.0	.0	.0	.0	.0	.0
01398500 - NO BR RARITAN R NR FAR HILLS NJ (LAT 40 42 30 LONG 074 38 11)									
OCT., 1968 25...	.00	.0	.0	.0	.0	.0	.0	.0	.0
01400000 - NO BR RARITAN R NR RARITAN NJ (LAT 40 34 10 LONG 074 40 45)									
OCT., 1968 25...	.00	.0	.0	.0	.0	.0	.0	.0	.0
01401000 - STONY BR AT PRINCETON NJ (LAT 40 19 59 LONG 074 40 56)									
SEP., 1967 15...	--	.0	5.0	2.0	20	.0	.0	.0	.0
MAY , 1968 20...	--	.0	2.0	.5	5.0	.0	.0	.0	.0
01401240 - CARNEGIE LK AT BOATHOUSE AT PRINCETON NJ (LAT 40 20 22 LONG 074 38 59)									
SEP., 1967 15...	--	.0	115	3.0	45	.0	.0	.0	<.1
MAY , 1968 20...	--	.0	200	15	75	.0	.0	.0	.0
01401260 - CARNEGIE LK BEL MILLSTONE AT PRINCETON NJ (LAT 40 20 48 LONG 074 37 42)									
SEP., 1967 15...	--	.0	110	2.0	25	.0	.0	.0	.0
MAY , 1968 20...	--	.0	45	6.0	11	.0	.0	.0	.0
01401290 - CARNEGIE LK .25 MI AB DAM AT PRINCETON NJ (LAT 40 21 58 LONG 074 37 30)									
SEP., 1967 15...	--	.0	55	3.0	15	.0	.0	.0	.0
MAY , 1968 20...	--	.0	40	4.0	8.0	.0	.0	.0	.0
01402000 - MILLSTONE RIVER AT BLACKWELLS MILLS, N.J. (LAT 40 28 30 LONG 074 34 34)									
OCT., 1968 25...	.00	.0	.0	.0	.0	.0	.0	.0	.0

Suspended-sediment samples were collected in the basin at nine gaging stations and five partial-record locations to estimate sediment yields and trends. The estimated annual suspended-sediment yields at these sampling sites is given in table 8. With the exception of yields for the Stony Brook at Princeton, these estimates were determined using a method described by Miller (1951). Yields for the Stony Brook are based on daily sediment-discharge records collected during 1956-70.

Several environmental factors control soil erosion and the delivery of suspended sediment to the basin's streams. The more significant variables include physical characteristics of the soils, land, slope, land use or vegetal cover, extent of precipitation and direct runoff, and capacity of the system to transport fine sediments.

The role of some of these environmental factors is illustrated by means of transport curves (fig. 13). For example, in the New England section (fig. 11) of the basin--represented by the High Bridge, Stanton, and Far Hills station curves--erosion rates and, consequently, suspended-sediment concentrations in streams are comparatively low. Poor surface-drainage characteristics combine with rather dense vegetal cover to produce comparatively low yields of sediment to local streams. Generally, in the Piedmont Lowland section--represented by the remaining curves--an abundance of silt- and clay-size sediments in the soils and less vegetal cover produce a higher sediment yield. Typical streams draining the Lowland often remain turbid for relatively long periods (3-6 days) after a storm.

Annual average suspended-sediment yields in streams draining the New England Upland are estimated to range from 25 to 150 tons/mi^2, (10-60 tons/km^2) while those draining the Piedmont Lowland are expected to range from 75 to 500 tons/mi^2 (25-200 tons/km^2). Based on data collected on Coastal Plain tributaries to the Delaware estuary (Mansue, 1972) and in the Millstone River basin above Princeton (Moore and others, 1952), suspended-sediment yields from streams draining the Inner Coastal Plain are expected to range from 50 to 150 tons/mi^2 (20-60 tons/km^2).

In addition to the determination of sediment concentration and load, several samples were analyzed for particle-size distribution. Samples were collected during period when direct runoff comprised most of the flow--usually at discharge rates equaled or exceeded 10 percent of the time--and when suspended-sediment concentrations were high. Because most of the sediment load is transported during storms, these samples closely represent the size distribution of the annual suspended-sediment load.

The average particle-size distributions are illustrated on figure 14 for selected sampling stations in the basin. The American Geophysical Union's classification of particle size is used (Lane and others, 1947). A tabulation of the average particle-size distribution in the suspended sediment samples is given in table 9 for basin sampling stations.

Table 8.--Estimated average annual suspended-sediment yield at selected sampling stations in the Raritan River basin.

Stream and location	Map no. (fig. 4)	Drainage area (mi^2)	Sediment yield ($tons/mi^2$)
South Branch Raritan River near High Bridge	1	65.3	73
South Branch Raritan River at Stanton	3	147	124
North Branch Raritan River near Far Hills	6	26.2	25
North Branch Raritan River near Raritan	8	190	151
Raritan River at Manville	9	490	302
Stony Brook at Glenmoore	--	17.6	169
Honey Branch near Rosedale	--	4.02	139
Stony Brook Tributary No. 3 near Hopewell	--	2.57	28.4
Baldwin Creek at Pennington	--	1.92	405
Woodsville Brook at Woodsville	--	1.86	273
Stony Brook at Princeton	14	44.5	198
Millstone River at Blackwells Mills	17	258	135
Raritan River at Queens Bridge, at Bound Brook	21	799	200

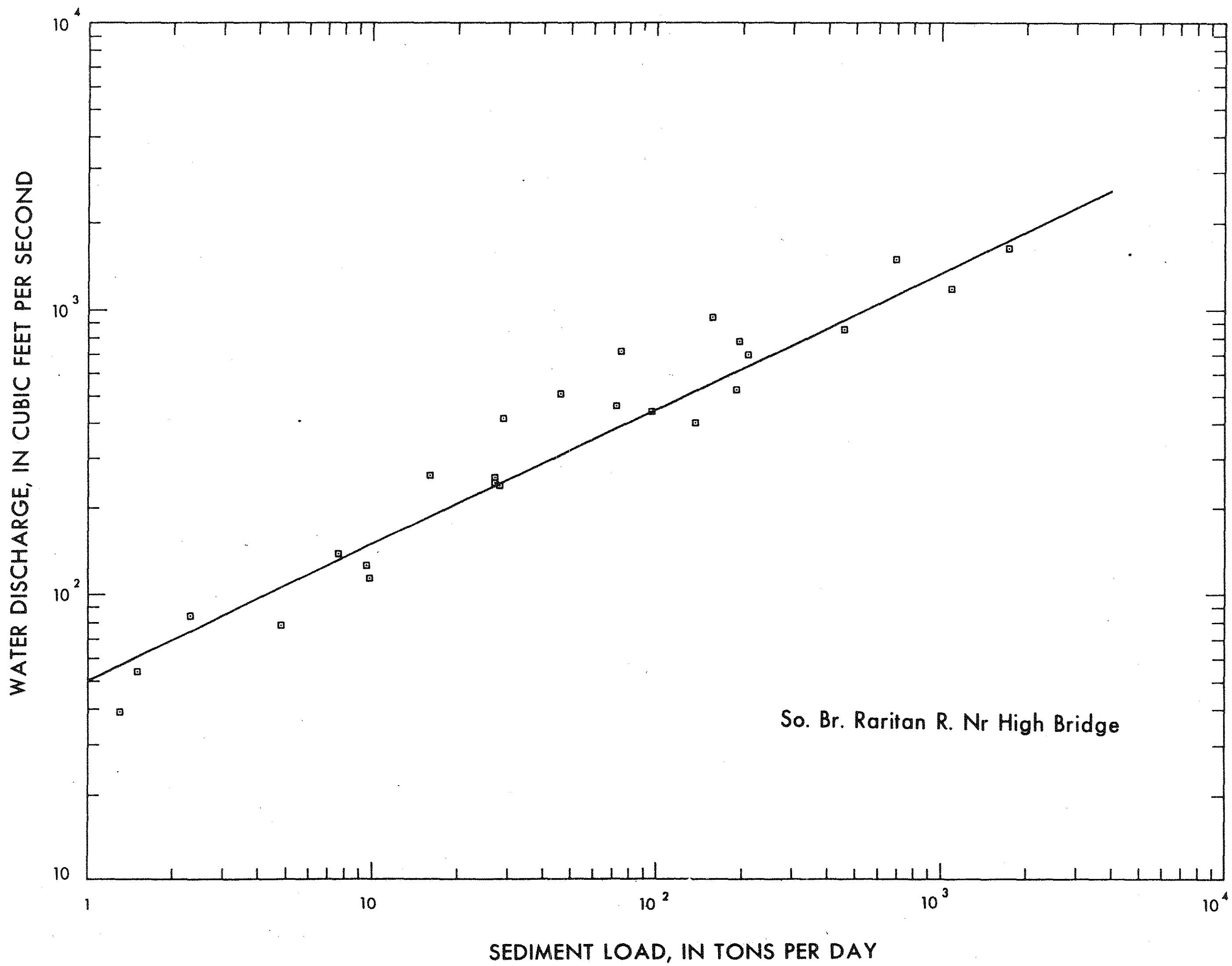

Figure 13.--Relation between suspended sediment load and streamflow at seven sampling locations.

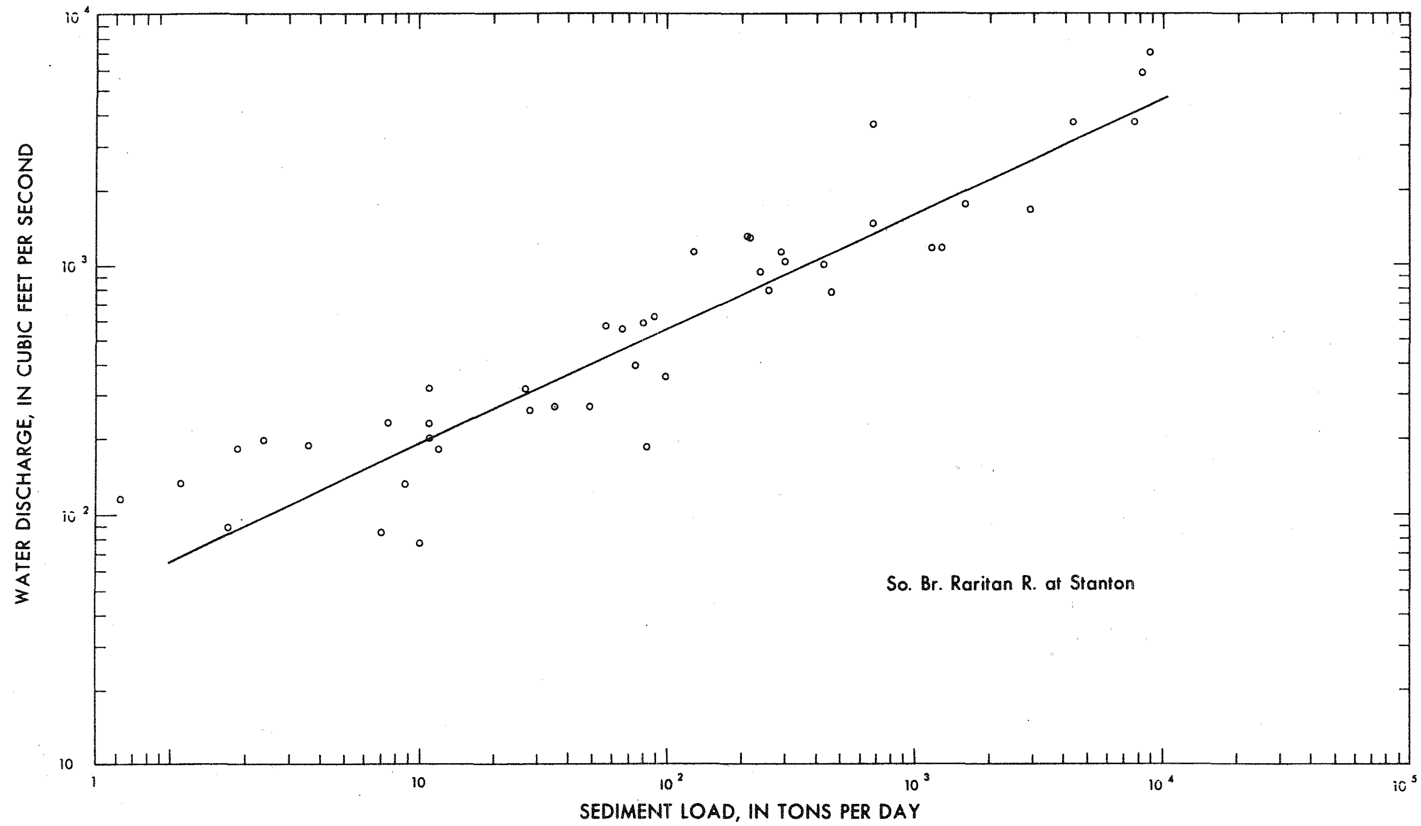

Figure 13.--Continued

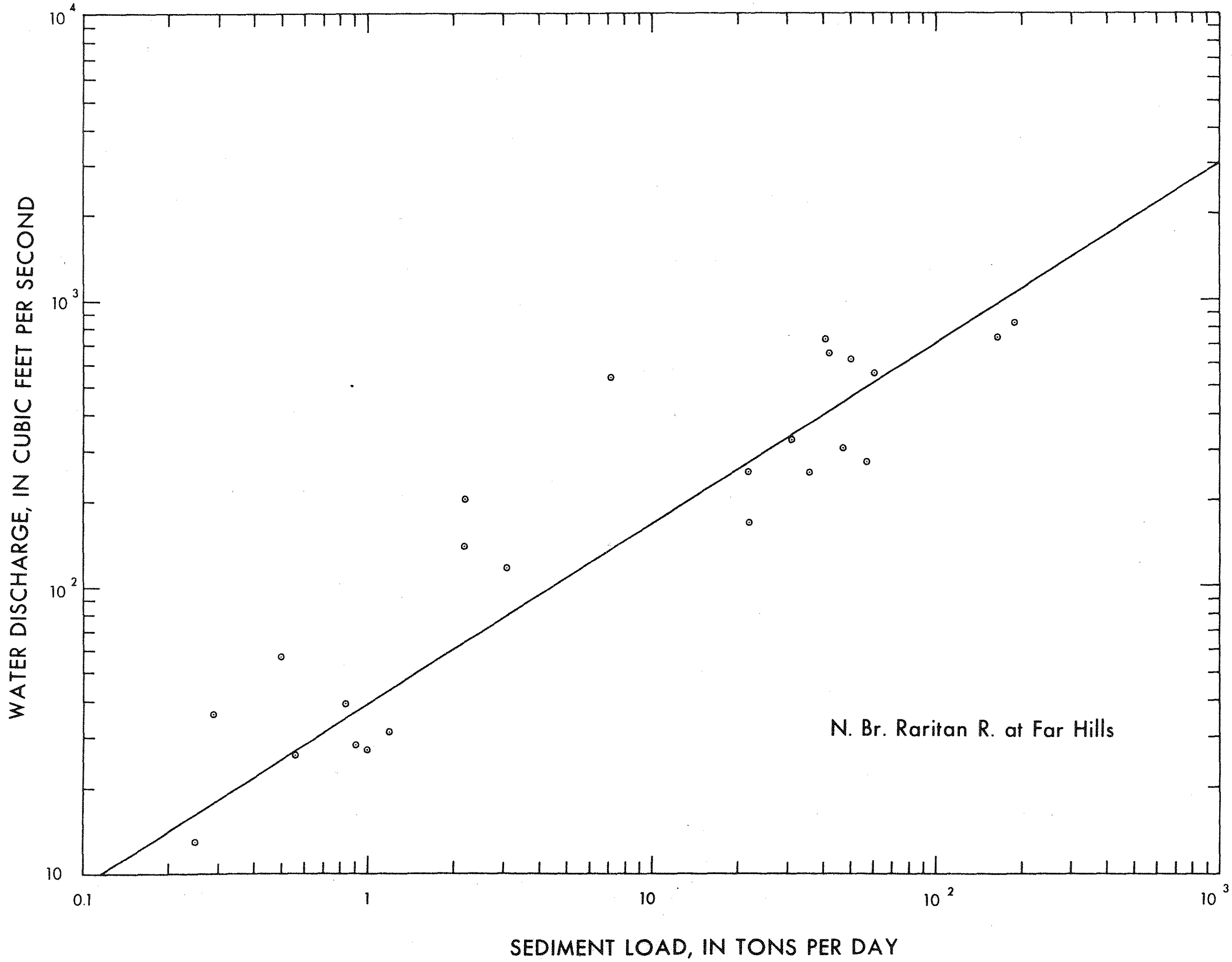

Figure 13.--Continued

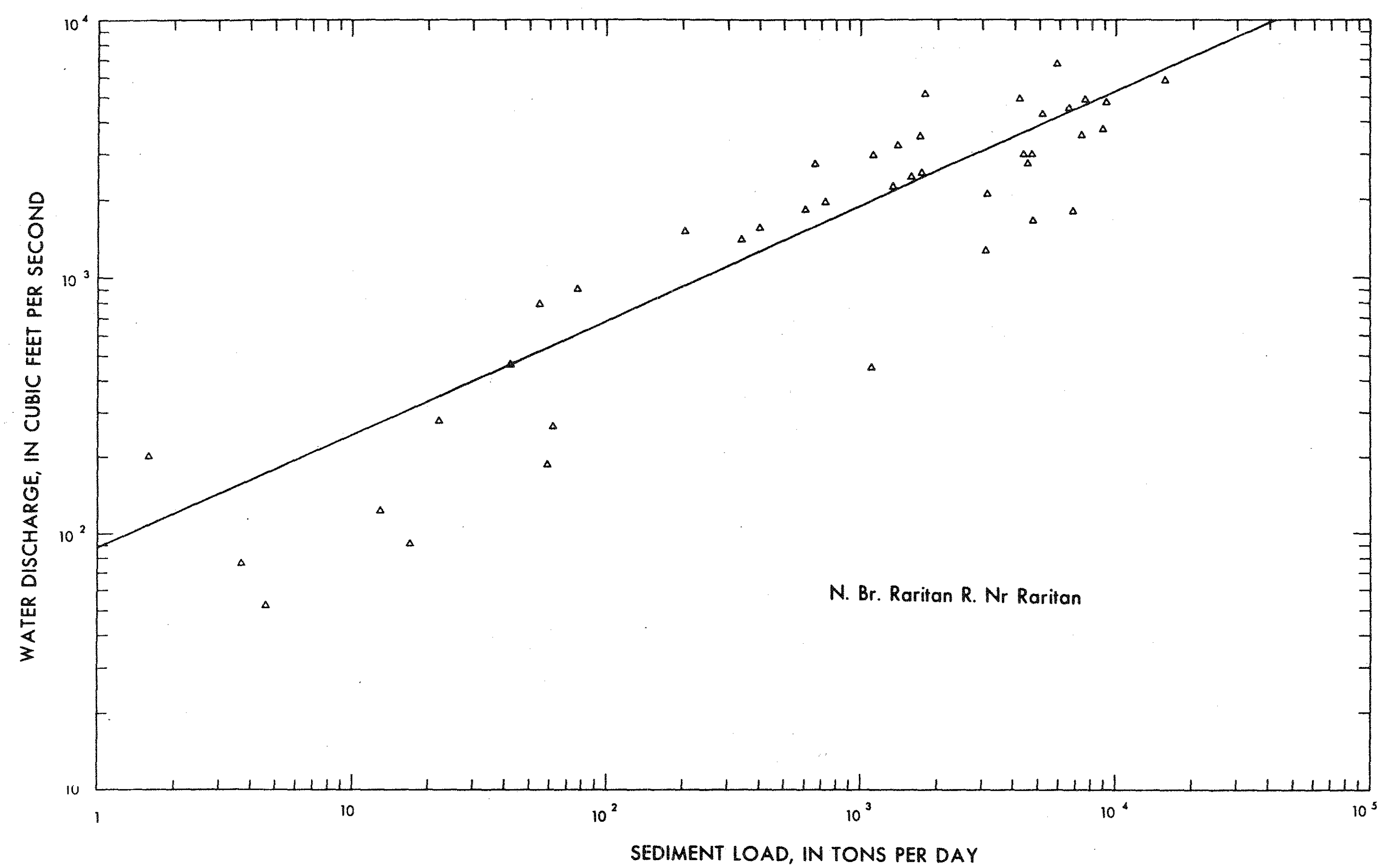

Figure 13.--Continued

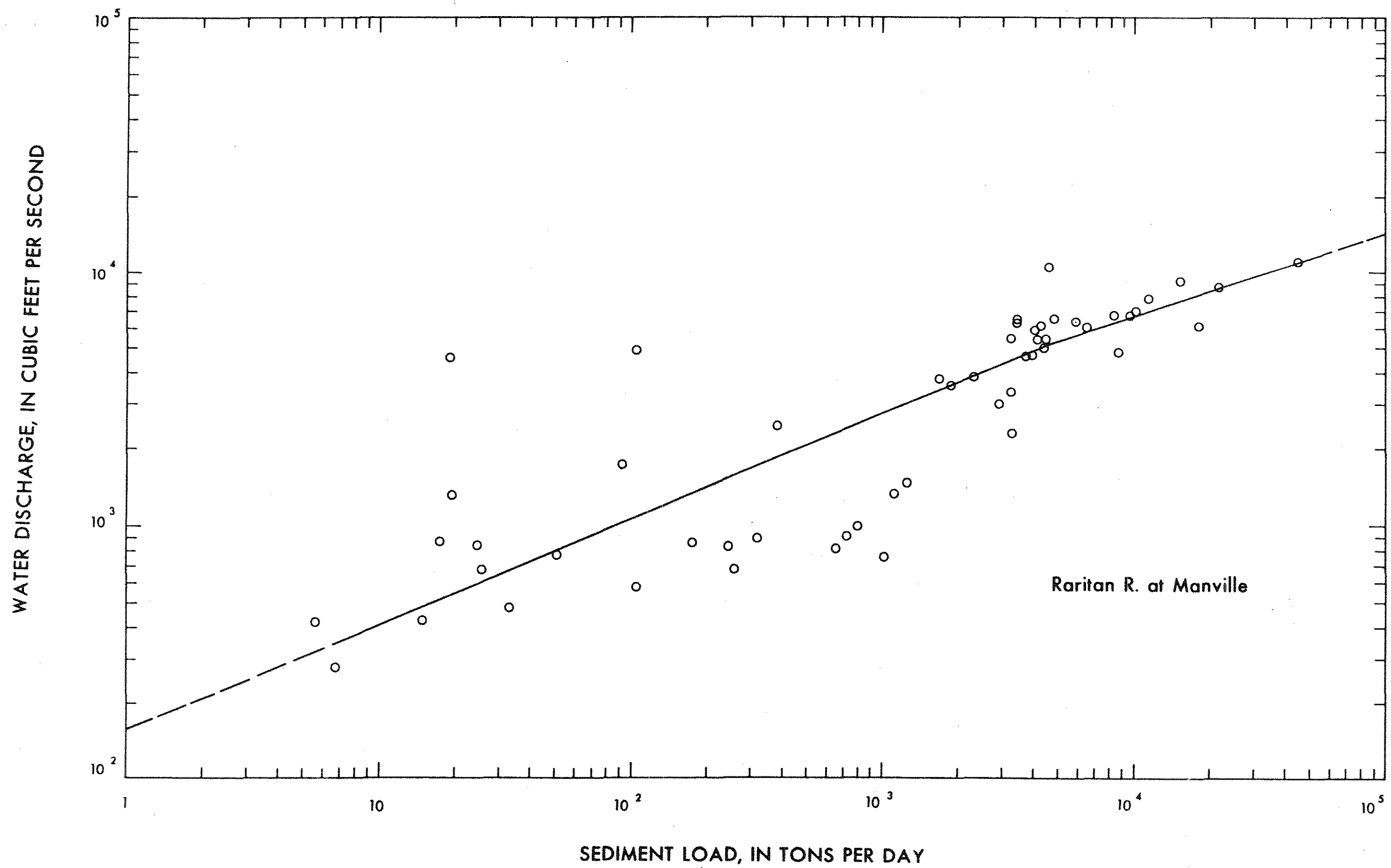

Figure 13.--Continued

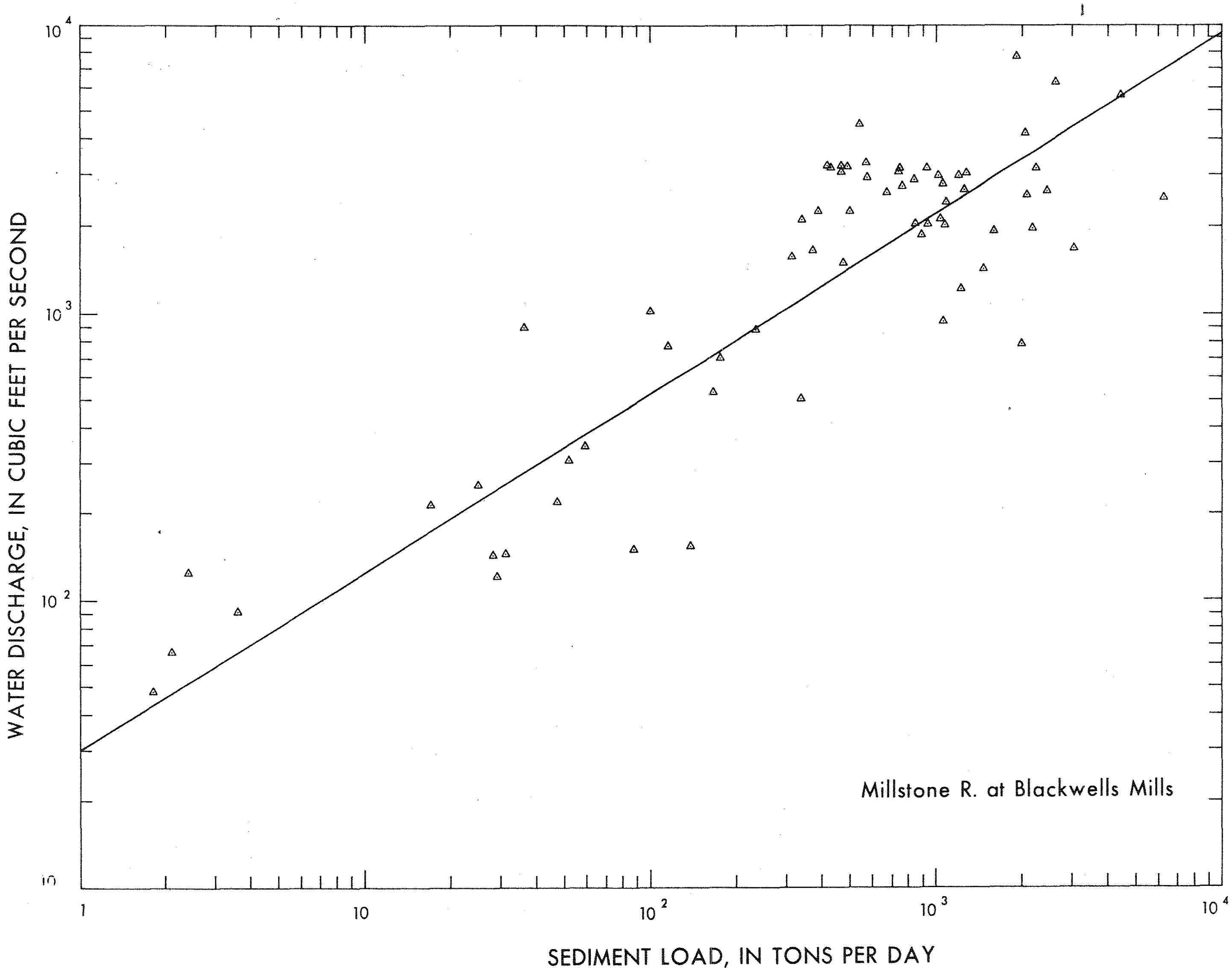

Figure 13.--Continued

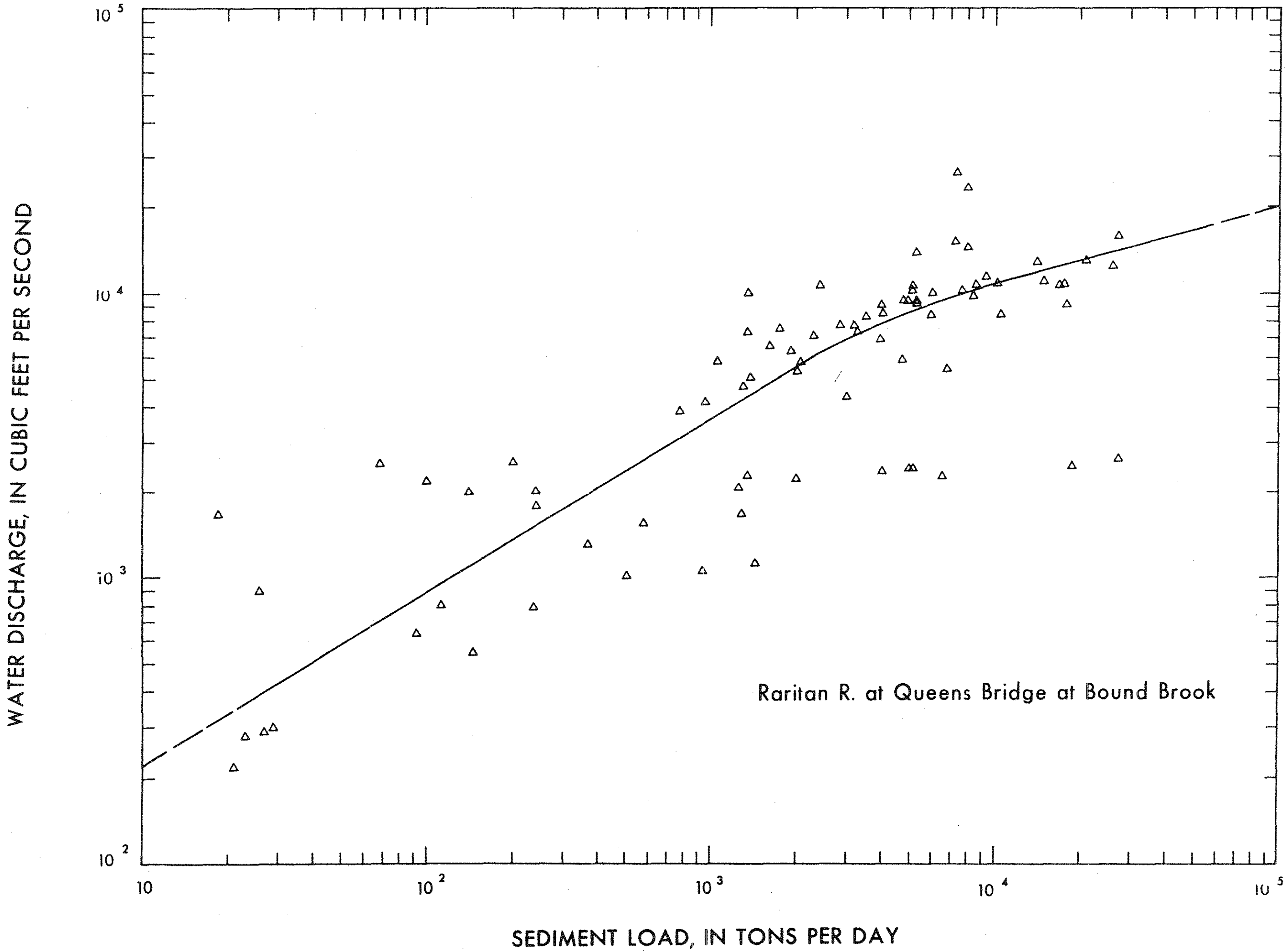

Figure 13.--Continued

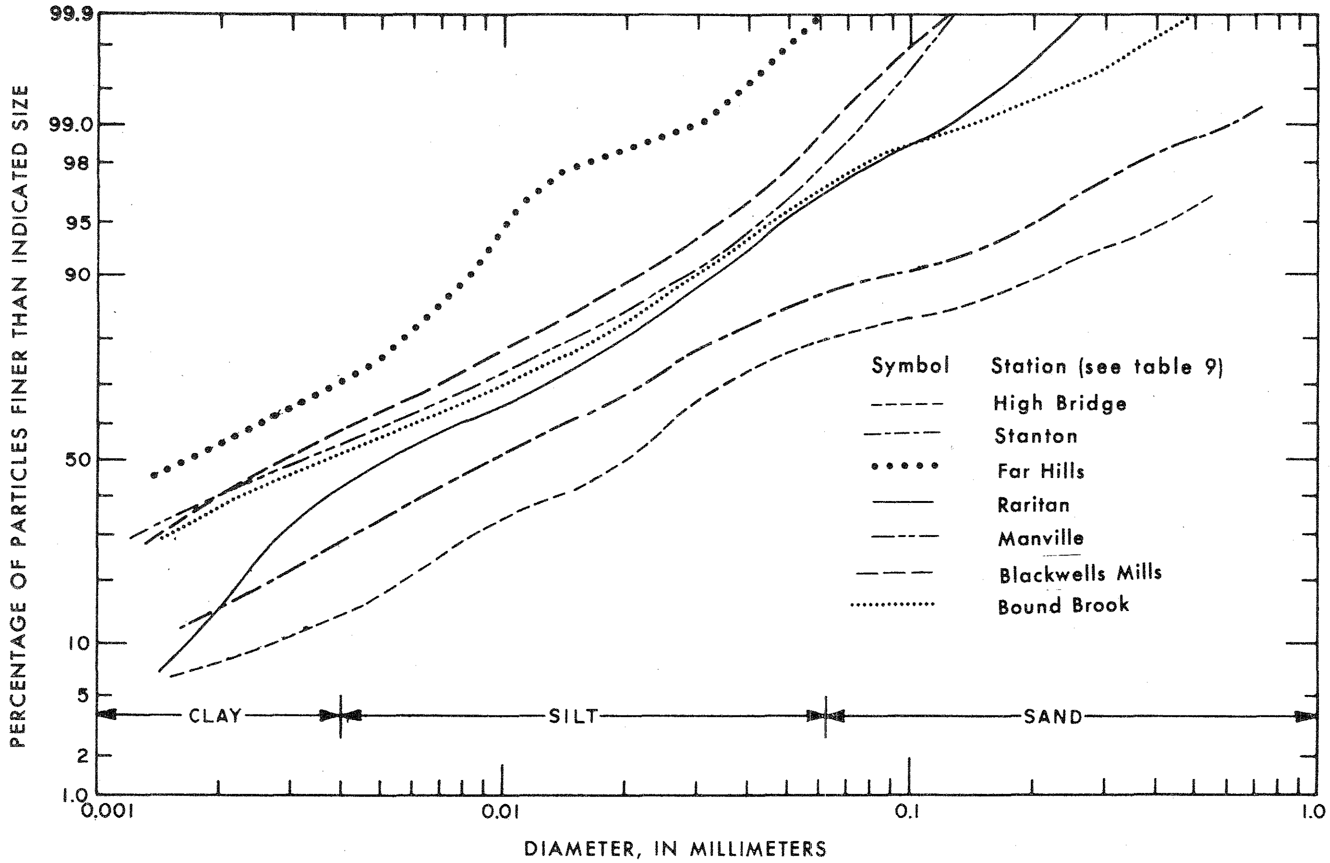

Figure 14.--Particle-size distribution of suspended sediment at selected sampling sites.

Table 9.--Average particle-size distribution of suspended sediments at selected sampling sites in the Raritan River basin, 1955-72.

Stream and location	Percentage of Soil Class		
	Clay	Silt	Sand
South Branch Raritan River near High Bridge	14	66	20
South Branch Raritan River at Stanton	29	59	12
North Branch Raritan River near Far Hills	72	28	0
North Branch Raritan River near Raritan	48	49	3
Raritan River at Manville	54	44	2
Stony Brook at Princeton	50	45	5
Millstone River at Blackwells Mills	60	39	1
Raritan River at Queens Bridge, at Bound Brook	50	47	3

Clay- and silt-size particles predominate (80-100 percent) in suspended sediments transported by streams draining the New England Upland and Piedmont Lowland section of the basin. The high clay fraction reported for the Far Hills sampling site reflects the trapping of larger sizes by a reservoir immediately upstream from this site. Excluding data collected at Far Hills, one notes a lower percentage of clay-size particles at sampling sites in the New England Upland (14-48 percent) than observed at sites in the Piedmont Lowland (50-60 percent). Likewise, silt-size particles predominate (49-66 percent) in Upland streams and are higher in percentage than in streams draining the Lowland (39-47 percent). As noted earlier in discussions regarding time-of-travel measurements (p. 17), velocities in headwater areas of the North and South Branch Raritan Rivers (Upland streams) were among the highest observed in the basin. These higher velocities and, therefore, the greater inherent capacity of these stream waters to transport larger and heavier particles in suspension are reflected in the relatively larger percentages of silt- and sand-size particles observed at stream-sampling sites in the New England Upland.

While particle-size distributions in suspended sediments transported by Inner Coastal Plain streams were not determined during the project, a reasonable estimate can be made based on data collected on Coastal Plain tributaries to the Delaware estuary (Mansue, 1972) and in the upper Millstone River basin (Moore and others, 1952). Clay-size particles (50-65 percent) are dominant, whereas silt sizes make up 10-40 percent and sand sizes 5-25 percent.

Time Variations

Variations in the dissolved-solids content of the Raritan and Millstone Rivers near Manville (fig. 4, sites 10 and 20) between 1957 and 1972 are plotted in figure 15. The 12-month moving average plots of dissolved-solids content is based on once-monthly samples. When these curves are compared with similar plots of streamflow (fig. 6), an inverse relation between the two parameters is evident. Although definite upward trends are apparent, particularly on the plot for the Millstone River, these trends may be related to generally decreasing streamflow. Flow augmentation in the Raritan River since 1964 during low-flow periods, by release of relatively good quality water from Spruce Run Reservoir (table 3, Spruce Run at Clinton), probably accounts for the lesser upward trend in dissolved solids of the Raritan River in relation to that of the Millstone River.

Further comparison of trends in dissolved solids (fig. 15) with similar graphs of streamflow trends (fig. 6) suggested a divergence in the plots with time; that is, the dissolved solids per unit volume of water are increasing with time. For example, the average streamflow of the Millstone River at Blackwells Mills (fig. 4, site 17) during calendar year 1960 was 398 ft^3/s. ($11.3\ m^3/s$), and the average dissolved-solids content in samples collected near Manville, 126 mg/l. However, in 1967 at a flow of 456 ft^3/s, ($12.9\ m^3/s$), dissolved solids increased to 162 mg/l. One would expect that the higher flows during 1967 would have resulted in lower concentrations. Thus, it is postulated that dissolved solids were increasing per unit volume of water at these two sampling sites.

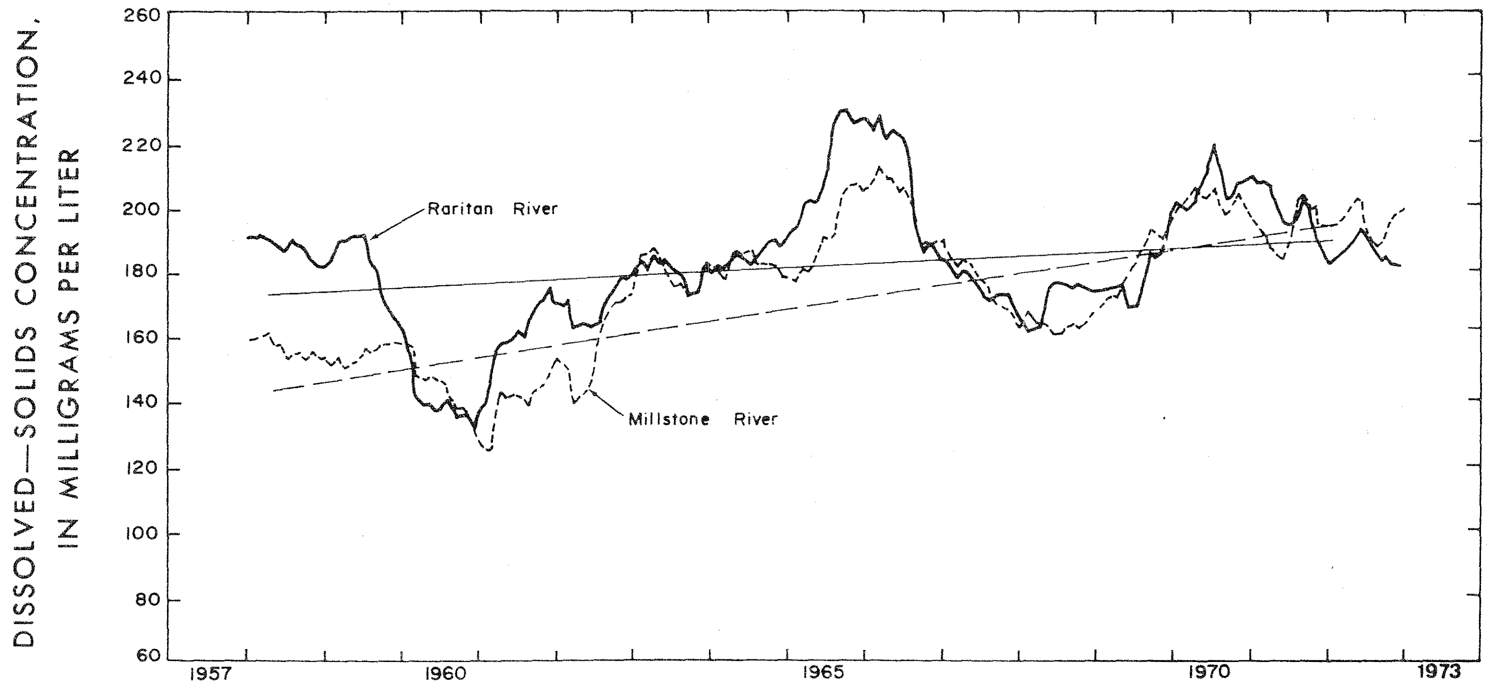

Figure 15.--Trend analyses, based on twelve-month moving averages, of dissolved-solids content, Raritan and Millstone Rivers near Manville. (Based on chemical analyses by the Elizabethtown Water Co.).

This postulation was tested by linear-regression analysis (Steel and Torrie, 1960, p. 161-193). Changes in the relation between dissolved solids (dependent variable) near Manville and log streamflow (independent variable) on the Raritan River at Manville and Millstone River at Blackwells Mills are illustrated in figure 16. These biannual regression analyses are based on once-monthly data collected during 1957-70 by the Elizabethtown Water Company. The curves can be used to describe time trends in dissolved solids, since the influence of streamflow variations caused by water diversions, flow augmentation, flood, or drought are cancelled in that the plots permit comparison at any selected flow condition.

The curves indicate that dissolved solids of the Millstone River generally increased during the period, particularly at low streamflows. For example, at 100 ft^3/s (2.83 m^3/s) the Millstone River is estimated to have carried 159 mg/l (43 tons/day) in 1957-58, 174 mg/l (47 tons/day) in 1961-62, 197 mg/l (53 tons/day) in 1965-66, and 200 mg/l (54 tons/day) in 1969-70. Note that here and in later comparisons of regression estimates, percentage increases for other flow rates may not be of the same magnitude.

However, no significant trend in dissolved solids is apparent on the Raritan River. For example, at 100 ft^3/s (2.83 m^3/s) the dissolved solids of the Raritan River are estimated to be 228 mg/l (62 tons/day) in 1957-58, 211 mg/l (57 tons/day) in 1961-62, 230 mg/l (62 tons/day) in 1965-66, and 211 mg/l (57 tons/day) in 1969-70. The absence of a definite trend in dissolved-solid content at this sampling site may be attributed to flow augmentation from Spruce Run Reservoir during the latter time periods.

A linear-regression analysis of quarterly groupings of once-monthly dissolved-solids and streamflow data of the Raritan and Millstone Rivers near Manville was made to indicate seasonal variations. A plot of the linear-regression lines obtained from the quarterly analysis for 1957-70 is presented on figure 17.

The inverse relation between dissolved solids and log streamflow noted between biannual groupings (fig. 16) also is evident on figure 17. Also note that the dissolved-solids content per unit of flow generally is lowest during April to June. Because much of the precipitation in this quarter runs off directly into the nearby stream channels, the lower dissolved solids reflect the greater influence of direct-overland runoff. Precipitation during other quarters replenishes losses in ground-water storage. The higher dissolved solids thereby reflect the greater influence of ground-water discharges to the streams; that is, ground-water inflows make up the greater percentage of flows in the river system during these quarters than during the second.

As in the earlier regression based on biannual data (fig. 16) a comparison of regression curves derived from quarterly data (not shown), collected on the Millstone River during 1957-61 and 1966-70, indicates an increase in dissolved-solids content per unit of flow. The earlier regression also indicates that this increase was greater during the winter quarter (January to March) than during other quarters. It is estimated from the regression models that at a flow of 100 ft^3/s (2.83 m^3/s), dissolved solids

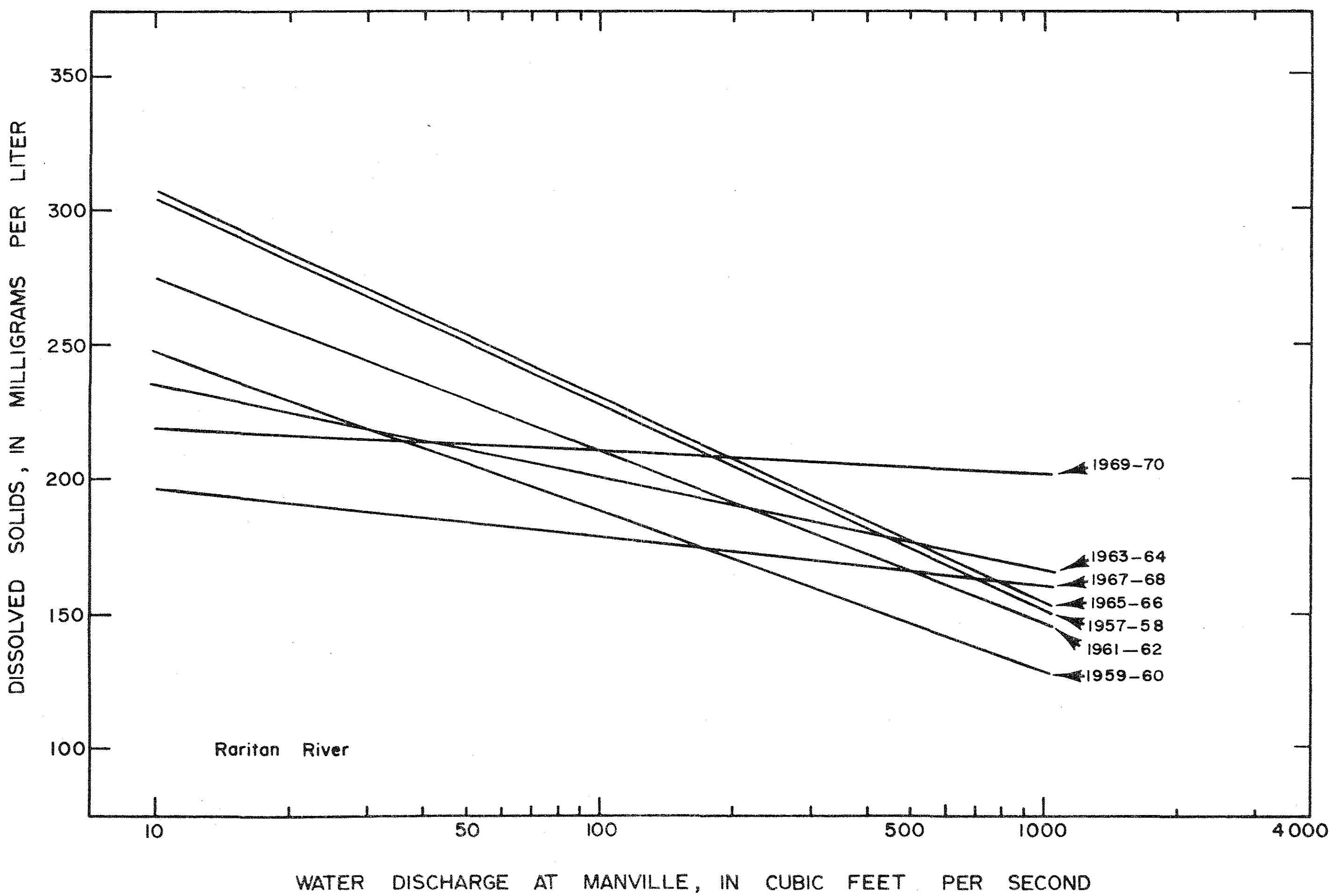

Figure 16.--Relation between water discharge and dissolved-solids concentration, Raritan and Millstone Rivers.

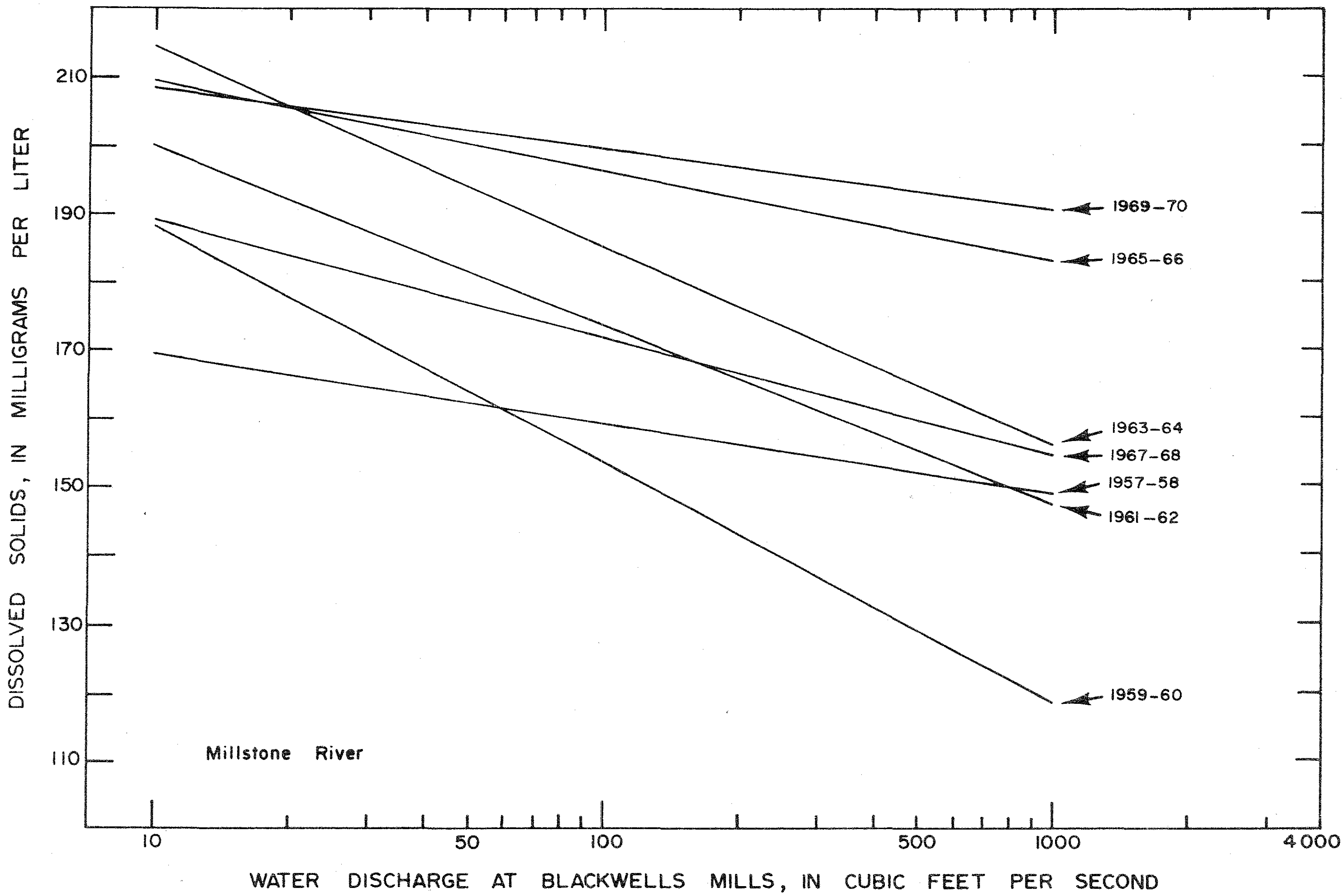

Figure 16.--Continued

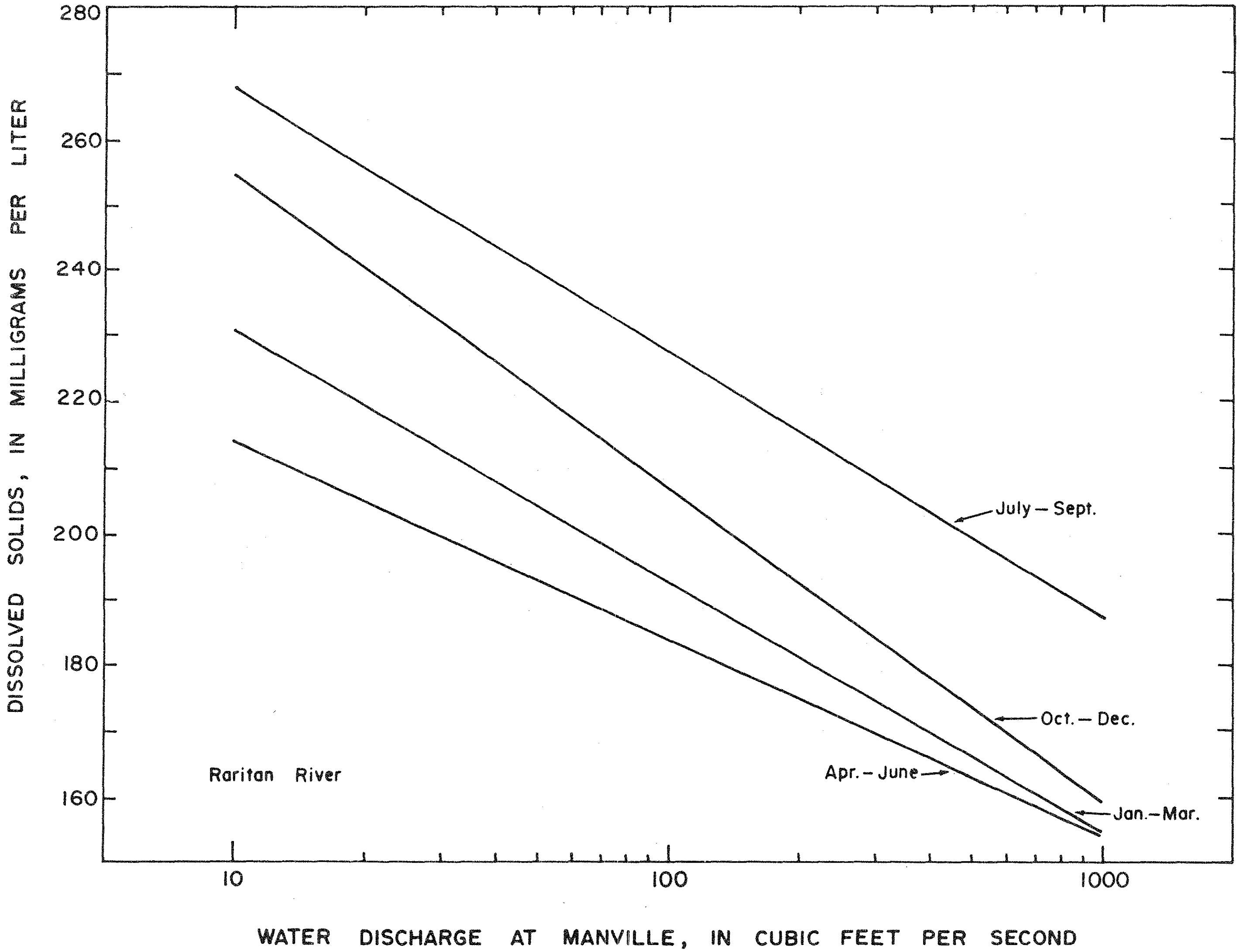

Figure 17.--Seasonal relation between water discharge and dissolved-solids concentration, Raritan and Millstone Rivers near Manville.

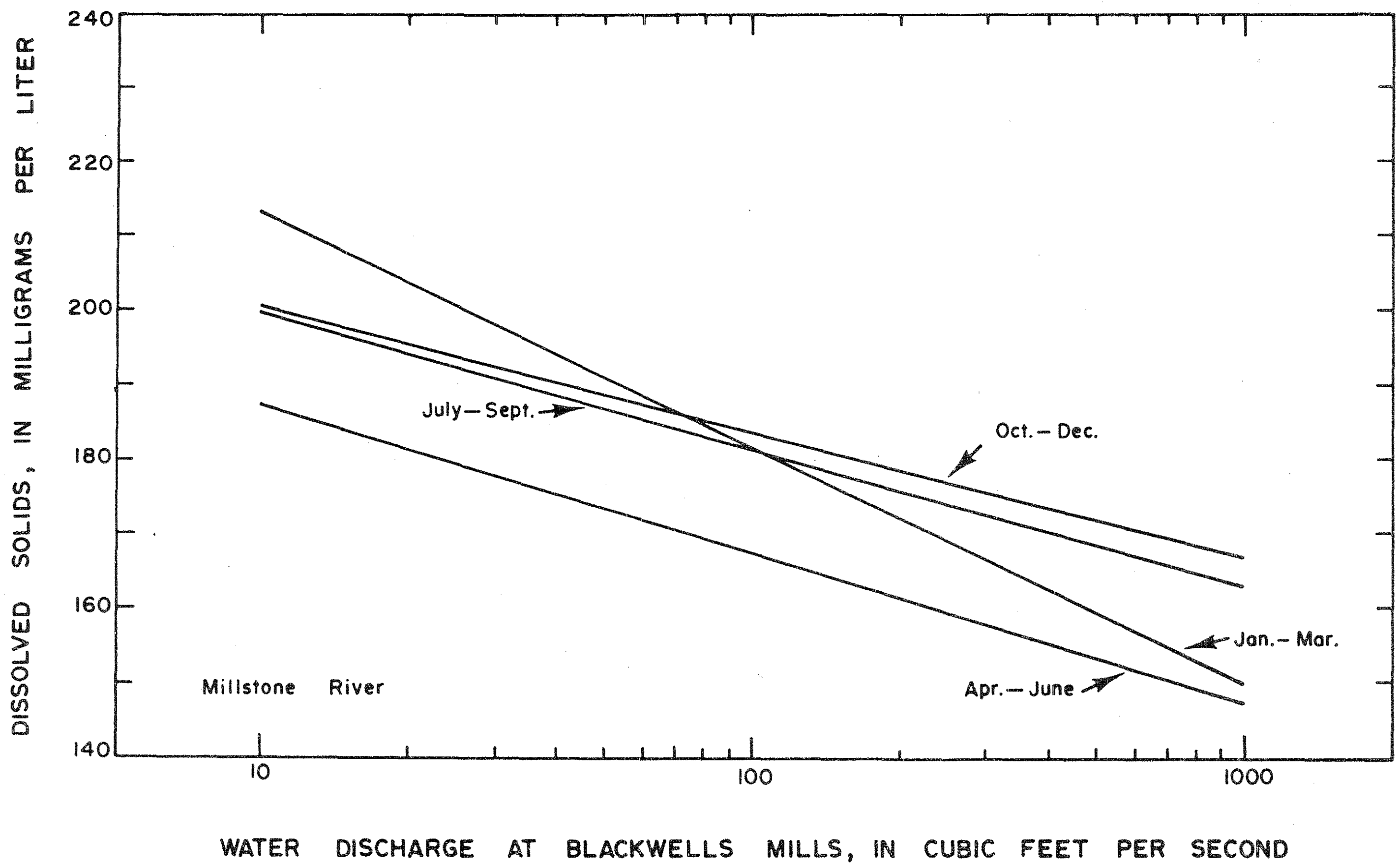

Figure 17.--Continued

increased 43, 17, 12, and 29 percent in the first, second, third and fourth quarters, respectively.

However, comparison of similar curves derived from data (not shown) collected on the Raritan River indicate that, except for the first quarter, there is a decrease in dissolved solids. An increase of 16 percent is estimated from the regression model during the first quarter for a flow of 100 ft^3/s (2.83 m^3/s). Similarly, a decrease of 17 and 13 percent is estimated for the second and third quarters, respectively, at the same flow. No change is estimated for fourth quarter dissolved solids between the two 5-year periods. As low-flow augmentation from Spruce Run Reservoir generally is practiced from July to October, the reduction in dissolved-solids content per unit of flow during the second and third quarters can be attributed to dilution provided by reservoir releases. Note, without the water releases, an increase in dissolved solids, similar to that observed during the first quarter, might be expected for other time periods.

Trend analyses of the dissolved-oxygen content of the Raritan and Millstone Rivers near Manville are shown in figure 18. Oxygen content is expressed as a percentage of saturation to nullify the effects of water temperature. Almost identical curves are developed if variations in oxygen content are expressed in concentration units. These data are somewhat biased in that they represent daytime conditions. However, it is apparent from these curves that prior to the late 1960's the streams were undersaturated, on the average, at these sampling sites during most of the time period illustrated. Thus, the rate of oxygen consumption through biochemical decomposition of organic matter exceeded the rate at which oxygen was replenished in the upstream hydrologic system through such processes as reaeration and photosynthesis. Note also that the oxygen levels exceed 100 percent saturation during 1970-71; that is, a supersaturated condition exists.

Does this trend reflect an improving stream-quality condition at these two sampling sites or are the increases related to: (1) flow augmentation in the Raritan River (note that the oxygen trend has improved consistently subsequent to the commencement of low-flow augmentation in 1964), or (2) increased reaeration resulting from generally higher streamflow rates (fig. 6), and thus increased turbulence, during the latter time period? These questions were tested by linear-regression analyses.

Regression analyses of biannually grouped data on the concentration of dissolved oxygen are shown in figure 19. There seems to be little or no significant decrease or increase with time in oxygen concentration for flow rates above 100 ft^3/s (2.83 m^3/s). There is, however, a tendency for the oxygen content to increase with increases in flow. Increased turbulence at higher discharge rates may produce an increase in the dissolved-oxygen content (Churchill and others, 1962). While a definite trend with time is not apparent at the Millstone sampling site, even at low flows, there seems to be an improvement with time in oxygen levels at low flows on the Raritan River. For example, prior to 1963 the oxygen concentrations at a flow of 50 ft^3/s (1.42 m3/s) was 6.6 mg/l or less. Subsequent to 1963, the oxygen content was greater than 6.6 mg/l for the same flow rate. This improvement also may reflect the generally better quality water and dilution of nonconcservative pollution loads afforded by flow augmentation from Spruce Run Reservoir.

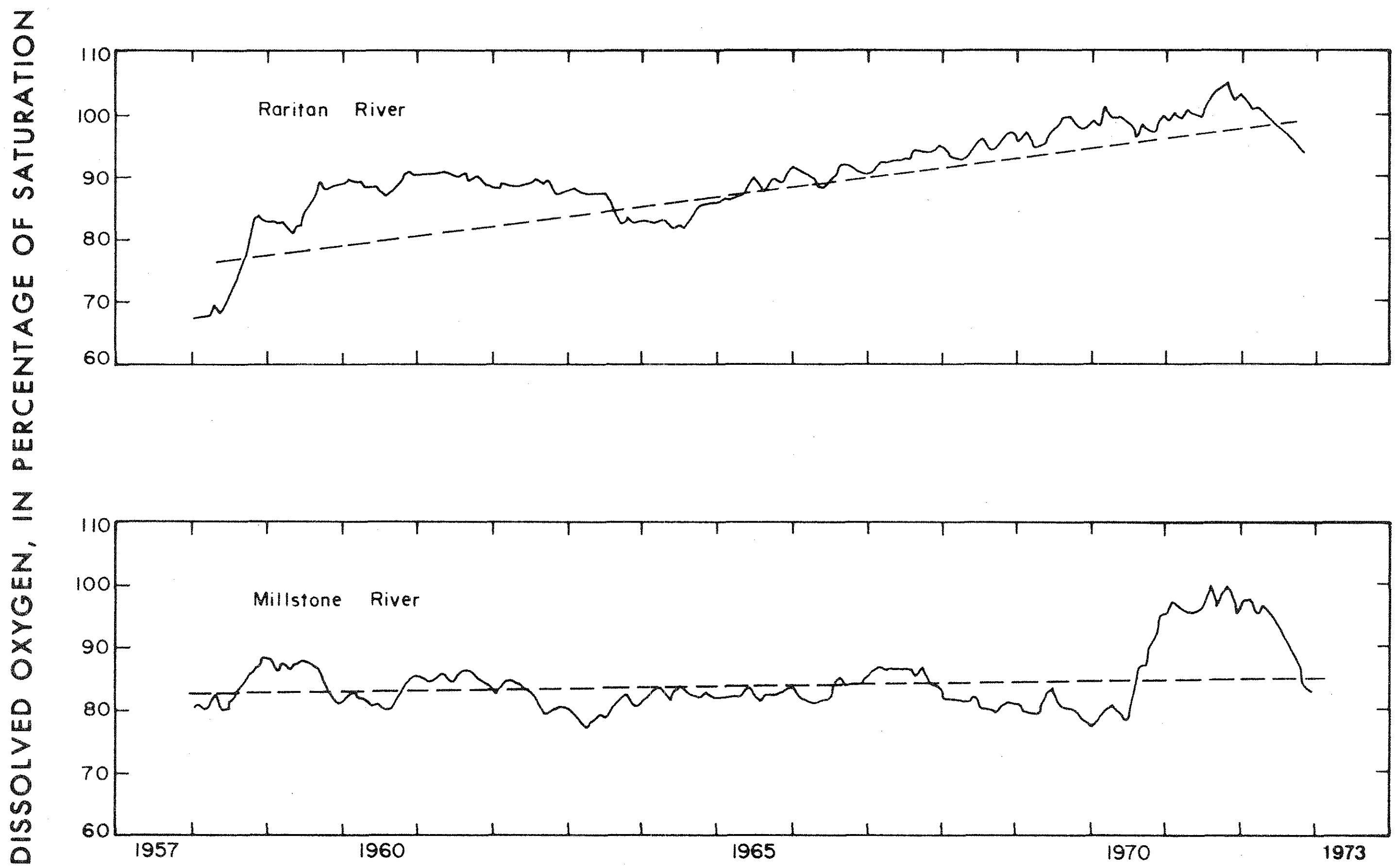

Figure 18.--Trend analyses, based on 12 month averages, of dissolved-oxygen concentration, Raritan and Millstone Rivers near Manville. (Based on chemical analyses by the Elizabethtown Water Co.)

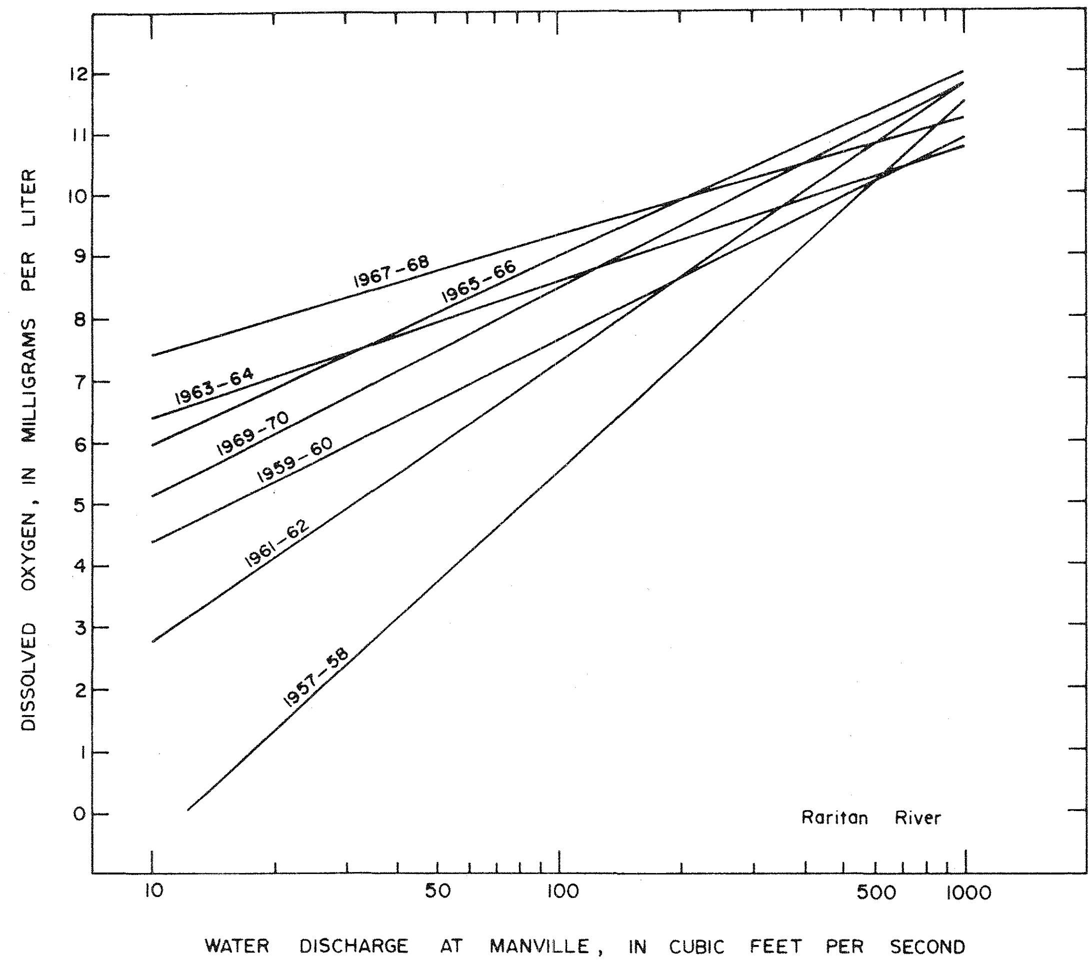

Figure19.--Relation between water discharge and DO concentration, Raritan and Millstone Rivers near Manville.

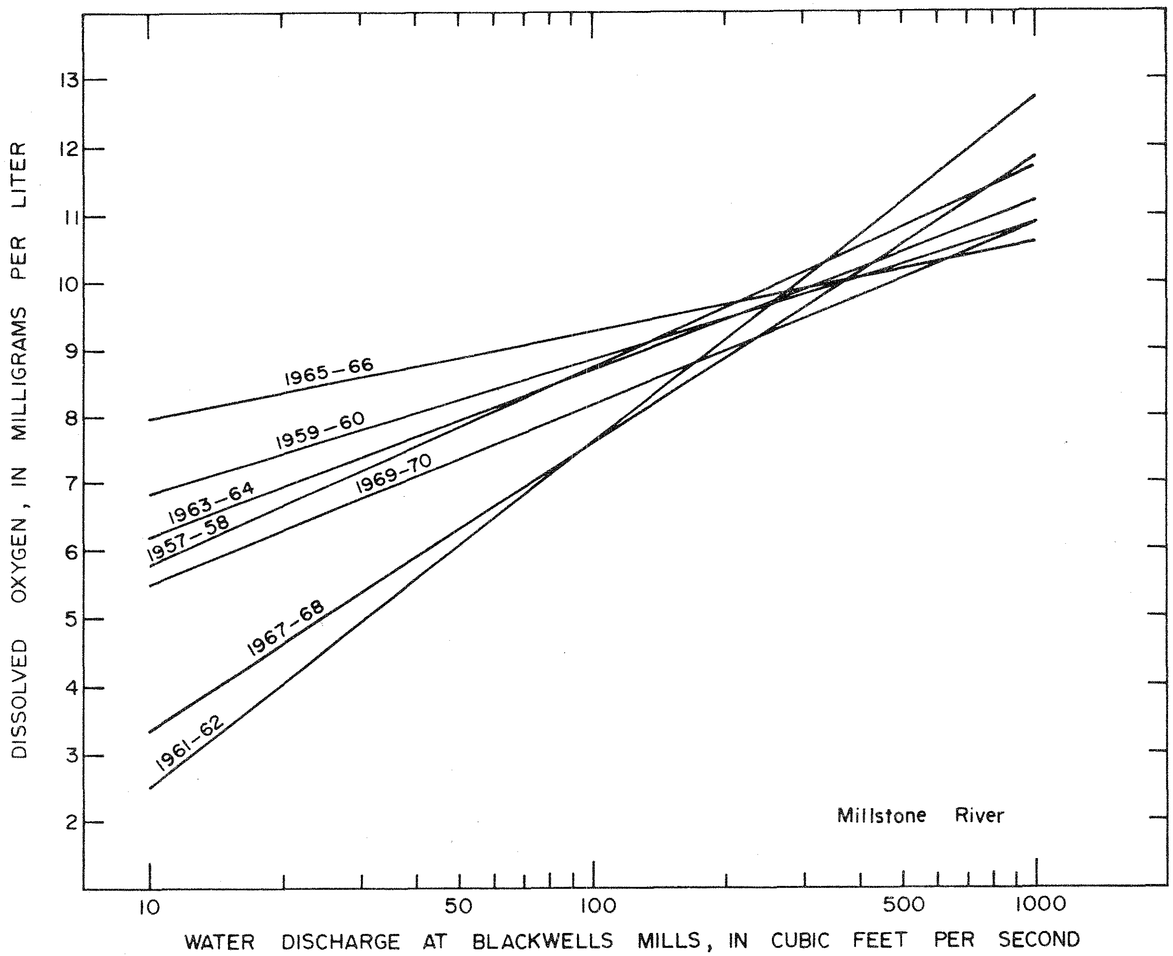

Figure 19.--Continued

Seasonal variations in dissolved-oxygen content by calendar quarters are presented in figure 20. Lowest concentrations at both sampling stations were observed during the second and third quarters (April to September), whereas the highest values were observed in the first (January to March) and fourth (October to December) quarters. This is in accord with expectations, as warmer ambient temperatures during April through September bring lower dissolved-oxygen levels through lower solubilities and higher utilization of oxygen in the biological decomposition of organic materials in the hydrologic system.

Several additional observations can be made regarding the curves illustrated in figure 20. Regression slopes (b) for the first and third quarters are gentle and, with the exception of the third quarter on the Raritan River, negative. As water temperatures during the first quarter are at or near freezing, oxygen levels are expected to be high and relatively constant. The slight decrease in oxygen with increases in flow may reflect the oxygen demand exerted by the flushing of accumulated detritus from the banks and nearby land surfaces by snowmelt and early spring storms. This oxygen demand, while potentially high, is underutilized as biological activity is hindered by the extreme low water temperatures.

Similarly, water temperatures during the third quarter generally are the highest observed and relatively stable. Consequently, oxygen solubilities are lower. Increased biological activity in the decomposition of organic materials at these higher temperatures, producing a demand upon the river's oxygen resources, also are reflected in the low oxygen levels observed during this quarter.

Slopes during the second and fourth quarters are steep and positive. This is to be expected and reflects both the generally higher base flow rates and resultant reaeration due to increased turbulence during these quarters and the rapid change in oxygen solubilities brought about by wide temperature variations. Also, low flow rates during these quarters are concurrent, in general, with high water temperatures.

The question arises, why are oxygen levels relatively unrelated to variations in streamflow during the winter and summer quarters? The answer is relatively simple with regard to the winter. As oxygen values are at or near their highest levels owing to freezing or near freezing temperatures and biological activity is extremely low, increased reaeration due to turbulence at high flows is negligible.

The explanation for the summer quarter is more complex. The time laps between storms is often longer than during other quarters, thus, allowing detritus to accumulate along the banks and nearby land surface. Runoff during storms flushes this detritus into the streams, and any degradable matter increases demand upon the stream's oxygen resources. This demand offsets any increase in oxygen due to turbulent reaeration. The slightly negative slope on the Millstone River may also reflect the generally higher photosynethic rates, or production of oxygen by aquatic plants during periods of base flow. The slightly positive slope observed in the relation

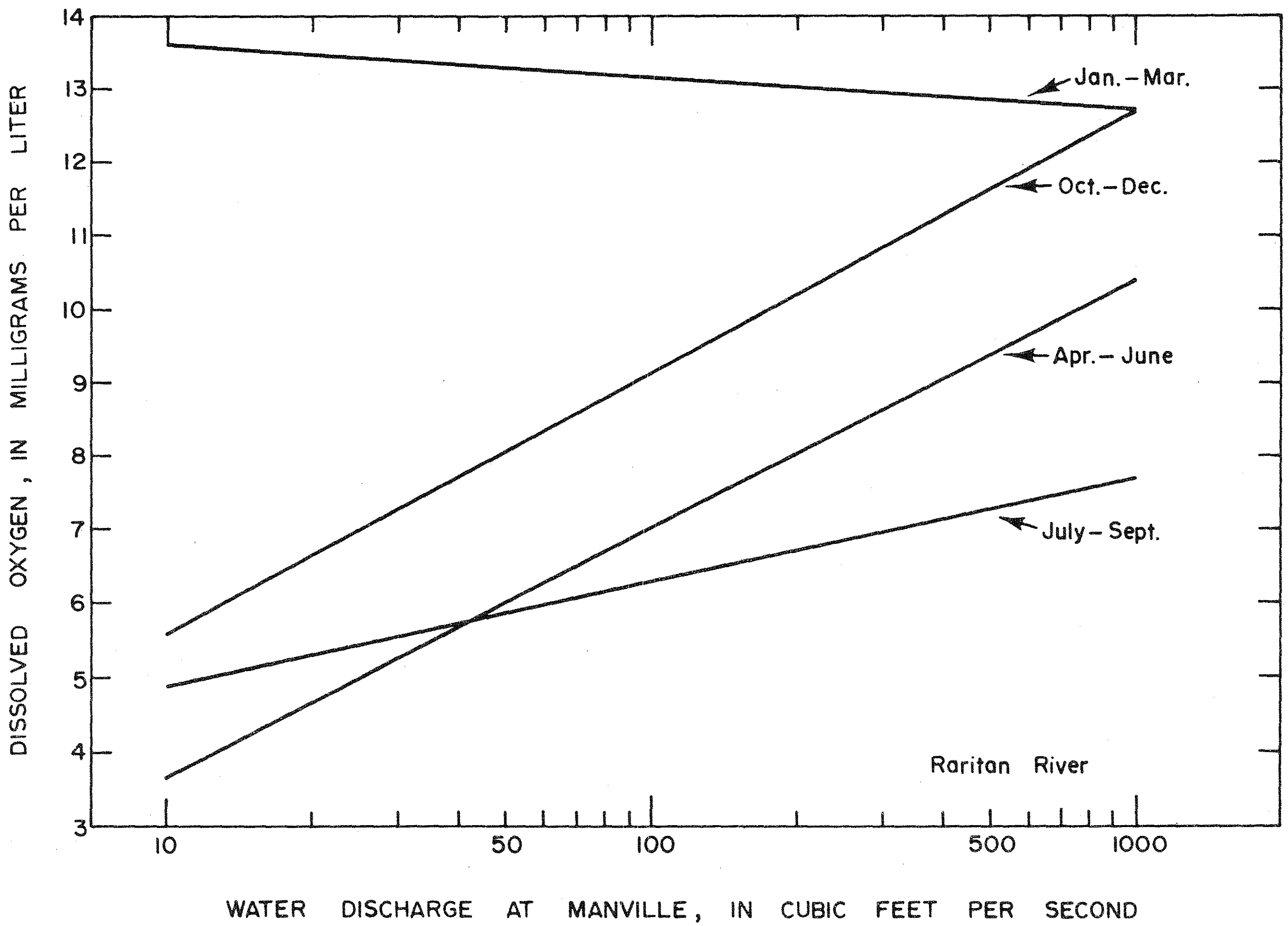

Figure 20.--Seasonal relation between water discharge and DO concentration, Raritan and Millstone Rivers near Manville.

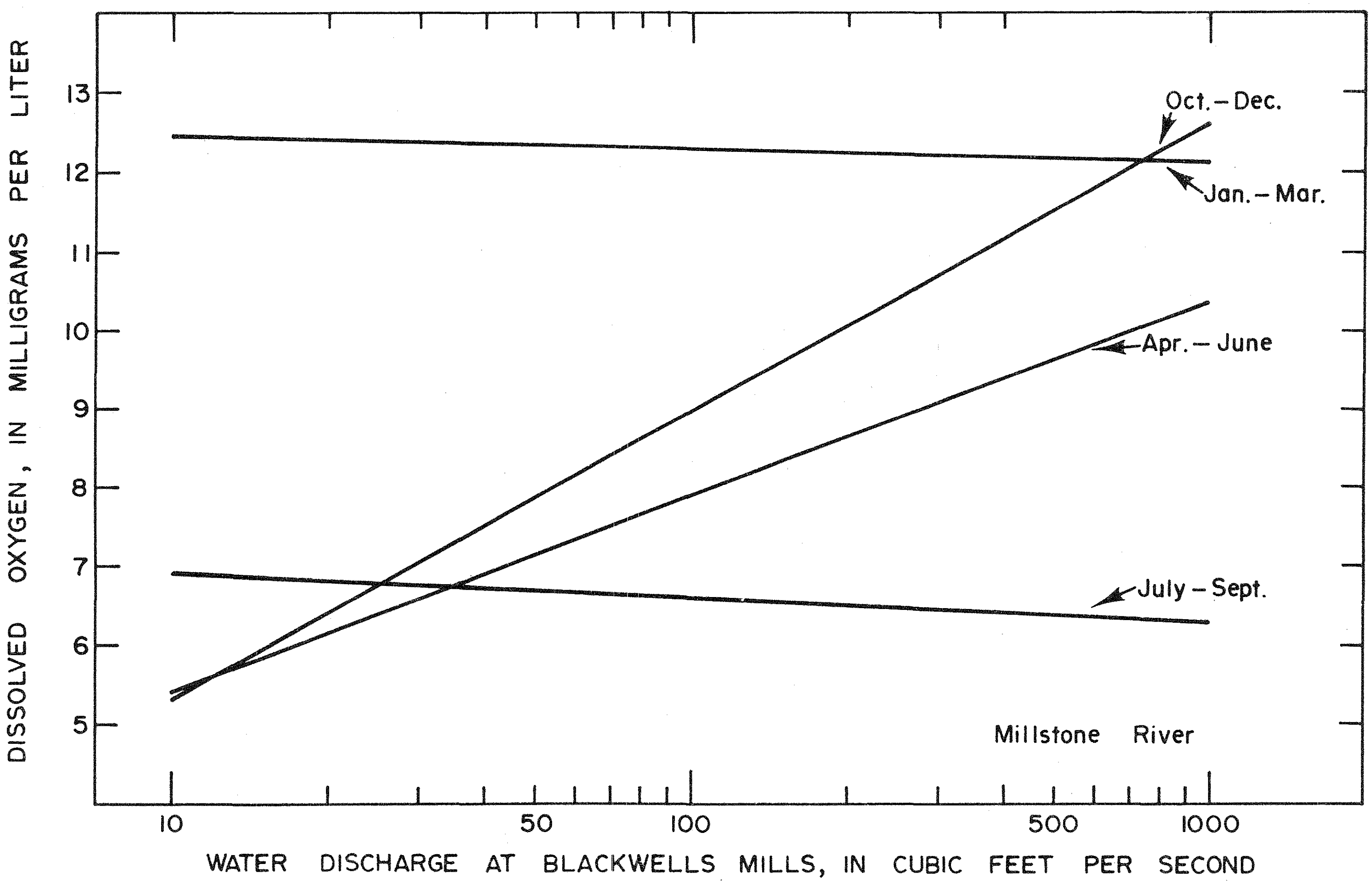

Figure 20.--Continued

between oxygen and flow on the Raritan River during the third quarter could be ascribed to the generally better quality water and dilution provided by flow augmentation. However, a comparison of slopes obtained in the regression of data collected during 1957-61 (b = 3.50) and 1966-70 (b = 0.02) suggests that this may be an inaccurate conclusion.

An observation was made in the analysis of biannually grouped data (fig. 19) that, while little or no significant variation in dissolved-oxygen content is apparent on the Millstone River, there seems to be an improvement with time on the Raritan River, particularly at low flows. Does this observation hold for all seasons? Comparison of regression estimates at 100 ft^3/s (2.83 m^3/s), based on data collected during 1957-61 and 1966-70, on the Millstone River indicate a decrease in oxygen levels during the first and fourth quarter of 18 and 13 percent, respectively, an increase of 5 percent during the second quarter, and little or no variation during the third quarter. Does this suggest an increase in discharges of oxygen-demanding materials during October to March? The authors are unable to explain this phenomenon. A similar comparison of data collected on the Raritan River indicates an increase in oxygen levels during the second and third quarters of 29 and 41 percent, respectively, a decrease of 12 percent in the first quarter, and little or no change in the last calendar quarter. The improvement in quality during April to September and possibly also during the last calendar quarter (note a 13 percent decrease during this period on the Millstone River) is perhaps another indication of the benefits derived by flow augmentation in this river system.

It can be interpreted from the curves presented on figures 18-20 that the capacity of the Raritan and Millstone Rivers to receive, transport, and assimilate decomposable materials and still maintain an oxygen level meeting the State's standard (New Jersey Department of Environmental Protection, 1971)-- that is a daily average of not less than 5.0 mg/l of dissolved oxygen and not less than 4.0 mg/l at any time--has not been exceeded at these two sampling sites and in the immediate upstream reaches. This statement becomes valid only if the data are considered broadly. There are periods of a week or more, particularly during the critical summer quarter, when hourly observations at these two sites show that the capacity of both rivers to maintain a dissolved-oxygen level in excess of 4.0 mg/l is exceeded. For example, hourly values below 4.0 mg/l were recorded on 28 of the 61 days in which oxygen levels were recorded on the Millstone River from July to September, 1970.

A review of dissolved-oxygen data collected during this investigation (table 3) and the State Division of Water Resources at sampling sites above Manville suggests that the river system's capacity to maintain 4.0 mg/l or more at most sampling sites is not exceeded as yet. However, some local streams below municipal waste-water treatment plants are observed to have low oxygen levels, particularly during summer months. As an example, in a survey of the North Branch Raritan River (Philadelphia Acad. Nat. Sci., 1968) gross changes in the normal flora and fauna and, in some cases, prolonged low oxygen levels were observed on four tributaries; Lamington (Black) River near Ironia, Mine Brook near Bernardsville, India Brook near Mendham, and South Branch Rockaway Creek near Whitehorse Station. Also, based on once or twice-monthly sampling during 1968-70 at six sampling sites on the Millstone River below Carnegie Lake in Princeton, the U.S. Environmental Protection Agency (written commun., 1971) observed dissolved-oxygen levels below 4.0 mg/l on several occasions, particularly during late summer and early fall. Roughly 30 percent of the samples collected at each site were below 4.0 mg/l. The only exception was at the site immediately below Carnegie Lake, where oxygen levels were above this value in all samples, probably reflecting reaeration of the water as it drops over the dam.

The above analyses (figs. 18-20) of oxygen data at the two Manville sites suggest that oxygen levels varied slightly or increased. However, does this indicate a healthy river? The upward trend and supersaturated levels shown on both streams by the moving-average technique (fig. 18) suggest that an enriched nutrient condition exists and that increased photosynthetic processes are producing a pseudoimprovement. Future increases in the present nutrient laods above Manville (note nitrate and phosphate levels on table 3) through improper management of waste-water discharges may produce a detrimental demand on the oxygen resources of these two streams.

Additional evidence of photosynthetic activity can be noted on figure 21. Illustrated are the diurnal variations in dissolved-oxygen and pH values recorded hourly at Manville and South Bound Brook (fig. 4, sites 10, 20, and 26). During daylight hours, photosynthetic activity results in a net production of oxygen, often increasing the dissolved oxygen content above saturation values. Concurrent with the oxygen increase, the pH value also increases reflecting the intake of carbon dioxide in the metabolic processes of the photosynthetic plants. During non-daylight hours, respiration processes result in a net utilization of oxygen and a concurrent decrease in pH.

These diurnal variations in pH and dissolved oxygen are demonstrated quite well at the three sampling sites. Data at the Millstone sampling site shows that these variations can be extreme. For example, the pH on June 11, 1971 varied between 5.7 and 11.5 and dissolved oxygen between 54 and 139 percent of saturation. Variations in pH of the Raritan River at Manville are less severe and were, for the most part, in the alkaline range. At the South Bound Brook site, the pH varied from about 7.0 to 8.0 and dissolved oxygen from 60 to 100 percent. These smaller variations may reflect the buffering of the river water by waste-water discharges below Manville.

The time periods illustrated (fig. 21) are those of extreme dissolved oxygen variation, presumably during algae blooms. Similar diurnal patterns are noted during all seasons of the year, although the variations are generally less than 2 mg/l of dissolved oxygen and 1.5 pH units at these three sampling sites.

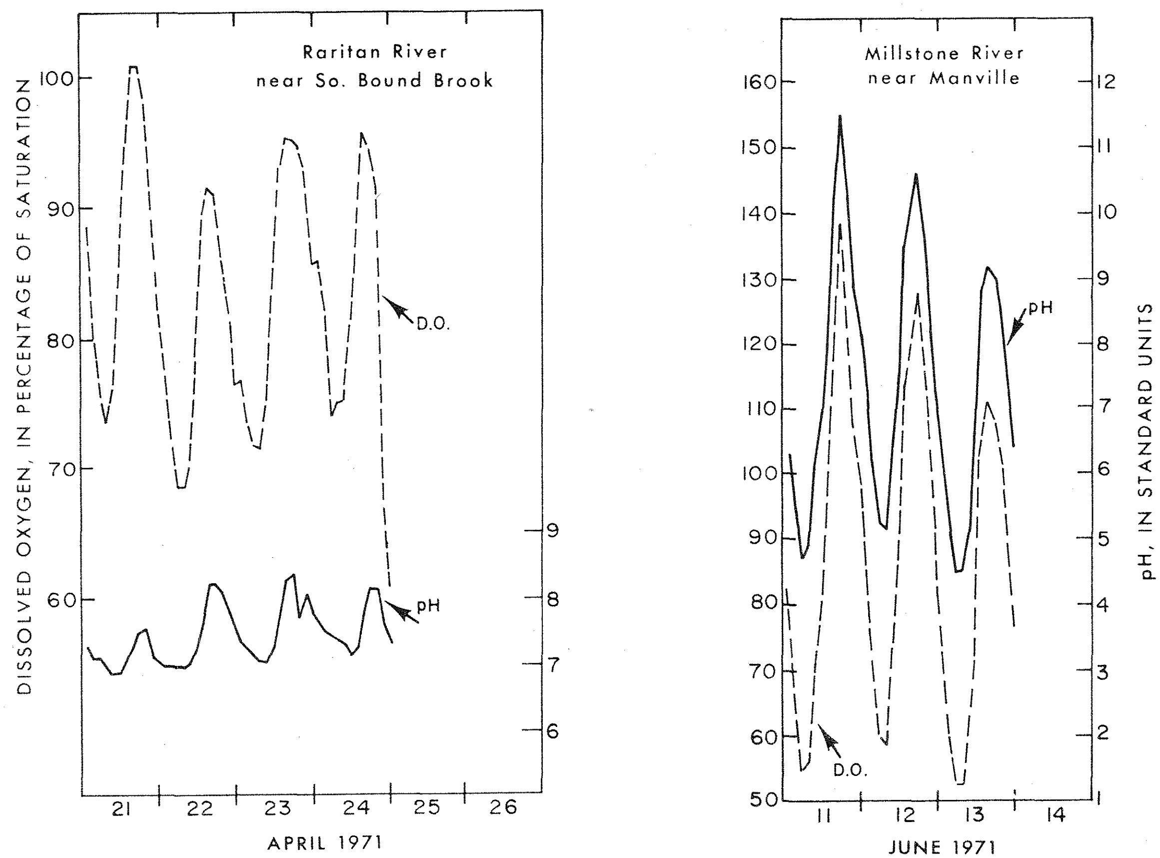

Figure 21.--Hourly variations in DO concentration and pH at three sampling sites.

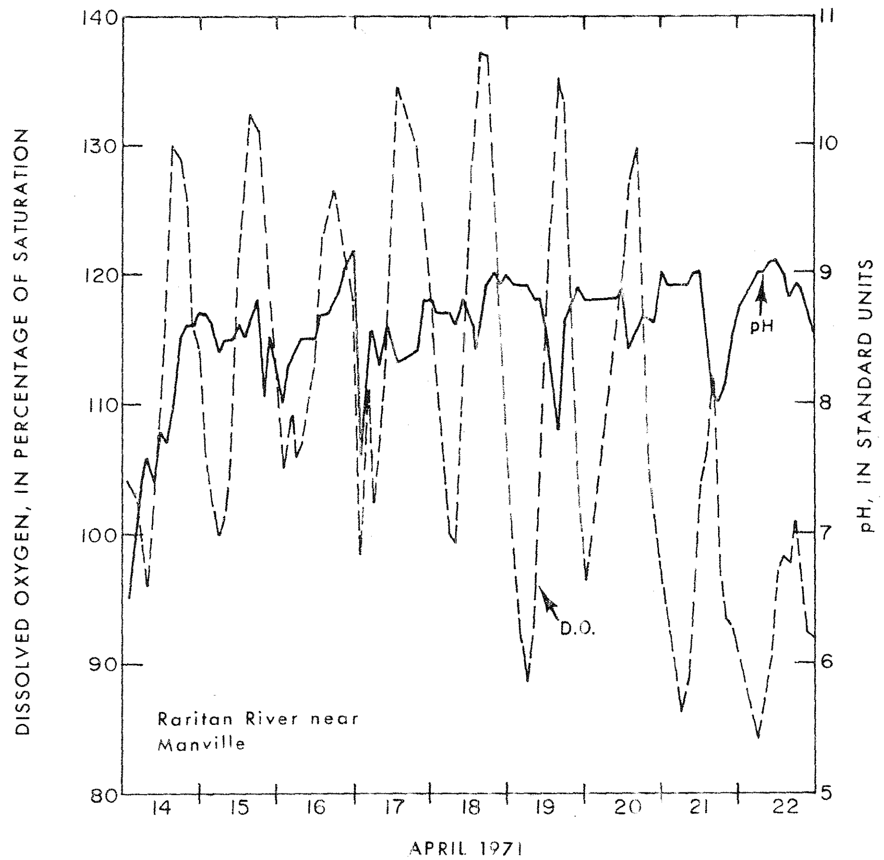

Figure 21.--Continued

The stream quality of the Raritan River main stem below its confluence with the Millstone River is influenced greatly by municipal and industrial waste-water discharges (fig. 2) in excess of 125 mgd (5.48 m^3/s). The occurrence of higher than normal concentrations of major chemical constituents (table 3), phenolic materials (table 7), trace elements (table 5), and orthoposphate (table 3) at sampling sites in this area of the basin was noted earlier (p. 26-40). Rudolfs and Heukelekian (1942) in their studies of pollution in the Raritan River during 1940-41 reported that "the greatest density of oxygen-demanding pollution in the river occurred between the Manville and Bound Brook sampling stations." To illustrate the increases in oxygen-demanding materials in the Manville-Bound Brook area, they plotted the average of 5-daybiochemical-oxygen demand (BOD) determinations of all samples collected at individual sampling stations for the period of their study, 1940-41. BOD is used as an indirect measure of the organic-matter content in water. Similar plots of data collected during two preceding studies (Rudolfs and others, 1929, Rudolfs, 1939) covering the periods, 1927-28 and 1937-38, also were included for comparative purposes by Rudolfs and Heukelekian (1942). These plots are reproduced on figure 22, together with average results of twice monthly data collected during 1969-70 by the U.S. Environmental Protection Agency (unpub. records).

The earlier investigators recognized that large amounts of oxygen-demanding materials, as measured by the BOD test, were introduced into the hydrologic environment between Manville and Bound Brook. They also reported that there were increases in the amounts of these materials in the river system, especially between 1937-38 and 1940-41. The increases in biochemical oxygen-demanding materials were reported to have produced an increase in undersaturated conditions with respect to dissolved-oxygen levels between Manville and Bound Brook. Below Iscataway, dilution through tributary and ground-water inflow, self purification processes and reduced waste-water sources resulted in a gradual decrease in BOD and an increase in oxygen level. However, concentrations of these two parameters, which existed upstream of Manville, generally were not reached even in the tidal areas below New Brunswick.

Comparison of data reported by Rudolfs and Heukelekian (1942, p. 856) with recent data (1969-70) collected by the U.S. Environmental Protection Agency indicate a continued input of oxygen-demanding material into the river between Manville and Bound Brook. Although BOD in this reach remained above that observed in 1927-28 and 1937-38, it is significantly lower than that observed in 1940-41. Note also that there is a slight increase in oxygen demand at sampling sites above Manville and that the demand in areas below Bound Brook while receding, never quite reach the upstream concentration levels. Flows of the Raritan and Millstone Rivers were reported by earlier investigators to average 1,176 ft^3/s (33.3 m^3/s) in 1927-28, 959 ft^3/s (27.2 m^3/s) in 1937-38, and 895 ft^3/s (25.3 m^3/s) in 1940-41. Records at the Bound Brook gaging station (fig. 4, site 21) indicate an average flow of 1,000 ft^3/s (28.3 m^3/s) in 1969-70.

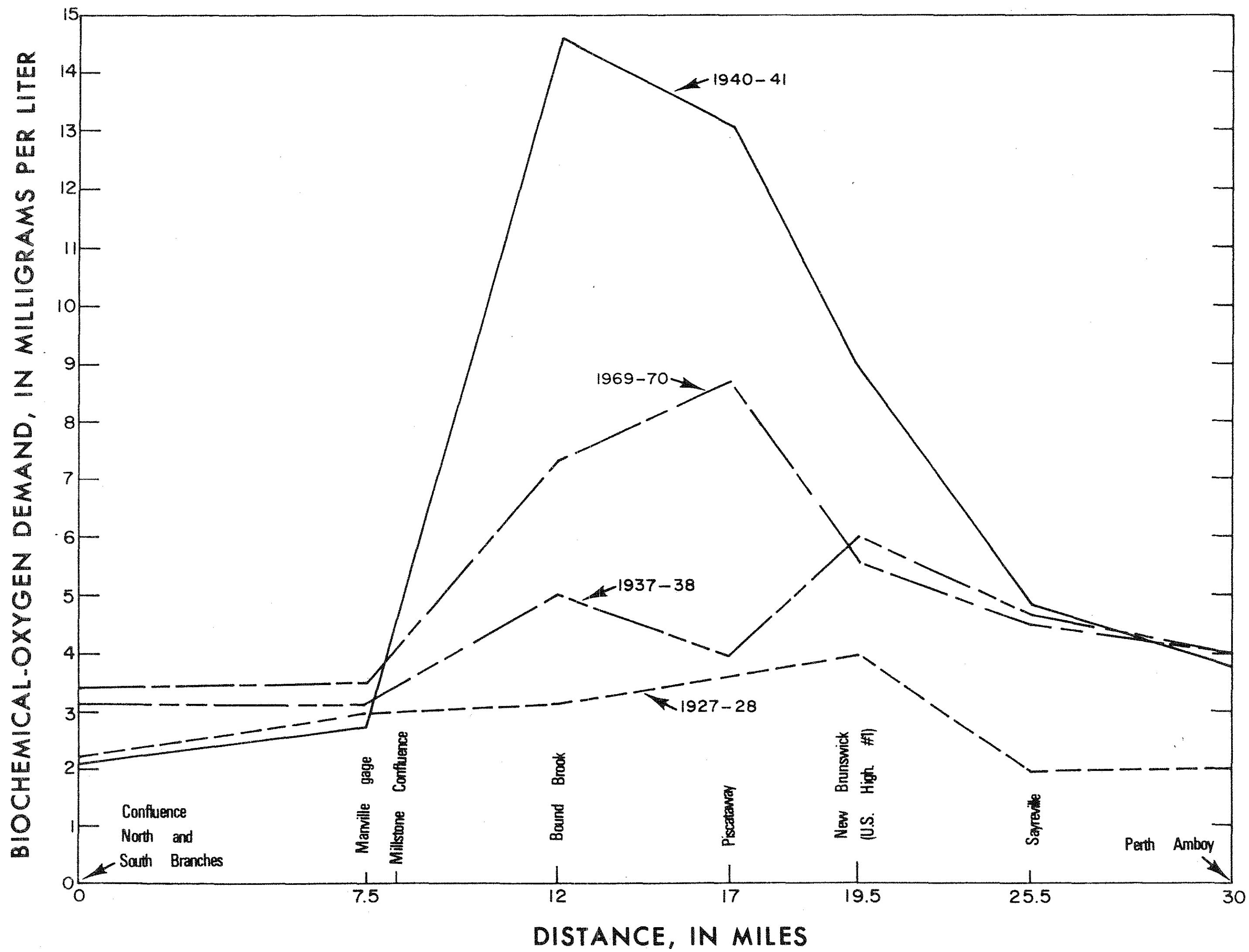

Figure 22.--Time comparison of the average BOD and DO values during four stream surveys in the Raritan River basin.

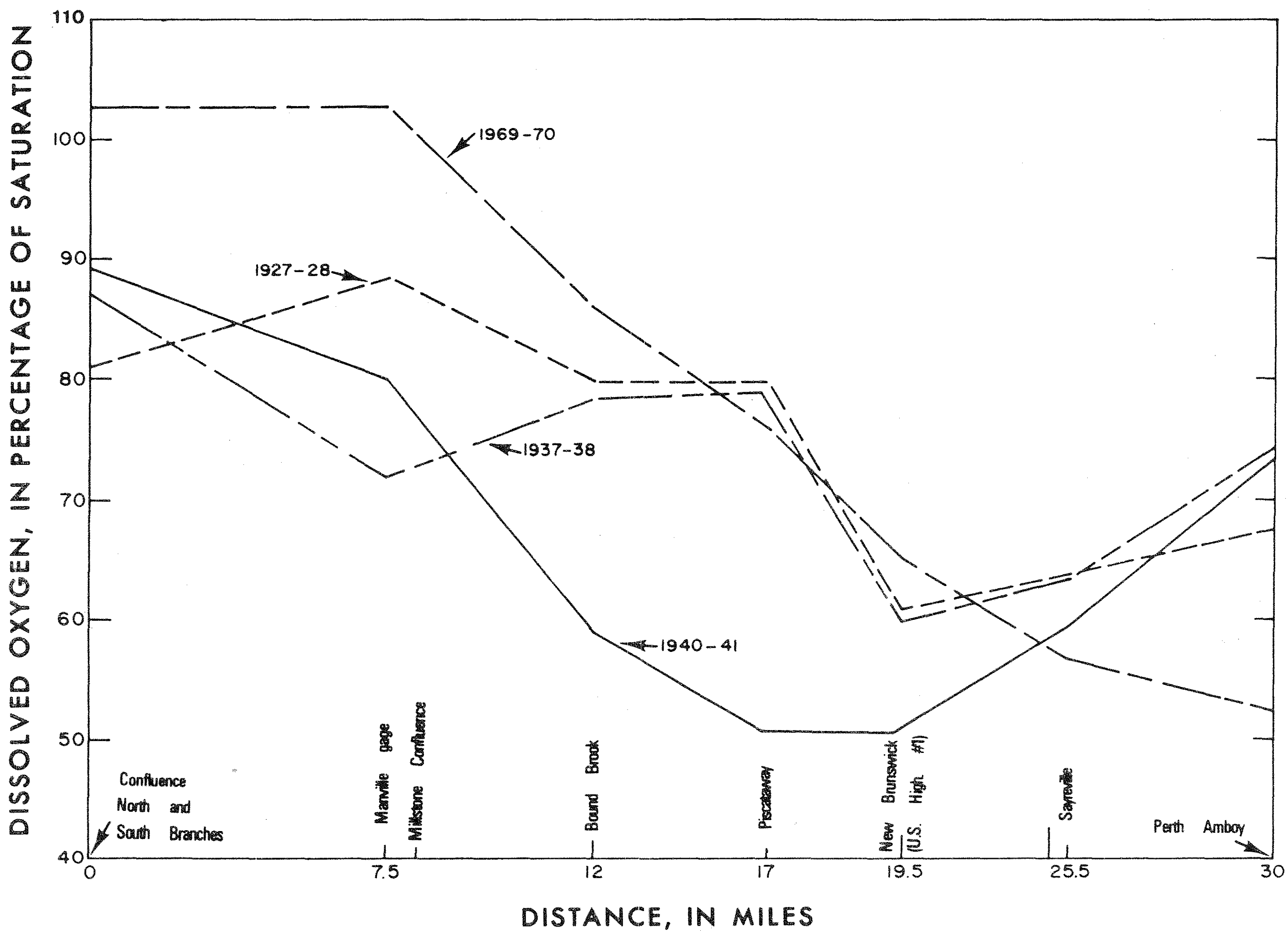

Figure 22.--Continued

Variations in dissolved-oxygen content as observed in 1969-70 are, however, significantly different from those reported in the earler studies. Oxygen levels are highest in the upstream area, that is above Manville, as they generally were in the earlier periods illustrated (fig. 22). However, saturation levels at the two upstream sampling sites were from 10-20 percent higher than those reported in the earlier research. The 100 plus percent average observed at these two sites in 1969-70 is consistent with data collected by the Elizabethtown Water Company at Manville (fig. 18). Below Manville oxygen levels reflect the input of oxygen -demanding materials and are undersaturated. However, the recovery in oxygen levels noted during the earlier sampling periods in the river below New Brunswick are not evident during the 1969-70 sampling period. Levels recede fairly consistently throughout the reach between Manville and Perth Amboy.

Data points plotted on figure 22 are those at sampling sites used by Rudolfs and Heukelekian (1942, p. 843). The U.S. Environmental Protection Agency between 1968 and 1970 operated sampling stations at these and several additional sites in this reach of the river. Data collected at sites other than those plotted on the dissolved-oxygen and biochemical-oxygen demand curves are not significantly different from the extrapolated lines connecting data points.

Cole (1968), in a study of water-quality trends in the Raritan River and Bay between 1950 and 1966 and based on data collected by the Middlesex County Sewerage Authority, reported the following observations:

> "The geometric means of coliform MPN [most probable number] and arithmetic means of dissolved oxygen and biochemical-oxygen demand were compared for summer periods of years since 1950. The water quality at Manville as indicated by these parameters has significantly improved since 1950. However, the quality at Bound Brook and New Brunswick only improved immediately after operation of [a trunk sewer line by the] Middlesex County Sewerage Authority began in the spring of 1958 and has steadily decreased since 1960 and is approaching conditions previous to 1958. This trend is illustrated by changes adjacent to New Brunswick. The MPN of coliform per 100 ml was 5.7 million in 1950, 380 in 1958, and 15,500 in 1966. The biochemical-oxygen demand was 23.0 mg/1 in 1950, 6.0 mg/1 in 1958, and 12.1 mg/1 in 1966. Similarly, dissolved oxygen was 3 percent of saturation in 1950, 80 percent in 1958, but only 38 percent in 1966."

Thus, based on Cole's work and data presented on figure 22, it is evident that stream quality below Manville generally deteriorated during 1927-58, particularly in the late 1930's and early 1940's. Construction and operation of a trunk sewer in 1958 carrying the wastes of 18 municipal and nine industrial contributors to the Authority's treatment plant in Sayreville effectively have reduced the pollution loadings in lower reaches of the river and bay. However, continued and increased discharges by nonusers of the Authority's treatment plant are reflected in a deterioration as indicated by data collected in 1966 (Cole, 1968), in 1968-70 (U.S. Environmental Protection Agency, written commun. 1971), and during this investigation, 1968-72 (table 3).

DISCUSSION

The Raritan River basin comprising 1,105 mi^2 (2,862 km^2) in central New Jersey is the second largest within the State, exceeded only by the Delaware River basin (2,345 mi^2 or 6,074 km^2 in New Jersey).

Some recreational and agricultural water uses are found in the basin above Manville (fig. 1). However, the river system is used mainly as a source of water supply for both public and industrial needs and as a medium for the disposal of municipal and industrial waste waters. In 1972, three of six water-supply purveyors in the basin withdrew water from basin streams or the adjacent Delaware and Raritan Canal at or below Manville. These three purveyors diverted about 95 percent of the total 120 mgd (5.26 m^3/s) diverted basinwide. Similarly, 37 of 126 municipal and industrial waste-water treatment plants in 1972 used the basin streams at or below Manville for disposal of treated effluents, discharging about 80 percent of the total 150 mgd (6.57 m^3/s) basinwide. Projected population increases suggest a continued expansion in the demands upon the basin's water resources. To meet these present and future demands, efficient and prudent water-resource management is indicated.

Precipitation in the basin is ample (Dunlap, 1966, p. 19) and averages 47 in (120 cm) per year, or roughly 3-5 in (8-12 cm) per month. Four general trends (fig. 3) were noted in precipitation patterns during the period of study (1955-72). Precipitation was slightly less than normal between 1955 and late 1961; was extremely deficient during 1962-66; returned to slightly less than normal between late 1966 and 1971; and recovered to above normal after late 1971.

Trends in streamflow are illustrated (fig. 6) for eight gaging stations on the Raritan River main stem and its three major tributary systems, the South Branch Raritan River, the North Branch Raritam River, and the Millstone River. In general, the highest 12-month average flow were observed in 1952, concurrent with the maximum annual precipitation during the study period, whereas the lowest were observed in 1965, concurrent with the minimum annual precipitation. A direct relation between precipitation and streamflow is evident. A general trend toward decreasing flows during 1955 to 1970 is attributed to the general pattern of less than normal precipitation.

A generalized plot (fig. 10) of dissolved-solids concentration and streamflow, for five sampling sites on the main stem and three major tributaries, illustrates the inverse relation that exists. Inverse relations also were found to exist between streamflow and calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chloride, and hardness. Suspended sediment and dissolved oxygen were observed to have direct relations, while iron, fluoride, and nitrate, showed little or no significant relation with flow.

For water-quality evaluation, the Raritan River basin was divided into three general regions of similar water quality (fig. 11) on the basis of predominant chemical constituents and dissolved solids, as measured during low streamflow of over 50 sampling sites. Because, under natural conditions, the major part of low streamflow in gaining streams is caused by ground-water inflow, the mapped water types normally reflect the chemical quality of ground-water inflow.

A comparison of the chemical-quality map with physiographic boundaries indicates that in most areas of the basin chemical weathering in the geologic environment is the predominant factor influencing stream quality. However, man's activities along the main stem below Manville have altered the natural solute-solvent relation in this area.

The predominant cations found in the basin's streams during low flow are calcium plus mangesium; usually exceeding 60 percent of the total cations. In two of the three regions, that is in streams draining the Piedmont Lowland and Inner Coastal Plain, the predominant anions are those associated with salinity. Sulfate is the major anionic component, with lesser amounts of chloride, nitrate, anf fluoride. Bicarbonate is predominant in the remaining region, that is in streams draining the New England Upland. Dissolved solids throughout the basin during low flow generally range from 40 to 200 mg/l, but occasionally are higher in areas where man's activities have altered the chemistry of the stream waters. The highest dissolved solids during low flow generally are found in streams draining the Piedmont Lowland (75-200 mg/l) and the lowest in those draining the Inner Coastal Plain (40-75 mg/l).

Average annual suspended-sediment yields of basin streams range from 25 to 500 tons/mi^2 (10-200 tons/km^2). The highest yields are found in streams draining the Piedmont Lowland (75-500 tons/mi^2 or 25-200 tons/km^2) and the lowest in those draining the Inner Coastal Plain (50-150 tons/mi^2 20-60 tons/km^2). Streams draining the New England Upland part of the basin are estimated to transport 25-150 tons/mi^2 (10-60 tons/km^2) of suspended material annually.

In general, the water quality of basin streams above Manville and in most tributary streams below Manville is good for most industrial, domestic, and recreational uses. Some areas of local pollution, as indicated by low dissolved oxygen and high biochemical-oxygen demand, nutirent levels, and coliform bacteria counts, have been reported. These areas are normally in the vicinity of municipal waste-water treatment plant discharge. A comparison of chemical analyses of water samples collected in the 1920's (table 4) with those collected during the study period (table 3) suggest that the concentration per unit of discharge of sulfate, chloride, and nitrate in the river system above Manville have increased significantly, reflecting increased waste-water discharge and nutrient levels in agricultrual runoff.

Although an upward trend in dissolved solids with time is apparent from moving-average curves (fig. 15), particularly on the Millstone River, comparison of these curves with a similar plot of streamflow (fig. 6) indicates that the rising trend may be related to the concurrent decrease in discharge. Linear-regression analysis of dissolved solids and log streamflow was used to test the trend in dissolved solids per unit volume of water. If regressions of 2-year groups of the data (fig. 16) are compared, dissolved-solids content in the Millstone River at Manville is shown to increase with time, particularly at low streamflow. For example, at 100 ft^3/s (2.83 m^3/s) the Millstone River is estimated to have transported 13 percent more dissolved solids in 1969-70 than in 1957-58. However, in a similar comparison of the Raritan River, no significant trend is apparent.

The absence of a trend in dissolved solids on the Raritan River was assumed to be due to augmentation of flows during low-flow periods with generally better quality water from Spruce Run Reservoir subsequent to 1964. A comparison of data collected on the Raritan River during 1957-61 and 1966-70, grouped by calendar quarters, indicates an increase of 16 percent in dissolved solids during January to March at a flow of 100 ft^3/s (2.83 m^3/s). Similarly, a decrease of 17 and 13 percent is esimated for the second and third quarters, respectively, at the same flow. No change is estimated for October to December. In the Millstone River an increase of 43, 17, 12, and 29 percent in dissolved solids was indicated in the first, second, third, and fourth calendar quarters, respectively. The reduction in dissolved-solids content per unit of flow during the second and third quarters on the Raritan River can be attributed to the dilution provided by reservoir releases, particularly in July through October. Without the releases, an increase in dissolved solids, similar to that observed on the Millstone River, might be expected.

Moving-average analyses of dissolved-oxygen data (fig. 18) collected on these two rivers at Manville indicate that prior to the late 1960's both streams were undersaturated. Thus, the rate of oxygen consumption through biochemical decomposition organic matter exceeded the rate at which oxygen was replenished in the hydrologic system through such processes as reaeration and photosynthesis. However, subsequent to the late 1960's oxygen content on an average increased to supersaturated levels. The upward trend and supersaturated levels of dissolved oxygen shown on both streams during recent years suggest that an enriched nutrient condition exists and that photosynthetic processes are producing a pseudoimprovement.

The upward trends also may be related either to increased atmospheric reaeration rates at generally higher streamflow rates (fig. 6) in the period subsequent to the late 1960's or to flow augmentation in the Raritan River. However, linear-regression models, based on biannually grouped data, of oxygen levels and streamflow (fig. 19), showed little or no significant time trend on either river at flow rate above 100 ft^3/s (2.83 $m/^3s$). There seems to be an improvement with time in oxygen levels at low flows on the Raritan River. For example, prior to 1963 dissolved-oxygen content was less than 6.6 mg/l at 50 ft^3/s (1.42 m^3/s) and greater than 6.6 mg/l subsequent to 1963. A comparison of data collected during 1957-61 and 1966-70, based on a regression of quarterly grouped data, indicates an increase in oxygen content in the Raritan River during April to September and possibly during the last quarter, while little or no variation was indicated for the Millstone River. This improvement, as was noted earler with respect to dissolved solids, may reflect the generally better quality water and dilution of nonconservative pollutants by reservoir releases upstream.

The Raritan River main stem below Manville flows through a rather large urban and industrial complex. In addition, it is tidal below New Brunswick. Municipal and industrial waste-water discharges and urban runoff greatly influence the river's quality in this area. The concentrations of most constituents were generally higher than observed in other parts of the basin. For example, the dissolved solids (tables 3 and 6) at Manville ranged from 90 to 464 mg/l, phenolic materials from 2.5 to 22 ug/l, orthoposphate from 0.0 to 0.93 mg/l, and coliform bacteria from 6 to 13,300 colonies per 100 ml. At the head of tide near South Bound Brook dissolved solids ranged from 96 to 1,520 mg/l, phenolic materials from 3.0 to 312 ug/l, orthoposphates from 0.00 to 2.3 mg/l, and coliform bacteria from 1,100 to 100,000 colonies per 100 ml.

A general deterioration in quality also is indicated by dissolved-oxygen and biochemical-oxygen demand data (fig. 22) between Manville and Perth Amboy. The biochemical-oxygen demand in 1969-70 increased downstream from an average 5.6 mg/l at Manville to 9.0 mg/l at Fieldville dam, and thence decreased to 5.1 mg/l at Perth Amboy. The dissolved-oxygen content receded from an average 104 percent of saturation at Manville to 75 percent at Fieldville dam, and 51 percent at Perth Amboy.

Previous investigators (Rudolfs and Heukelekian, 1942, Cole, 1968) have reported (1) a general deterioration in quality on the main stem betwen Manville and Perth Amboy since the mid-1920's, particularly in the late 1930's and early 1940's, (2) an improvement in 1958 upon the construction of a trunk sewer by the Middlesex County Sewerage Authority, and (3) a further decline during recent years due to increased waste-water discharges and urban runoff.

Also presented in the report are the results of several time-of-travel measurements within the basin (table 2). These measurements allow the determination of reasonable estimates of the traveltime required for soluble contaminants to pass through particular parts of the river system during varying flow conditions. For example, during medium flow conditions the peak concentration of a contaminant introduced into the river system at Clinton on the South Branch Raritan River would be expected to travel the 34 mi (55 km) to the head of tide at Fieldville dam near South Bound Brook in approximately 126 hr, while at high flow, traveltine would be reduced to about 73 hr. Observed velocities during field measurements were variable and ranged from 1.62 ft/s (49 cm/s) on the main stem and the North Branch Raritan River to 0.063 ft/s (2 cm/s) through Carnegie Lake. A general decrease in velocity downstream was noted during each individual measurement, reflecting the lesser channel slopes, the broadening and deepening of the channel, and, in some reaches, the ponding effect of small dams.

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