Fresh-Water Discharge–Salinity Relations in the Tidal Delaware River

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1586–G

Prepared in cooperation with the city of Philadelphia and the Delaware Geological Survey

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By W. B. KEIGHTON

HYDROLOGY OF TIDAL STREAMS

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By W. B. Keighton

ABSTRACT

Sustained flows of fresh water greater than 3,500, 4,400, and 5,300 cubic feet per second into the Delaware River estuary at Trenton, N.J., assure low salinity at League Island, Eddystone, and Marcus Hook, respectively. When the discharge at Trenton is less than these critical values, salinity is very sensitive to change in discharge, so that a relatively small decrease in fresh-water discharge results in a relatively great increase in salinity. Comparison of the discharge-salinity relations observed for the 14-year period August 1949–December 1963 with relations proposed by other workers but based on other time periods indicate that such relations change with time and that salinity is affected not only by discharge but also by dredging; construction of breakwaters, dikes and tidal barriers; changing sea level; tidal elevation; tidal range; and wind intensity and direction.

INTRODUCTION

Anyone interested in water management in the Delaware River estuary longs for some simple formula that will enable him to estimate the fresh-water discharge required to maintain a particular salinity at, or downstream from, a specified location. No such formula has yet been developed, but the behavior of the river in this respect over a 14-year period can be reported concisely.

The U.S. Geological Survey, in cooperation with the city of Philadelphia, measured the chemical quality of tidal Delaware River water at eight locations once each month from August 1949 to the present time. These analyses are summarized in graphic and tabular form in a report prepared by the Geological Survey (Keighton, 1965). In the present report these analyses are examined to determine whether any general statements can be made about the relation between fresh-water discharge and the salinity as measured by the concentrations of dissolved solids or chloride in the river water.

Only the samples taken at League Island, Eddystone, and Marcus Hook are considered, for it is in this reach that salinity invasion generally takes place. The monthly samples were not all taken at the same tidal stage, but at random times. The analyses were grouped according to the antecedent fresh-water discharge at Trenton, N.J. For example, the analyses for all samples taken at water discharges of 1,500–2,500 cfs (cubic feet per second) are in one group, those taken at discharges of 2,501–3,500 cfs are in another group, and so on. Because the samples in each group were taken at random tidal stages, the specific conductance varies within any group. The median specific conductance for any group of discharges, however, probably best represents the specific conductance of the specified water discharge at mean tide. From specific conductances one can readily estimate dissolved-solids or chloride concentration.

Before relating salinity to discharge, "fresh-water discharge" must first be defined. Obviously, the daily discharge on the day the sample was taken cannot be used, for the salinity of the water depends upon the fresh-water discharge for some days preceding the day of sampling. At a flow of 4,000 cfs, it would take 49 days to replace the high-tide volume of water between Trenton and Marcus Hook. Dye experiments with the Corps of Engineers' Vicksburg Delaware River Model (U.S. Army Corps of Engineers, 1962) indicated that the mass transit time of water from Trenton to Marcus Hook, when the flow at Trenton is 4,000 cfs, is 43 days.

The salinity is flushed seaward by any flow of fresh water originating upstream from the salt front—that flowing into the estuary at Trenton, that from tributaries below Trenton, and that from the "fresh-water lake" in the river between Trenton and the salt front. In this report, however, "fresh-water discharge" will mean inflow into the estuary at Trenton and will neglect tributary flows.

Most of the water samples were taken early in the calendar month. Because the flow prior to sampling is a more significant factor in determining the salinity than the flow on the day of sampling, the flows used in the correlations are the average flows for the calendar month preceding the date of sampling. The results would be little changed if a shorter period than 1 month had been used. The median values of specific conductance were then plotted against average fresh-water flow at Trenton for the preceding calendar month, and smooth curves drawn through the plotted points.

No doubt the concentration of dissolved solids or of chloride in the river water is a more useful variable than the specific conductance. The dissolved-solids concentration can readily be estimated from the conductance by the relations:

$$S = 0.52K + 16 \text{ for } K < 300 \text{ micromhos}$$
$$S = 0.60K \text{ for } K = 300\text{–}4{,}000 \text{ micromhos}$$

where $S=$ dissolved solids, in parts per million, and $K=$ specific conductance, in micromhos at 25°C (Keighton, 1965, figs. 9, 10).

DISCHARGE-SALINITY RELATION

The dissolved-solids concentration is plotted against fresh-water discharge in figure 1. It is evident that the fresh-water flow is most effective in changing the concentration when the flow is less than a certain critical value. The critical flow values for League Island, Eddystone, and Marcus Hook are, respectively, 3,500, 4,400, and 5,300 cfs. For example, at flows of more than 5,300 cfs, the dissolved-solids concentration at Marcus Hook decreases only 16 ppm for each 1,000 cfs

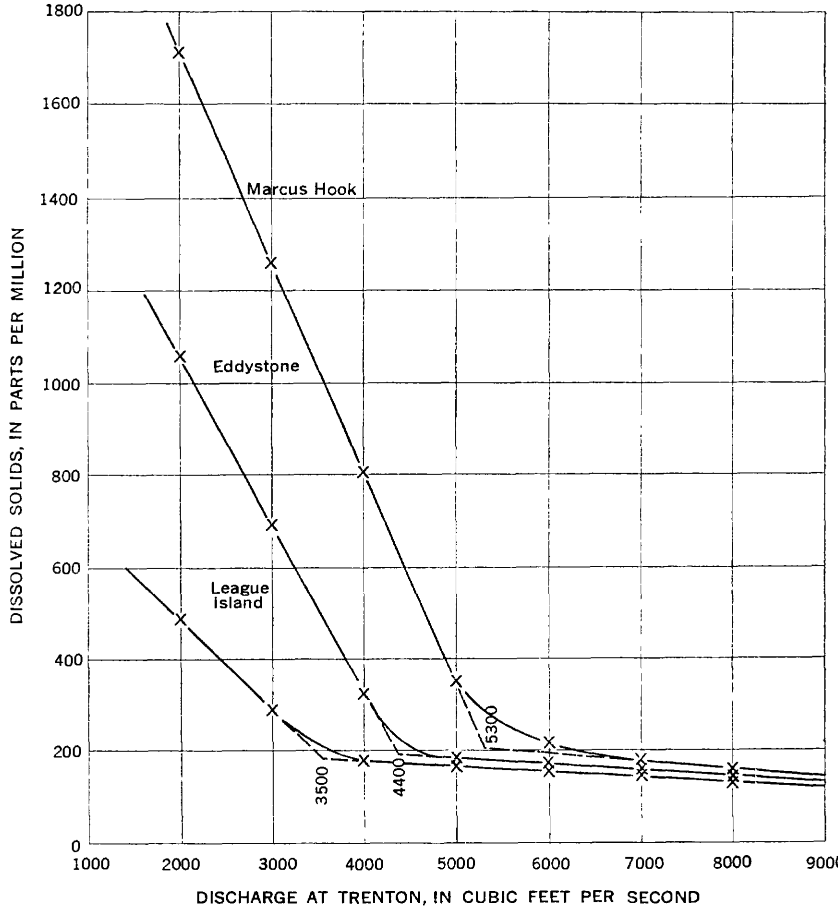

FIGURE 1.—Discharge and dissolved solids at three locations in the Delaware River, August 1949–December 1963.

increase in flow during the preceding month; but at fresh-water flows of less than 5,300 cfs, the change in dissolved-solids concentration is 470 ppm (parts per million) for each 1,000 cfs change in monthly mean flow. At League Island the change is 200 ppm per 1,000 cfs change at flows of less than the critical 3,500 cfs, and 11 ppm per 1,000 cfs at greater flows.

A similar plot (fig. 2) shows the relation between chloride concentration and fresh-water flow. To construct this plot, use was made of figure 16 in my earlier report (Keighton, 1965), which shows the percentage by weight of chloride in the dissolved solids for various dissolved-solids concentrations up to 4,000 ppm.

In table 1 are tabulated the dissolved-solids concentrations and the chloride concentrations found for various steady flow rates; and in table 2, the discharge rates required to maintain concentrations below specified levels.

TABLE 1.—*Concentration of dissolved solids and of chloride at League Island, Eddystone, and Marcus Hook at midtide for various discharge rates at Trenton, N.J.*

Discharge at Trenton preceding month (cfs)	League Island		Eddystone		Marcus Hook	
	Dissolved solids (ppm)	Chloride (ppm)	Dissolved solids (ppm)	Chloride (ppm)	Dissolved solids (ppm)	Chloride (ppm)
2,000	484	164	1,050	452	1,722	861
3,000	282	68	690	262	1,248	561
4,000	172	25	324	88	810	324
5,000	162	21	182	27	336	60
6,000	151	18	167	22	212	38
7,000	141	14	156	19	178	25
8,000	130	12	146	16	156	19
9,000	120	10	136	12	136	12
10,000	110	7.2	125	10	120	10

TABLE 2.—*Antecedent-discharge rates at Trenton, N.J., required to maintain midtide dissolved-solids and chloride concentrations at League Island, Eddystone, and Marcus Hook below predetermined levels*

[All discharge values represent discharge at Trenton, N.J., during preceding month]

DISSOLVED SOLIDS

Sampling site	Discharge (cfs) required to maintain indicated concentration (ppm)						
	200	400	600	800	1,000	1,200	1,500
League Island	3,600	2,400	1,400	------	------	------	------
Eddystone	4,500	3,800	3,250	2,700	2,100	1,000	------
Marcus Hook	6,200	4,900	4,400	4,000	3,500	3,100	2,500

CHLORIDE

Sampling site	Discharge (cfs) required to maintain indicated concentration (ppm)								
	50	100	200	300	400	500	600	700	800
League Island	3,250	2,600	1,600	------	------	------	------	------	------
Eddystone	4,200	3,900	3,400	2,800	2,300	1,800	------	------	------
Marcus Hook	5,100	4,900	4,500	4,100	3,700	3,400	3 000	2,600	2,200

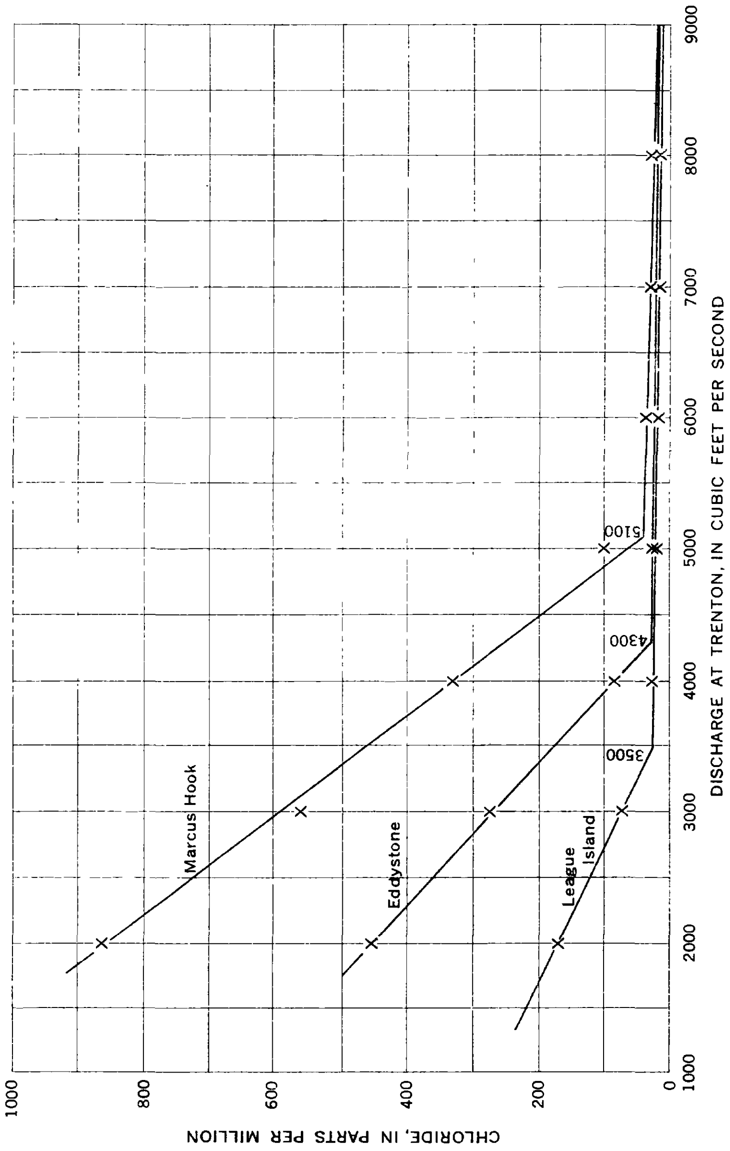

FIGURE 2.—Discharge and chloride concentration at three locations in the Delaware River, August 1949–December 1963.

VALIDITY OF DISCHARGE-SALINITY RELATION

The validity of the relation between salinity and discharge during the 14-year period can be demonstrated in several ways. First, note that the points plotted in figures 1 and 2 lie very close to the smooth curves plotted. Second, note the curves plotted in figure 3—showing the frequency with which specified dissolved-solids concentrations were equaled or exceeded. The dashed curves represent the observed frequencies and are copied from figure 13 of my earlier report (Keighton, 1965). The solid lines are synthesized from the discharge-salinity relation. The percent of time that various discharges were equaled or exceeded at Trenton was obtained from a streamflow frequency curve; then the dissolved-solids concentrations corresponding to each of these discharges was obtained from figure 1. These concentrations are plotted against percent of time to give the solid curves in figure 3. The solid and dashed curves nearly coincide 90 percent of the time. At the 5-percent frequency, the calculated dissolved-solids concentration is 15 percent lower than the observed concentration at Marcus Hook, and 22 percent lower than the observed concentration at Eddystone.

As a third demonstration of the validity of the discharge-salinity relation, figure 2 was used to estimate the average chloride concentration at Marcus Hook for 10-day periods during the calendar years 1960–64, based on the average flow for the previous 10 days. The estimates are plotted in figure 4 as the solid line. The actual chloride concentration for each 10-day period is plotted as a dot. In general, the highs and lows in the curve for estimated chloride concentration correspond in time with those in the curve for observed concentration, but they may differ in magnitude. The causes of some of the discrepancies are known and are being studied. For example, the observed salinity during the first 50 days in calendar year 1963 was greatly in excess of the computed chloride concentration based on flow at Trenton. The difference resulted from strong sustained winds from the northwest causing the lowest tide in recorded history in the Delaware estuary on December 31, 1962. As reported by Lendo (1966), this tide, some 1.7 feet lower than the previous record low tide at Philadelphia and as much as 9 feet lower than normal low tide at Trenton, was followed by a severe chloride invasion as saline water from the bay flowed in to replace the fresh water that had been lost. The persistence of high chloride concentrations in the estuary for many weeks after such an event is typical in the absence of major floods. It appears from figure 4 that actual chloride concentrations do not change as rapidly as the computations based on 10-day-discharge data would indicate. Chloride concentrations in the League Island to Marcus

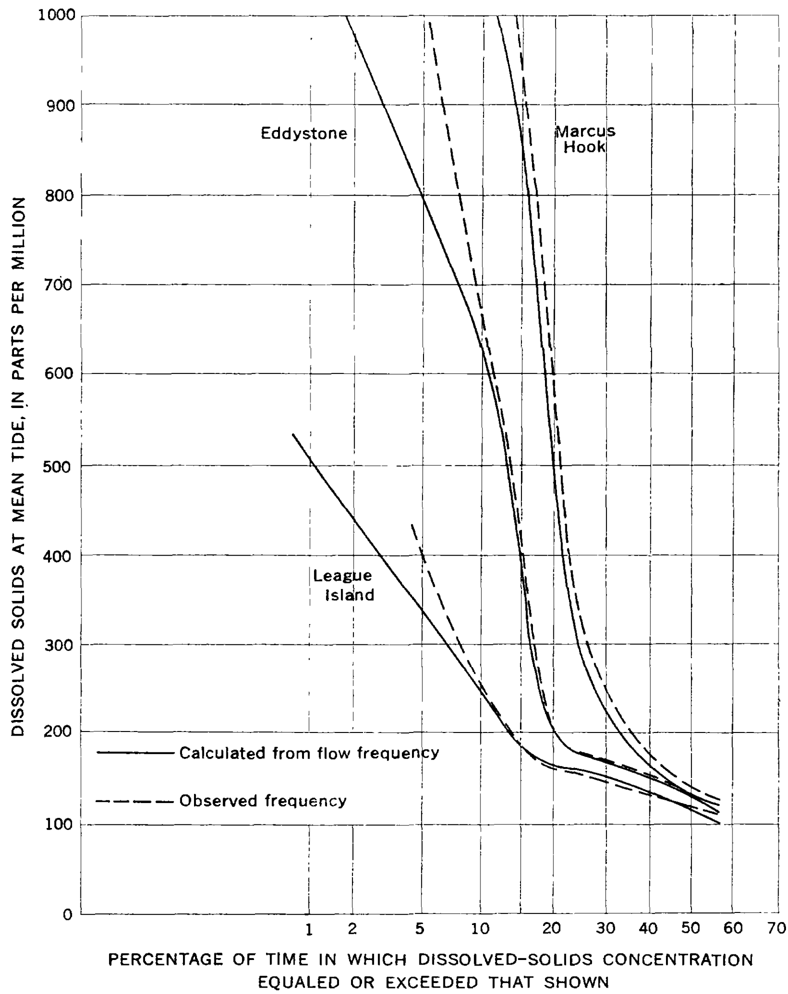

FIGURE 3.—Frequency curves of dissolved-solids concentrations in the Delaware River at three locations, 1950–62.

Hook reach of the river are little affected by momentary changes in fresh-water discharge. That the salinity is influenced only by the cumulative effect of persistent increase or decrease in fresh-water discharge justifies the use of monthly average data in the development of figure 2, although figure 4 shows greater detail. On the whole, however, the discharge-salinity relations presented in figures 1 and 2 and in tables 1 and 2 probably well represent the conditions during the 14-year period August 1949–December 1963.

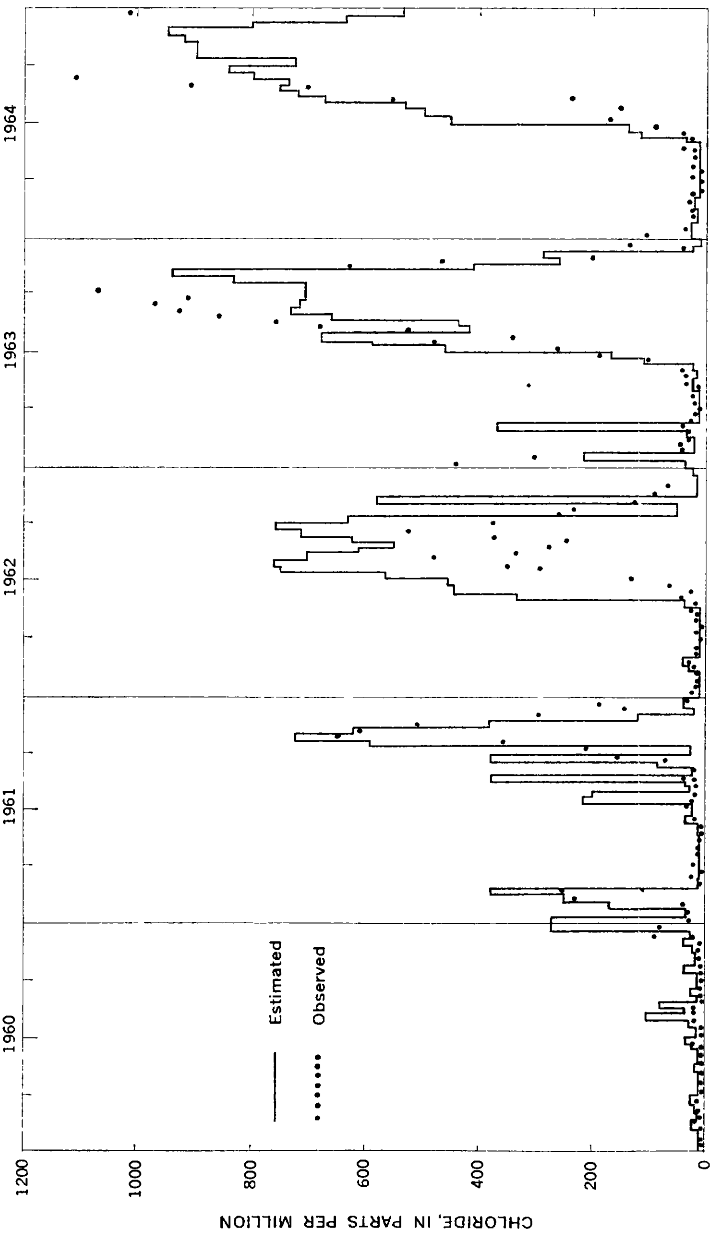

FIGURE 4.—Estimated and observed chloride concentration in the Delaware River at Marcus Hook, Pa., for the calendar years 1960–64.

OTHER FACTORS AFFECTING SALINITY

In the preceding discussion the discharge at Trenton was taken to be a measure of fresh-water flow into the estuary. There is also fresh-water flow from the Schuylkill River and from other smaller tributaries, but, except during short time periods, the discharge at Trenton is probably indicative of the total fresh-water flow. The salinities plotted were the medians of those at a number of random tidal stages and elevations. They are probably average salinities at midtide and at mean tidal height.

Salinity varies with both tidal stage and tidal elevation. In a tidal cycle, salinity is at a maximum at approximately the time of high slack water, and at a minimum at approximately the time of low slack water. When sea level, or mean tidal elevation, is high, salinities are greater than when sea level is low. These facts are illustrated qualitatively in figure 5 for February 27–March 14, 1962. A small tidal range produces a small range in salinity (maximum minus minimum), as is evident on March 1, 3, and 6, and a large tidal range results in a greater spread between maximum and minimum salinity, as on March 3 and 7. Furthermore, as the tidal stage rises (March 3–7 compared to March 8–10), the chloride concentration also rises. Excellent data are now available from continuous recording instruments, and from these data the effects of tidal elevation and range on salinity hopefully can be quantitatively developed. The effects of wind storms on tidal range and, thus, on salinity were discussed by Parker, Hely, Keighton, Olmsted, and others (1964, p. 156–157), by Cohen and McCarthy (1962), and by Lendo (1966).

Changes in the physical shape of the estuary also cause changes in the discharge-salinity relation. Dredging or the building of dikes and breakwaters may change the tidal regimen and, thus, the salinity of the river (Wicker and Rosenzweig, 1950; Keighton, 1954, p. 4, 5). The construction of tide barriers and tide gates on tributary streams in the upper part of the estuary tends to reduce the volume of flow required to fill the tidal prism between low- and high-tide levels. This may reduce or increase the salinity invasion from the Delaware Bay into the lower estuary. The intertidal volume upstream from any such tide barrier can roughly be converted into the number of cubic feet per second of flow that would be required to fill the volume in the approximately 19,000 seconds of a typical incoming tide. For each acre thus protected by a tide barrier in the upper estuary, where the normal tidal range is about 6.5 feet, the average upstream flow rate in the lower estuary would be reduced 15 cfs. This reduction would be very small compared with the average observed upstream flow rates of 400,000 cfs at Delaware Memorial Bridge and 100,000 cfs at Tacony-Palmyra Bridge; but as the protected acreage steadily increases over the years, so would the proportional reduction in salinity invasion.

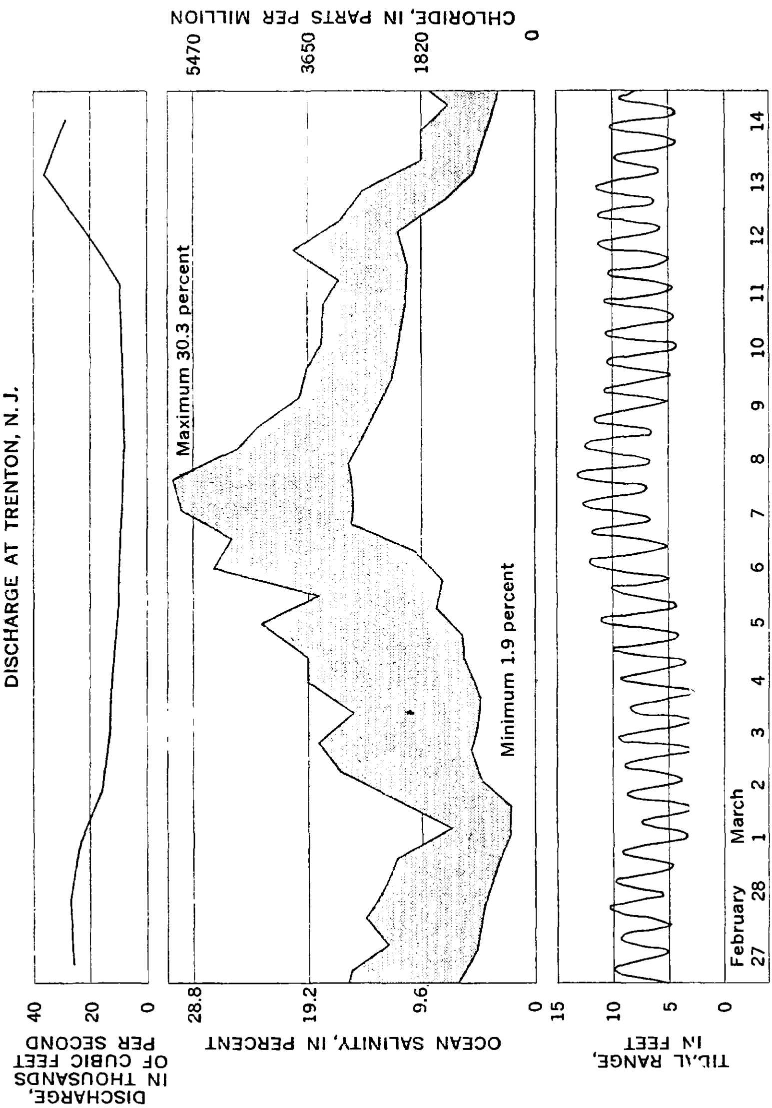

FIGURE 5.—Effect of tidal range, tidal elevation, and discharge on salinity, Delaware River at Reedy Island Jetty, Del., during storm of March 6–7, 1962. (Adapted from a slide used by David McCartney and N. H. Beamer in presenting a paper, "The Complexity of Water Quality in the Delaware Estuary," at the 52d national meeting of the American Institute of Chemical Engineers in 1964.)

Dredging the shipping channel does not increase the intertidal volume, as the channel is always filled even at low tide. Often the dredged material is dumped on tidal marshes, so that the intertidal volume is actually reduced.

The movement of salinity in the estuary is the result of a mixing process controlled by tidal movement. In this process the intertidal volume mixes with the low-tide volume of the adjacent downstream segment on each tidal exchange. Dredging in the shipping channel, in so far as it increases the low-tide volume, interferes with this dilution process and retards the rate of movement of salinity upstream or downstream. The construction of tide barriers in tributary streams, on the other hand, results in a decrease in intertidal volume and, thus, a reduction in the mixing process and in the rate of salinity invasion or flushing.

OTHER STUDIES OF DISCHARGE-SALINITY RELATIONS

Other discharge-salinity relations have been developed statistically. They may represent well the relations during the period for which they were developed, but they do not always correspond to the relations during the 14-year period described in this report. Likewise, the discharge-salinity relation presented here for the period August 1949–December 1963 may not be applicable to later periods, especially if physical changes in the estuary result in changes in tidal range or elevation or in the volume of water in various segments of the estuary.

The variation in the discharge-salinity relation is evident when the relations developed in this paper are compared with those developed by other workers for other periods of time. Pioneers in this field were Mason and Pietsch (1940), who developed an empirical chart based on more than 10,000 samples collected during the drought of 1930–31. Their estimates were for chloride, in parts per million, at midtide.

In their report (1940, p. 463), Mason and Pietsch listed the total runoff that would be required to halt the 50-ppm isochlor at various stations along the Delaware. To compare their estimates with those from the current study, it was necessary to interpolate between their estimates of discharge at Brammels Point and at Chester to determine discharge at Eddystone, and to estimate that the discharge at Eddystone and at Marcus Hook is 1.43 times that at Trenton. The discharge at Trenton required to halt the 50-ppm isochlor at Eddystone and at Marcus Hook, then, would be 4,500 cfs and 5,000 cfs, respectively, on the basis of Mason and Pietsch's data, and 4,200 cfs and 5,100 cfs, respectively, on the basis of current data (table 2).

The average duration of salinity in excess of 50 ppm from 1907 to 1938, as calculated by Mason and Pietsch from discharge, was 57 days per year at Marcus Hook, 40 days per year at Chester, and 3 days per year at Philadelphia. For the period 1949–63 (Keighton, 1965, fig. 21) the corresponding observations were 100, 80, and 18 days per year, average. Thus, for this recent 14-year period there are about twice as many days of salinity invasion as were calculated by Mason and Pietsch for the earlier 31-year period. This difference may be related to the increase in sea level.

Malcolm Pirnie Engineers and Albright and Friel, Inc. (1950), estimated the following flow-salinity relations, to which have been added the salinity estimates from figure 2:

Flow at Trenton (*cfs*)	*Salinity at Marcus Hook (chloride, in ppm)*	
	1950	*This report*
1,500	3,410	1,000
2,000	2,200	861
2,500	1,430	720
3,000	830	561
3,500	440	460
4,000	193	324
4,500	133	190
5,000	66	91

The Pennsylvania Water Resources Committee (1953, p. 39–40) said that 6,900 cfs at Fort Mifflin (4,800 cfs at Trenton) in 1931–32 was sufficient to prevent an average chlorinity in excess of 50 ppm at Marcus Hook, but that in 1952 a flow of 9,500 cfs (6,600 cfs at Trenton) was required. According to figure 2, in 1949–63 a flow of 5,100 cfs at Trenton was sufficient to hold a median concentration of 50 ppm chloride at Marcus Hook.

The Pennsylvania Water Resources Committee (1953, p. 40) also said that 4,000 cfs at Trenton would be insufficient to prevent monthly average chlorinities of 200 ppm or more at Marcus Hook. However, for 1949–63 a discharge of 4,500 cfs was sufficient. L. F. Connell, of Sun Oil Co., observed (written commun., 1951) "that while dry weather flows today (1951) are no lower than those of 20 years ago, the salt concentrations in the river at Marcus Hook are definitely much higher;" and Shephard T. Powell (written commun., 1952) believed that chlorinity at Chester, Pa., and at Paulsboro, N.J., was materially higher during 1943–44 than it was during 1930–32 and 1936 despite the fact that river flows were also slightly higher in 1943–44. He attributed that increase in chlorinity, or salinity, to the enlargement of the channel between the Navy Yard and the sea, which occurred between April 1939 and February 1942.

The Board of Water Supply of the city of New York made a comprehensive study of salt movement in the Delaware River, reported by Terenzio (1953). Terenzio "established that the flow-salinity relationship was a changing, rather than a constant, phenomenon; hence the work of earlier agencies, while helpful, was useless for specific conclusions during 1951" (p. 210). The study also showed that in 20 years the salt front had advanced upstream between 6 and 10 miles. From two diagrams in Terenzio's report (sheets 1 and 20), the flow required to maintain 50 ppm chloride can be estimated, as follows:

Locality	Discharge at Trenton (cfs)		
	1929–41	1951	This report
League Island	2, 450	3, 500	3, 150
Eddystone	3, 850	4, 900	4, 200
Marcus Hook	4, 900	7, 700	5, 100

The Pennsylvania Water Resources Committee (1953) made several estimates of the discharges at Trenton required to maintain specific chlorinities at or near Marcus Hook. They noted a rise in sea level and an increase in tidal range between 1932 and 1952 and postulated an increase in salinity as a result. Their estimates and those from the present study are given in the following table.

	Discharge at Trenton required to maintain specified chlorinities		
	1931–32	1952	This report
50 ppm, at Marcus Hook	4, 800	6, 700	5, 100
200 ppm, at Marcus Hook	------	4, 000	4, 500
100 ppm, at Chester	------	4, 000	4, 400

Incodel, the Interstate Commission on the Delaware River Basin, stated (1960) that "a regulated minimum flow into the tidal estuary equivalent to a daily rate at Trenton of approximately 4,700 cfs (as provided for under the Army Engineers proposed Delaware River Basin plan) will result in the maintenance of a chloride content of less than 50 ppm well below Marcus Hook." From figure 2 of the current study, a discharge of 4,700 cfs at Trenton (during 1949–63) resulted in a salinity of 140 ppm chloride at Marcus Hook. A minimum freshwater discharge of 5,100 cfs at Trenton would reduce the salinity to 50 ppm chloride at Marcus Hook.

The Delaware River Basin Commission (1964, p. 6) says "It is estimated that a sustained fresh water flow of 1,600 mgd at Trenton would be required to provide a hydraulic barrier in the Delaware estuary to limit the salt water intrusions to approximately 50 ppm of chloride at or below the Benjamin Franklin Bridge."

From figure 2, based on data for 1949–63, it can be seen that a flow of 1,600 million gallons per day, or 2,480 cfs, at Trenton would limit the salinity at League Island to 120 ppm chloride, at Eddystone to 360 ppm chloride, and at Marcus Hook to 720 ppm chloride.

The Delaware River Basin Commission also stated (1964, p. 44) that "it has been estimated by the U.S. Army Corps of Engineers that a continuous fresh-water flow of 7,700 mgd (11,900 cfs) would be required to maintain the line of 50 ppm of chloride from penetrating above Marcus Hook." If one assumes that this flow corresponds to 8,300 cfs at Trenton, it would be 160 percent of the fresh-water discharge required to hold 50 ppm chloride at Marcus Hook during 1949–63 (fig. 2).

CONCLUSIONS

This statistical study is based on the period August 1949–December 1963. During this period the average annual discharge of the Delaware River at Trenton, N.J., ranged from 7,090 cfs to 17,557 cfs, and monthly average discharges ranged from 1,828 cfs to 39,230 cfs. The period includes three consecutive low-flow years (1961, 1962, and 1963).

The relation between salinity and discharge at Trenton for this 14-year period is exhibited in figures 1 and 2 and in tables 1 and 2. From these sources one can readily determine what salinity resulted at League Island, Eddystone, or Marcus Hook from specific antecedent fresh-water flows. Also, one can estimate the sustained fresh-water flows which held the dissolved-solids or chloride concentrations at specified values at any of these three locations. The critical flows at Trenton which control salinities at League Island, Eddystone, and Marcus Hook are 3,500, and 5,300 cfs. Sustained discharges greater than these assure low salinity at these three locations.

The estimates of salinity in this report are for salinity at midtide and probably represent average salinities. However, the salinity (except where very low) has two maximums and two minimums each day. Whether the two maximums are nearly the same or are very different depends upon the range of the the two daily tidal cycles. Likewise, the rate at which salinity moves upriver is influenced by the tidal range, for the tide governs the mixing of downstream saline water with upstream fresher water.

Short-term increases in fresh-water flow may reduce the salinity, although not by precisely the amount indicated in table 1 for sustained flows. For example, the quantity of fresh water may be just sufficient to replace saline water with less saline water from the adjacent upstream segment of the river. Each of these three locations is under the influence of fresh-water flow from the Schuylkill River and from overland runoff, but in the long run the quantities of these are proportional to the flow at Trenton. Local storms may increase the flow of the Schuylkill River without affecting the flow of the Delaware River at Trenton.

Sea level, as it changes the hydrostatic head of salt water at the mouth of the estuary, affects the movement of salinity in the estuary. In the last 25 years, sea level at Atlantic City, N.J., has increased an average of 0.0009 ft per year. Seasonal changes in sea level average 0.5 ft per year. Onshore winds raise sea level and cause a slight temporary increase in salinity in the river. Offshore winds may blow water out of the bay so that fresh water moves downstream. When the offshore winds cease, however, salt water moves in to replace the fresh water blown out. Widening, deepening, or straightening a river channel or building dikes or jetties often affects tidal conditions in tidal estuaries or tidal rivers and may affect salinity.

Comparison of river salinities in 1949–63 with those estimated by other workers for other time periods indicates that the relations change with time. Consequently, care should be exercised in applying the relations developed in this report to time periods other than 1949–63. The U.S. Geological Survey and cooperating agencies propose to make further statistical studies to evaluate the effects of factors other than fresh-water discharge, such as tidal elevation, tidal range, and sea level.

At present, the Geological Survey, in cooperation with the city of Philadelphia and the Delaware Geological Survey, is operating instruments at seven locations on the estuary to record water-quality characteristics. The data from these instruments provide a more detailed representation of the movement of salinity in the estuary than was obtained by the once-a-month sampling during the 14-year period covered by this report. In addition, using newly developed technology, the Survey began in December 1962 to collect and publish data on tidal discharge volumes for each tide cycle and each calendar day at Palmyra, N.J., about 26 miles downstream from Trenton. This record includes the instantaneous upstream or downstream flow of the tidal river at any time and reflects tidal range as well as fresh-water discharge at Trenton. It may, therefore, correlate better with salinity advances or retreats than fresh-water flow alone, and it will be useful in extending these statistical studies. Hopefully, theoretical studies of mixing processes in estuaries will be undertaken with the aim of finding a mathematical approach that will include all the significant variables. This problem was discussed by Pyatt (1964, p. 54), who concluded that the statistical approach is the most useful way to study pollutant distribution in estuaries, but that attempts to reach a mathematical solution should not be abandoned.

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