Salinity of the Delaware Estuary

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1586–B

Prepared in cooperation with the City of Philadelphia and the State of Delaware

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By BERNARD COHEN *and* LEO T. McCARTHY, Jr.

HYDROLOGY OF TIDAL STREAMS

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ABSTRACT

The purpose of this investigation was to obtain data on and study the factors affecting the salinity of the Delaware River from Philadelphia, Pa., to the Appoquinimink River, Del. The general chemical quality of water in the estuary is described, including changes in salinity in the river cross section and profile, diurnal and seasonal changes, and the effects of rainfall, sea level, and winds on salinity. Relationships are established of the concentrations of chloride and dissolved solids to specific conductance. In addition to chloride profiles and isochlor plots, time series are plotted for salinity or some quantity representing salinity, fresh-water discharge, mean river level, and mean sea level.

The two major variables which appear to have the greatest effect on the salinity of the estuary are the fresh-water flow of the river and sea level. The most favorable combination of these variables for salt-water encroachment occurs from August to early October and the least favorable combination occurs between December and May.

INTRODUCTION

This progress report summarizes the U.S. Geological Survey's water-quality investigation of the Delaware River between the Walt Whitman Bridge, Philadelphia, Pa. (Gloucester City, N.J.), and the Appoquinimink River, Del., from July 1954 through December 1958.

The Delaware River (fig. 1) is tidal from Trenton, N.J., to Delaware Bay. Trenton is 34 miles above the Walt Whitman Bridge and the reach of the river under investigation extends 44 miles below this bridge to the Appoquinimink River, Del. Many tributaries enter the Delaware River in this reach; the major ones are the Schuylkill and the Christina Rivers. The Delaware River is 2,700 feet wide at the Walt Whitman Bridge; 6,600 feet wide at the Delaware Memorial Bridge; and 12,300 feet wide at Reedy Point. The navigation channel is approximately 35 feet deep and 800 feet wide in this reach of the river. There are five islands in the area of study—Little Tinicum Island on the Pennsylvania side of the channel off Essington, Pa.; Chester Island on the New Jersey side of the channel off Chester, Pa.;

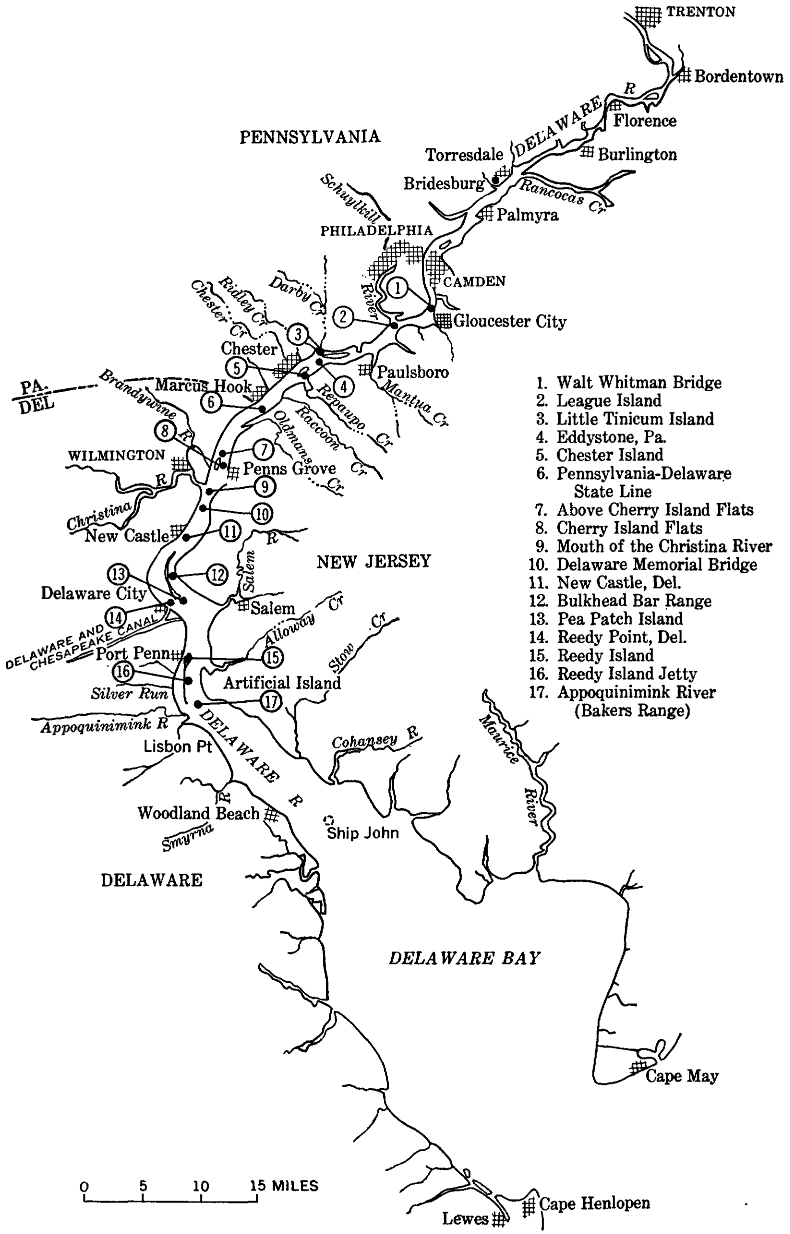

FIGURE 1.—Location of sampling stations between Philadelphia, Pa., and Appoquinimink River, Del. (Bakers Range).

Cherry Island Flats off Edgemoor, Del., on the New Jersey side of the channel; Pea Patch Island on the Delaware side of the channel off Delaware City, Del.; and Reedy Island on the Delaware side of the channel off Port Penn, Del.

Several important cities are along the reach of the river studied; Philadelphia is the largest. Among the others are Gloucester City, N.J.; Chester, Pa.; Marcus Hook, Pa.; Wilmington, Del.; New Castle, Del.; Delaware City, Del.; Paulsboro, N.J.; and Penns Grove, N.J. These cities use river water for many purposes. Numerous industrial plants are on both sides of the Delaware River between the Walt Whitman Bridge and the Delaware Memorial Bridge, most of which use Delaware River water. In addition to the municipal and industrial interests, in the water usage, there are State and Federal interests as the Delaware River is an interstate stream. The Delaware River Amended Decree of the United States Supreme Court provided for a River Master and directed him, among other things, to "observe, record and study the effect of developments on the Delaware River and its tributaries upon water supply and other necessary, proper, and desirable uses."

There is much to be learned about the factors controlling salt-water invasion into tidal rivers, and this report presents and examines some of the general problems. The chemical characteristics of the water, some of the variables (including hurricanes) affecting salinity, and some of the methods of studying salinity, such as chloride profiles and isochlors, are described and discussed.

The term "salinity" refers to the total salt content or the concentration of dissolved solids of the water. The term "salt water" is used to denote river water which has been mixed with water from the bay or ocean. Chloride content refers to the chloride-ion concentration in parts per million.

ACKNOWLEDGMENTS

This investigation was conducted under the direction of N. H. Beamer, district chemist of the Pennsylvania, Delaware, and New Jersey areas. The investigation was made in cooperation with the city of Philadelphia through its Water Department (S. S. Baxter, water commissioner); the Delaware River Master, C. G. Paulsen; and the State of Delaware through its Geological Survey (J. J. Groot, State geologist). The U.S. Coast and Geodetic Survey furnished data on the tides at Philadelphia, Pa., and Atlantic City, N.J. The U.S. Coast Guard at Gloucester City, N.J., furnished a boat for the collection of water samples.

Acknowledgment is made to the Corps of Engineers, Department of the Army, for assistance in the collection of samples, and to the authorities of the Delaware Memorial Bridge for their cooperation. Data on hurricanes were supplied by the Philadelphia Weather Bureau. Acknowledgment is also made to the Scott Paper Co., Chester, Pa., the Deepwater Operating Co. of New Jersey, and many other industries who helped in this study.

PREVIOUS INVESTIGATIONS

The Pennsylvania Department of Health (1935) issued a comprehensive report on studies of salinity in the Delaware estuary. Mason and Pietsch (1940) developed a diagram which was intended to show the rate of fresh-water discharge required to hold the 50 ppm (parts per million) isochlor at several locations in the river. Terenzio (1953) also studied the behavior of salinity of the estuary and established relationships between the fresh-water flow and the distribution of salinities. Ketchum (1952) prepared a report on "The distribution of salinity in the estuary of the Delaware River." Durfor and Keighton (1954) described the chemical characteristics of Delaware River water from Trenton, N.J., to Marcus Hook, Pa. The Corps of Engineers, Department of the Army, has analyses of chloride content of Delaware River water on file in Philadelphia.

FIELD PROGRAM

During the investigation an intensive study was made of the chemical quality of the Delaware River water. It was assumed that the maximum salinity occurred at the time of high-water slack in the tidal cycle and the minimum salinity at the time of low-water slack (Keighton, 1954). Since most salt-water invasions in the Delaware River occur in the summer and fall months, samples were collected at frequent intervals during these months. During 1954 samples were collected at seven sites between Philadelphia, Pa., and the Delaware Memorial Bridge, Del. In 1955 samples were taken at 11 locations between Philadelphia, Pa., and Reedy Point, Del. In 1956 two additional sites were added which extended the reach of study to Appoquinimink River, Del., (Bakers Range). Table 1 gives the locations of the sampling points by buoy numbers which appear on navigation maps (U.S. Coast and Geodetic Survey Navigation Maps 294 and 295). During the period of study in 1956 and 1957 samples were collected as close as possible to the time of slack water. A Coast Guard utility boat used in sampling maintained the speed (20 knots) necessary to follow slack water upstream. Most samples were collected within 1 hour of the predicted time of slack water. The approximate times of slack water were obtained from "Current Tables, Atlantic Coast, North America" (U.S. Coast and Geodetic Survey).

TABLE 1.—*Midstream stations, Delaware River*

[Based upon Corps of Engineers, U.S. Army data using an arbitrary datum line at New Castle, Del. of 400,000 ft]

Buoy marker [1]	Location	Thousands of feet
"39"	Walt Whitman Bridge	243. 5
R44A	League Island	255. 0
R "2T"	Eddystone	303. 1
Quarantine Pier	Marcus Hook	322. 5
C "3B"–R "6B"	Above Cherry Flats	353. 1
C "5C"–RB	Mouth of Christina River	373. 5
	Delaware Memorial Bridge	386. 5
"5D"–N "6D"	New Castle	399. 3
"1B"–R "4B"	Bulkhead Bar Range	414. 7
Bell on Island RN "2"	Pea Patch Island	428. 0
C "27"–N "2N"	Reedy Point	442. 3
C "3R"–N "4R"	Reedy Island Jetty	462. 5
C "1B"–R "2B"	Appoquinimink River (Bakers Range)	478. 3

[1] See U.S. Coast and Geodetic Survey Navigation Maps 294 and 295.

Several trips were made to collect top and bottom samples across the navigation channel at selected locations to determine salt-water distribution with depth and cross section at those locations.

From July 1955 to September 1958 comprehensive analyses were made of samples collected once a month at the Delaware Memorial Bridge, Del. (table 11), and at Reedy Point, Del. (table 12). These samples were either collected at a particular stage of tide or composited from daily samples. The comprehensive analyses of these samples consisted of determinations of silica, iron, calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chloride, fluoride, nitrate, dissolved solids, hardness, specific conductance, pH, and color. For the majority of samples collected, determinations were made only of specific conductance, chloride, sulfate, and dissolved solids.

A Geological Survey bucket sampler holding a 12-ounce bottle with pressure seal was used to collect top samples, and a Foerst sampler was used to collect bottom samples. Top samples were collected 3 feet below the surface to avoid getting scum, oil, or other debris in the sample, and bottom samples were collected 3 feet from the bottom of the river to avoid picking up mud or sediment from the bottom. A metal armored glass thermometer (20°–110°F graduated to 1°F) was used to measure the temperature of the samples. All field measurements of conductivity were made with a wheatstone bridge using an electron ray eye tube as a balance indicator.

An instrument which continuously measured and recorded specific conductance was in operation for a short period in 1955 at the Delaware Memorial Bridge. Two of these instruments were used in the study during 1956, 1957, and 1958—one at the Delaware Memorial Bridge, Del., and the other at Reedy Island Jetty, Del. In 1957 and 1958 additional instruments were installed at Marcus Hook, Pa., and Delair, N.J., to record specific conductance. A water-stage recorder was put into operation at Reedy Island Jetty in September 1956.

CHEMICAL CHARACTERISTICS OF THE WATER

The principal dissolved constituents in the water in the reach of the river between the Delaware Memorial Bridge, Del., and Reedy Point, Del., are calcium, magnesium, sodium, potassium, bicarbonate, sulfate, and chloride. Smaller quantities of silica, iron, fluoride, and nitrate are also present.

The specific conductance, the concentration of dissolved solids, and the concentration of most of the constituent increased from Philadelphia, Pa., downstream to Reedy Island, Del. However, the concentration of nitrate at Reedy Point was slightly less than at the Delaware Memorial Bridge. The concentrations of fluoride, iron, and silica were not significantly different in the downstream direction.

At low rates of fresh-water flow the salinity increased sharply at points downstream from the Delaware Memorial Bridge. Under the conditions of heavy runoff following the hurricanes of 1955, the chloride concentration was less than 30 ppm at stations as far downstream as the Delaware Memorial Bridge but increased downstream from this point. There was a tendency for salt water to move upstream on the bottom of the river at times of low rates of fresh-water flow.

Most mineral matter dissolved in water is dissociated into positive and negative ions which are capable of conducting electricity. Since the specific conductance of water increases with the concentration of the ions, it is a useful, approximate measure of the dissolved mineral matter.

Figure 2 illustrates the relationship between the concentration of dissolved solids and specific conductance for Delaware River water. The plot is based upon samples whose specific conductance ranges from 4,000 to 16,500 micromhos. The approximate equation defining the curve in the range 2,500 to 10,500 ppm of dissolved solids is:

$$\text{Dissolved solids (ppm)} = \frac{\text{Specific conductance (micromhos)} - 780}{1.5}$$

A plot of specific conductance (micromhos) against chloride concentration (ppm) on rectilinear paper (fig. 3) is a straight line from

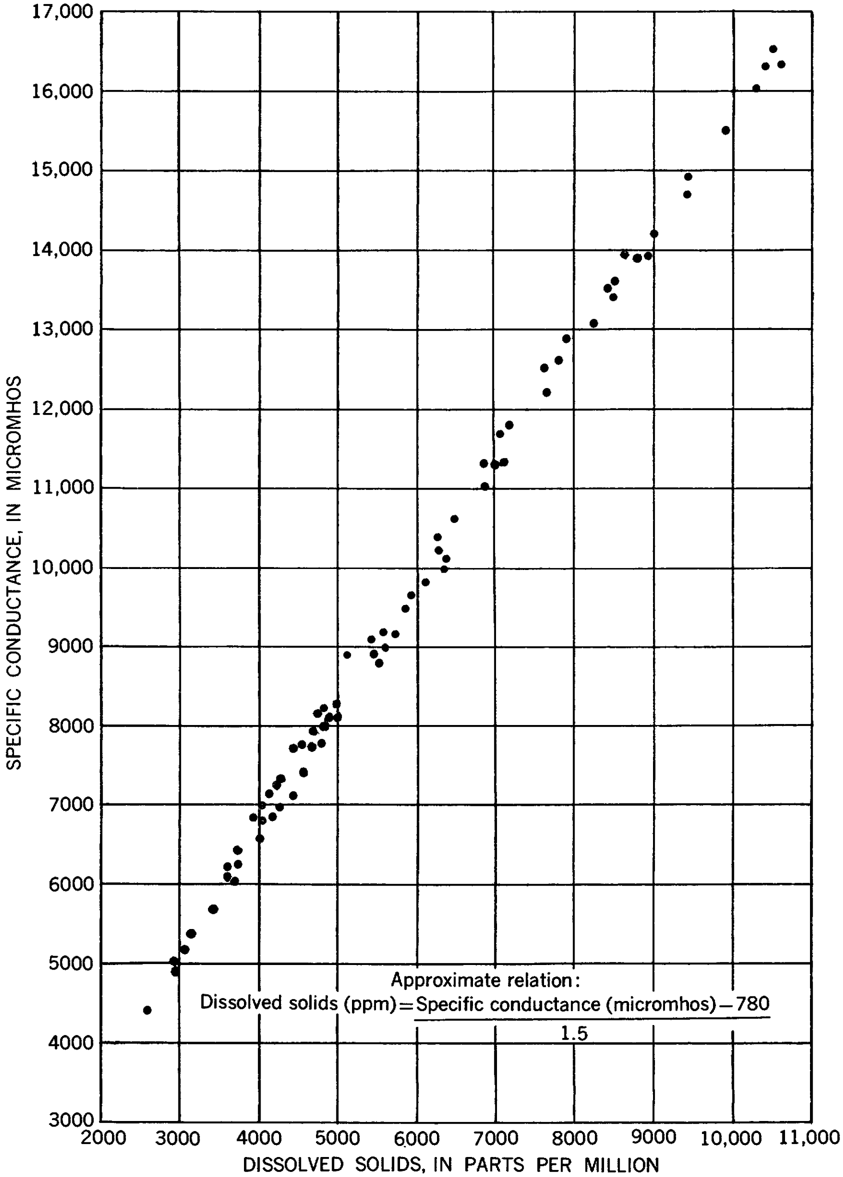

Figure 2.—Relation between specific conductance and dissolved solids (2,500–10,500 ppm).

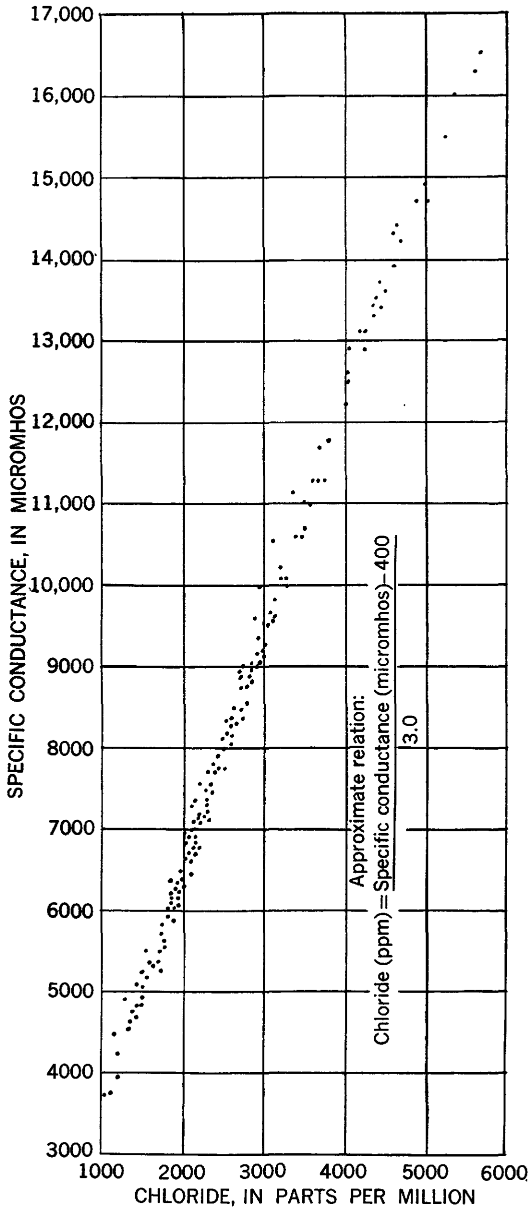

FIGURE 3.—Relation between specific conductance and chloride concentration (1,000–6,000 ppm).

4,000 to 16,000 micromhos. A good approximation of the chloride concentration (ppm) can be made by using the equation for a straight line over this range of specific conductance. The equation is:

$$\text{Chloride concentration (ppm)} = \frac{\text{Specific conductance (micromhos)} - 400}{3.0}$$

Maximum concentration of dissolved solids occurs when the fresh-water flow is lowest, usually between June and October, owing to the encroachment of salt water from Delaware Bay into normally fresh-water regions of the river.

VARIATION IN CONCENTRATION AND MOVEMENT OF CHLORIDE

The Delaware River is tidal as far upstream as the "falls" at Trenton, N.J. Below Trenton the downstream flow is reversed twice a day by tidal water moving upstream. The flood tide is the flowing of water into the estuary from the ocean or bay, and the ebb tide is the flowing of water from the estuary into the ocean or bay. The change in direction of flow from flood to ebb tide and vice versa is accompanied by a slack-water period (a period of weak current velocity) (fig. 4).

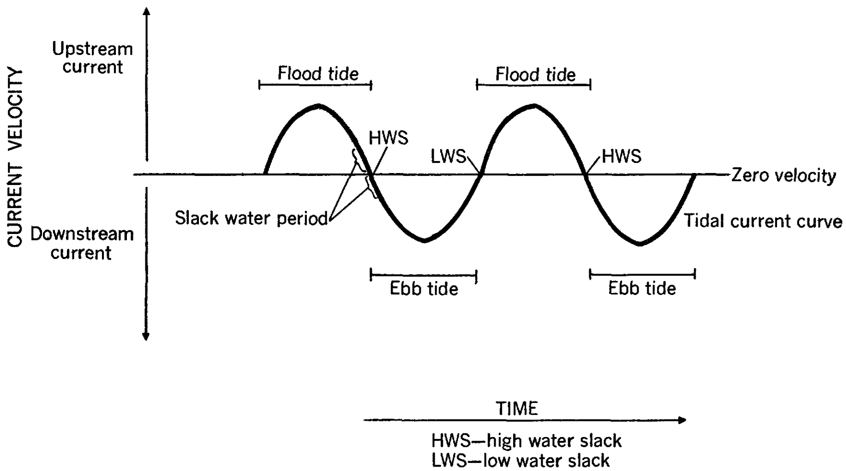

FIGURE 4.—Diurnal variation in river current. The actual current curve of the Delaware River is not a perfect sine curve although it is similar in shape.

High-water slack (HWS) is a momentary zero velocity when the current changes from flood to ebb tide, and low-water slack (LWS) a momentary zero velocity when the current changes from ebb to flood tide.

The tide is related to the relative positions of the moon, sun, and earth. The tidal day has an average length of 24 hours and 50 minutes, like the lunar day. Tides of greatest range (called spring tides) occur at the time of new and full moon; tides of least range (called neap tides) occur at the time of the moon's first and third quarters. When the moon is in the perigee, closest to the earth, higher high tides and lower low tides than usual occur. When the moon is in the apogee, farthest from the earth, the rise and fall of the tides are less than usual. When moon is at the equator, the two high waters for a day do not differ much nor do the two low waters. The greater the moon's declination (from the equator), the greater the difference between the two high and the two low waters. For a more comprehensive explanation of the above phenomena, Marmer (1951) or any good encyclopedia should be consulted.

In the tidal reaches of the Delaware River two complete tidal cycles, each accompanied by one high-water slack and one low-water slack, usually occur each calendar day. The slack-water period in the Delaware River occurs from 1 to 2 hours after high or low tide. At the Delaware Memorial Bridge, the time between a high-water slack and a low-water slack is usually about 6.5 hours, and between low-water slack and high-water slack 6.0 hours. The duration of flood tide decreases and the duration of ebb tide increases upstream.

At the Delaware Memorial Bridge maximum and minimum values of conductivity at the site of the conductivity recorder usually occur within 15 minutes of the predicted times of slack water in the navigation channel. At the conductivity recorder at Reedy Island Jetty the maximum and minimum values of conductivity occur within 30 minutes of the predicted times of slack water in the navigation channel. These factors are demonstrated by the data in table 2.

As fresh water is discharged seaward during the ebb tide, the concentration of dissolved solids decreases until the flood tide begins. Salt water is diluted and pushed downstream by fresh-water discharge. The flushing action continues until low-water slack, after which the ensuing flood waters carry the salt water upstream.

Figure 5 illustrates a continuous record of specific conductance at the Delaware Memorial Bridge. It will be noted from figure 5 that the general shape of the specific-conductance curve through a tidal cycle is sinusoidal; rapid fluctuation occurs after each maximum.

A comparison of the tidal stage and specific conductance appears in figure 6. Maximum and minimum specific conductance occur after maximum and minimum tidal stage and at about the time of slack water.

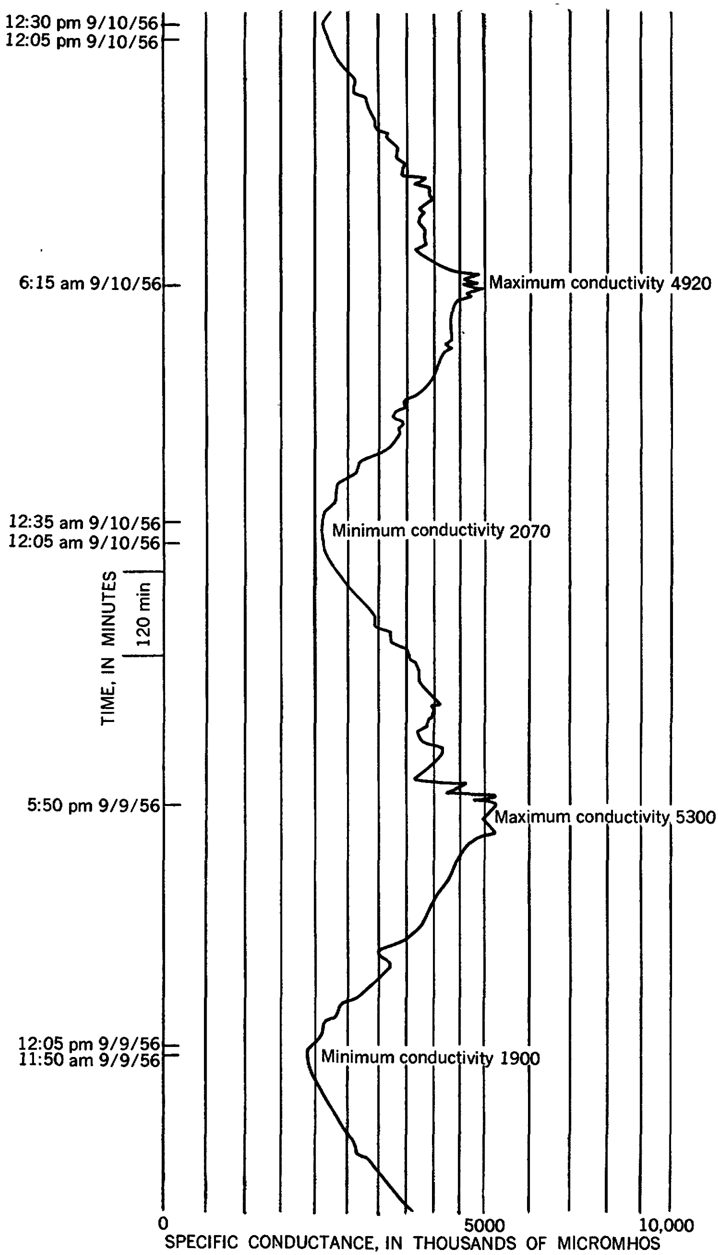

Figure 5.—Section of chart from continuous recorder (of specific conductance) at the Delaware Memorial Bridge, Delaware.

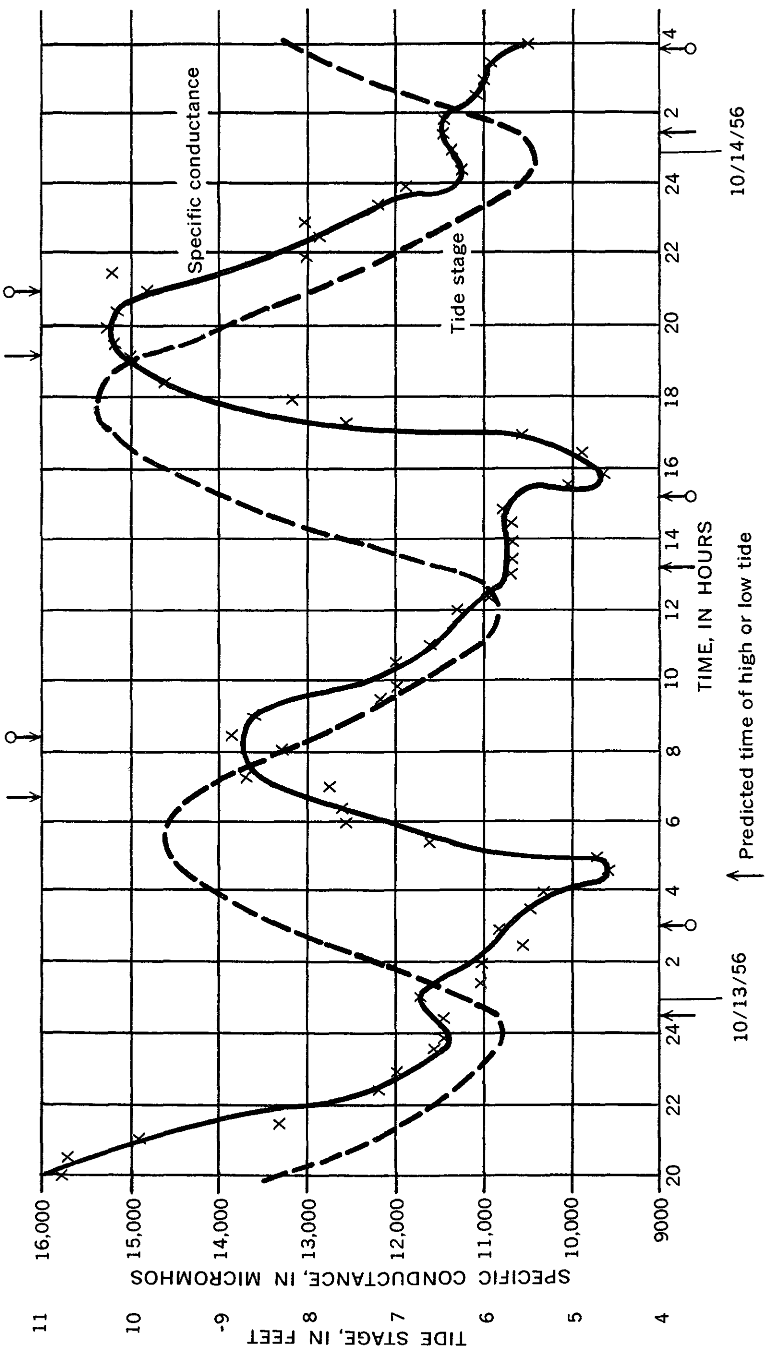

FIGURE 6.—Relationship of stage of tide to specific conductance at Reedy Island Jetty, Delaware.

TABLE 2.—*Comparison of predicted time of slack waters and of maximum and minimum chloride concentration at the Delaware Memorial Bridge and Reedy Island Jetty*

[HWS, high-water slack; LWS, low-water slack; all times are e.s.t.]

Delaware Memorial Bridge					Reedy Island Jetty				
Date (1956)	HWS or LWS	Predicted time of slack for navigation channel	Time of maximum and minimum chloride concentration	Difference in minutes	Date (1956)	HWS or LWS	Predicted time of slack for navigation channel	Time of maximum and minimum chloride concentration	Difference in minutes
Sept. 1	Low	4:10 a.m.	4:25 a.m.	+5	Sept. 1	Low	3:45 a.m.	3:20 a.m.	−25
	High	9:50	9:50	0		High	9:15	8:10	−65
	Low	4:20 p.m.	4:05 p.m.	−15		Low	3:45 p.m.	4:25 p.m.	+40
	High	10:35	10:05	−30		High	10:00	9:50	−10
2	Low	5:20 a.m.	5:05 a.m.	−15	2	Low	4:45 a.m.	5:50 a.m.	+65
	High	11:00	10:50	−10		High	10:20	10:15	−7
	Low	5:20 p.m.	5:05 p.m.	−15		Low	4:45 p.m.	4:50 p.m.	+5
	High	11:30	10:55	−35		High	10:55	10:35	−20
3	Low	6:15 a.m.	5:45 a.m.	−30	3	Low	5:40 a.m.	5:25 a.m.	−15
	High	12:00	11:50	−10		High	11:20	10:45	−35
	Low	6:20 p.m.	6:10 p.m.	−10		Low	5:45 p.m.	5:40 p.m.	−5
	High	12:25 a.m.	12:00	−25		High	11:50	11:20	−30
4	Low	7:00	7:05 a.m.	+5	4	Low	6:30 a.m.	6:05 a.m.	−25
	High	12:50 p.m.	12:35 p.m.	−15		High	12:15 p.m.	11:50	−25
	Low	7:10	7:05	−5		Low	6:35	6:20 p.m.	−15
5	High	1:10 a.m.	1:05 a.m.	−5	5	High	12:35 a.m.	12:40 a.m.	+5
	Low	7:50	7:45	−5		Low	7:15	7:05	−10
	High	1:40 p.m.	1:40 p.m.	0		High	1:05 p.m.	1:05 p.m.	0
	Low	8:00	7:45	−15		Low	7:25	8:45	+80

A chloride profile is a plot of chloride concentration against distance downstream. The chloride profiles in figure 7 represent the farthest advance of salt water in the center of the channel at a high-water slack on a particular day. They do not represent a condition actually existing at any given time, but rather the succession of maximum concentrations of chloride, that occur at the stations at various times, after the crest of the tidal wave advances upstream. Since it is difficult to collect samples in a number of sampling locations at exactly high-water slack, a method was devised for the Delaware River to estimate the chloride concentration at high-water slack (Pennsylvania Department of Health, 1935). The method is satisfactory only for samples collected within 1 or 2 hours of high-water slack. The estimation involves converting the specific conductance of the water to chloride concentrations or analyzing water samples for chloride content. Figure 3 has been used to estimate chloride concentration from specific conductance. The method was checked by estimating the maximum chloride concentration from samples taken before and after high-water slack.

By plotting two profiles on the same graph and measuring the horizontal distance between the two curves at any location, the resultant net advance or retreat of the chloride between sampling periods may

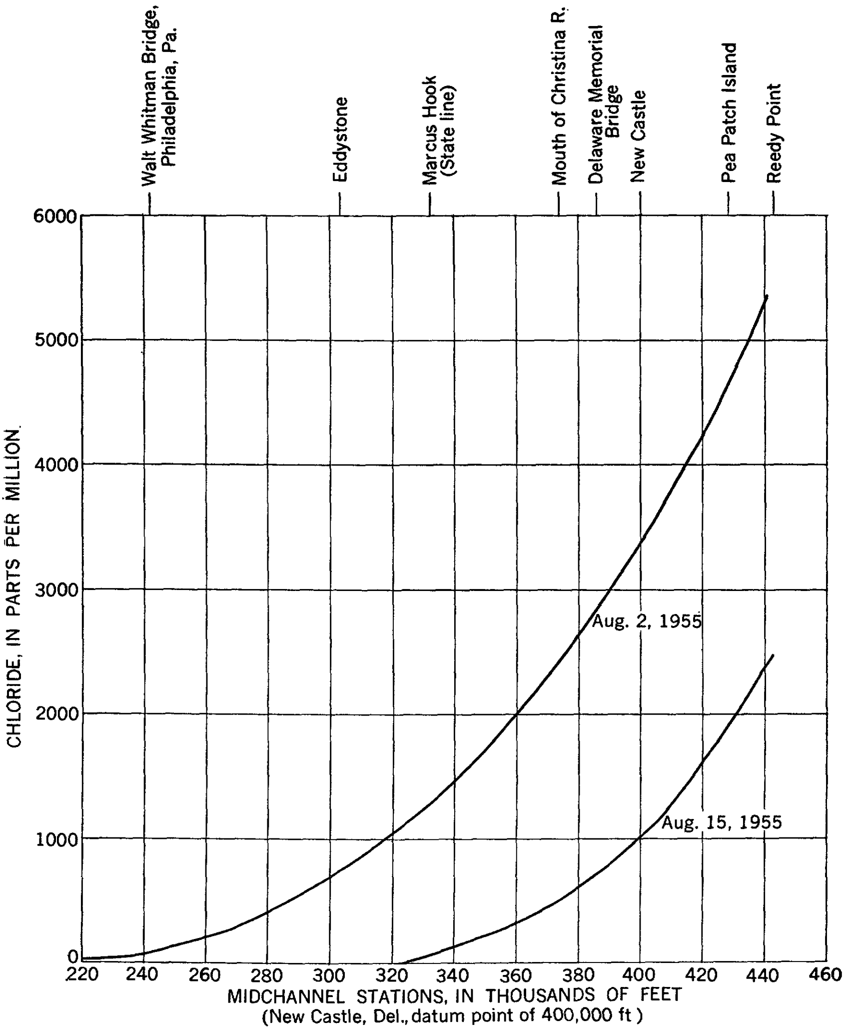

FIGURE 7.—Chloride profiles for August 2 and 15, 1955.

be ascertained. When chloride profiles are plotted as shown in figure 7, movement of a curve to the left indicates an upstream displacement of salt water; movement to the right indicates a downstream displacement of salt water. The amount of displacement between the two curves represents the distance moved by the salt water. Since the movement shown in figure 7 is to the right, it represents a decrease in salinity. From August 2 to 15, the salt water may actually have advanced and retreated, but the net movement was a decrease. In this graph both the 250 and 500 ppm isochlor moved about 86,000 feet seaward, while the 2,000 ppm isochlor moved only 72,000 feet seaward from August 2 to 15.

Profiles for low-water slack can be established, but since there is no reliable way at present of converting chloride concentrations to minimum values, it is necessary that samples be collected at low-water slack.

This method of determining the extent of chloride advance or retreat has certain limitations. The profile curves are based on estimates of the chloride concentrations at high-water slack, and the estimates are made from measurements usually not made at high-water slack. As a result of uncertainties in the estimate, the error in the position of a chloride profile is ±4,000 feet. Therefore, an apparent movement of a chloride concentration of ±4,000 feet or less may be due to errors in the estimate, and may not necessarily represent an actual advance or retreat of salt water.

An isochlor is a line representing equal values of chloride concentration. Chloride profiles are used to arrive at the positions of the various isochlors. Figures 8 and 9 are graphs of the position of isochlors at high-water slack in the center of the navigation channel between July and November for 1954 and 1955. During 1954 sufficient information was collected for seven high-water slack profiles (seven points on the 1954 isochlor curve). In 1955 there were sufficient data for nine points. Table 3 gives data on the movement of several isochlors during 1954 and 1955.

Although it is to be expected that an increased flow of water downriver would flush the salt water seaward, one cannot state that under all conditions some specified minimum flow of fresh water is required to keep the isochlors from moving upstream. For example, from August 10 to 24, 1954 (table 3) the 500 ppm isochlor moved an average of 1,300 feet per day, while the average flow at Marcus Hook was 3,390 cfs (cubic feet per second). The advance was checked by an increase of flow to 5,150 cfs (average for August 27 to September 10). On the other hand, an average flow from September 1 to 13, 1955 of 11,100 cfs at Marcus Hook was insufficient to prevent the advance of the 500 ppm isochlor an average of 1,200 feet per day (table 3). An isochlor may be held in a relatively stationary position in the Delaware River by a specific fresh-water flow, all other factors remaining constant.

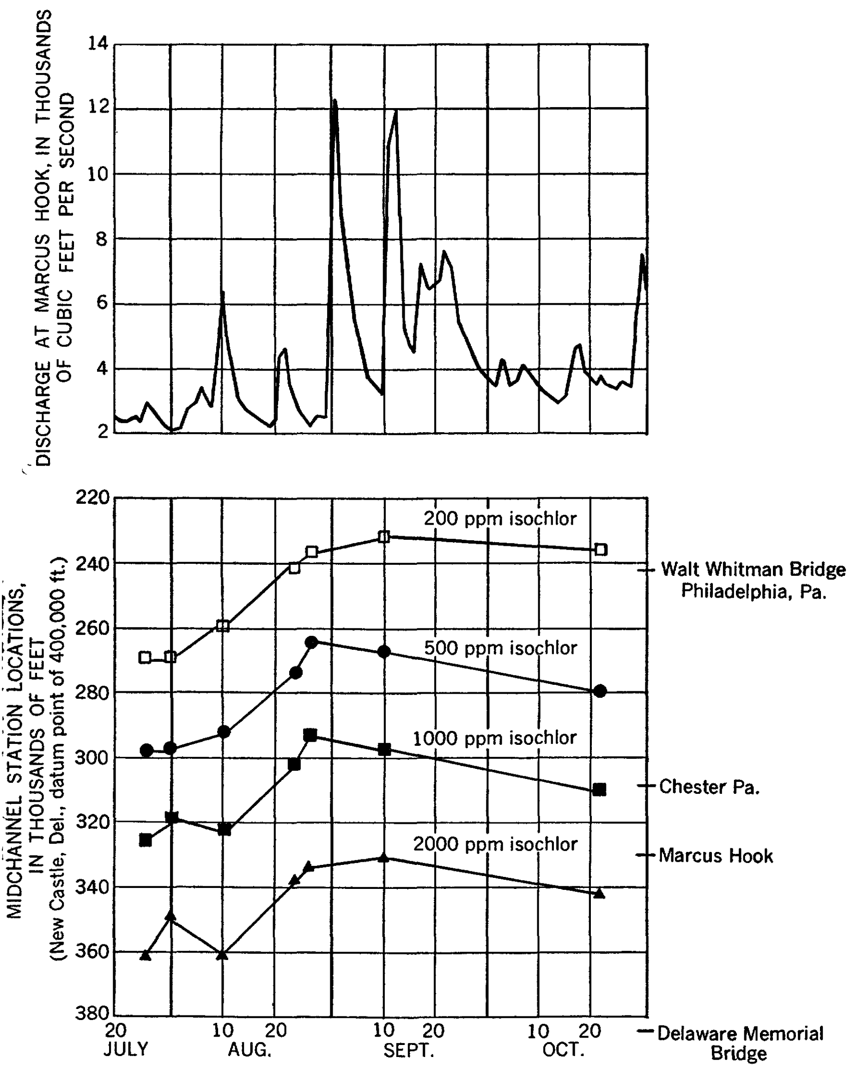

FIGURE 8.—Position of isochlors, 1954. (Isochlors for selected days with a hydrograph at Marcus Hook, Pa. Points are connected by straight lines for clarity; between points the interpolations are not necessarily correct. Isochlor values are at high-water slack.)

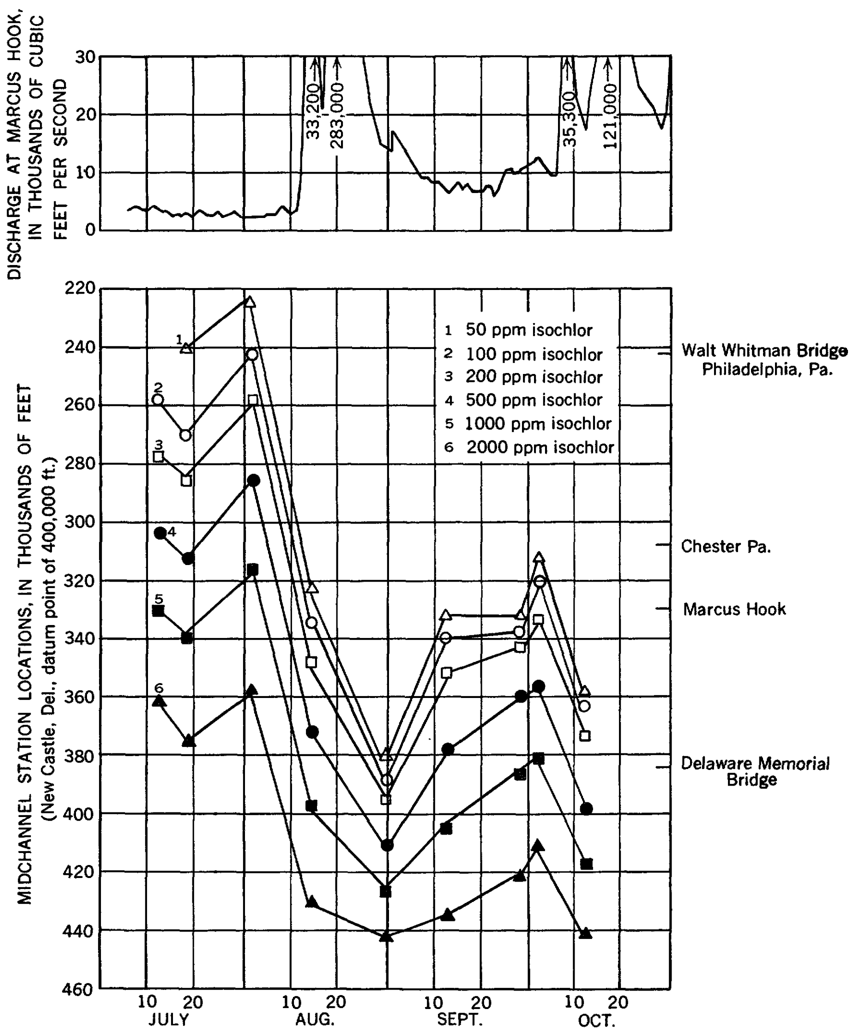

FIGURE 9.—Position of isochlors, 1955. (Isochlors for selected days with a hydrograph at Marcus Hook, Pa. Points are connected by straight lines for clarity; between points the interpolations are not necessarily correct. Isochlor values are at high-water slack.)

TABLE 3.—*Movement of Isochlors*

Period of observation	Isochlor advance or retreat	Net isochlor (ppm) movement, in thousands of feet, during period of observation			Average net isochlor (ppm) movement, in thousands of feet per day, during period of observation			Average discharge at Trenton, N.J. (cfs)	Average estimated discharge at Marcus Hook, Pa. (cfs)
		500	1,000	2,000	500	1,000	2,000		
1954									
July 26-30	Advance	0	6	12	0	1.5	3.0	1,680	2,620
July 30-Aug. 10	Retreat	0	2	7	0	.18	.40	1,730	2,840
Aug. 10-24	Advance	18	20	22	1.30	1.4	1.6	1,780	3,390
Aug. 24-27	do	6	6	4	2.0	2.0	1.3	1,700	2,720
Aug. 27-Sept. 10	No change	------	------	------	------	------	------	3,230	5,150
Sept. 10-Oct. 22	Retreat	10	12	10	.33	.40	.33	2,820	4,960
1955									
July 13-19	Retreat	26	8	12	1.0	1.3	2.0	2,250	3,090
July 19-Aug. 2	Advance	24	23	16	1.7	1.6	1.1	2,240	2,860
Aug. 2-15	Retreat	86	81	72	6.6	6.2	6.0	6,320	14,400
Aug. 15-30	do	36	28	12	2.4	1.9	.80	55,600	74,400
Aug. 30-Sept. 1	Advance	10	5	4	5.0	2.5	2.0	11,300	14,300
Sept. 1-13	do	14	6	0	1.2	.50	.00	8,950	11,200
Sept. 13-29	do	17	19	13	1.1	1.2	.81	6,170	7.820
Sept. 29-Oct. 3	do	4	5	10	1.0	1.3	2.5	8,690	11,200
Oct. 3-13	Retreat	19	18	17	1.9	1.8	1.7	10,700	20,700

Many difficulties arise in using isochlors to trace salinity variations when there are large gaps between samplings. In the example cited for August 10–24, 1954 and September 1–13, 1955 the advance of salt water for the August 10–24 period was more than likely checked by the heavy discharge at the beginning of September rather than the average fresh-water flow for the period. Another factor which has to be taken into consideration is the location of the isochlor in the river. In the example cited the 500-ppm isochlor in 1954 was approximately 28 miles farther upstream than the 500-ppm isochlor for 1955 to which it was compared.

In the two cases analyzed the data are scattered and compared only to the variable of flow. From the analysis it is evident that this approach is of limited value. Data from a study undertaken during October and November 1957 are presented in figure 10. Here, from data obtained at daily sampling stations and specific conductance recorders, chloride profiles were established for each day of the month and the isochlors obtained from these data. It is evident that the movement of the isochlors is not completely explained by changes in the fresh-water flow at Trenton. Apparently some other factors influence isochlor movement. Change in sea level is one such factor. Sea-level changes are reflected in mean river level, which is also plotted in figure 10. Peaks and troughs in the river-level curve are reflected in the isochlors. Quantitative agreement is lacking between the two curves as can be easily seen by comparing the data for October 27 and November 1. The river-level peak is greater on November 1

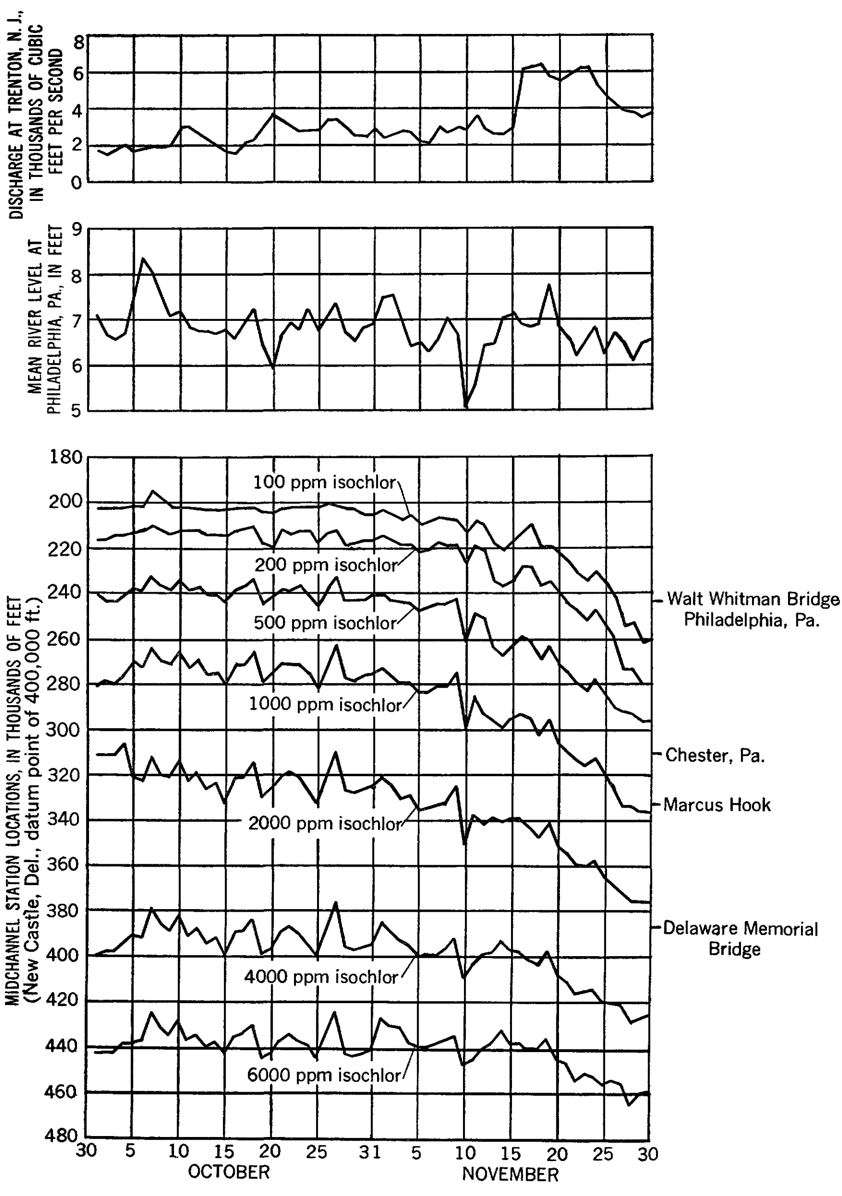

FIGURE 10.—Position of isochlors for October and November 1957. (Isochlor values are at high-water slack.)

than on October 27, yet the isochlor advancement is less. Similar examples occur frequently in the data. These inconsistencies can be accounted for by the fresh-water flow due to runoff from rains below the head of tide. The isochlor movement is, therefore, controlled by sea-level changes during periods of relatively constant flow but, in general, is a reflection of both flow and sea level.

In the Delaware River, as an isochlor moves upriver, its rate of advancement decreases with distance moved upstream. The isochlors of the lower ranges of chloride concentration appear to be more sensitive to changes such as flow and sea level and will advance or retreat more rapidly than isochlors representing higher chloride concentrations.

EFFECTS OF FRESH- AND SALT-WATER INFLOW ON DISTRIBUTION OF SALINITY

The distribution of salinity in a tidal river is, for the most part, a resultant of the fresh-water outflow and the salt-water inflow. Fresh water flows from above the head of tide, from tributaries, as direct runoff from the land, and from ground-water seepage. The total outflow of fresh water above the head of tide may be measured by a gaging station. The fresh water which enters the river below the gaging station, when significant, should be considered when working with the total fresh-water outflow of the estuary. Ocean water inflow is caused by rises in sea level, and will increase the salinity of the river.

The mixing of salt and fresh water and the distribution of the mixed water are related to river flow and tidal action. The tidal prism concept (Ketchum, 1951) has been used to evaluate the ability of an estuary to distribute salinity. The tidal prism is equal to the difference between the volumes of water in the estuary at high and low tide. Part of the volume in the tidal prism is contributed by the fresh-water flow and part of it by salt water entering from the ocean on the floodtide. The boundary between fresh water and salt water in the estuary moves upstream and downstream with changes in the volume of riverflow and tidal action. By means of this dynamic tidal exchange salt water may move up or downstream.

The fresh-water discharge in the Delaware River varies with the season. In general, it is greatest in March and April owing to spring thaws and least from June to October when the growing plants are removing soil moisture rapidly and evaporation is at its peak. Normally during the summer and early fall a greater proportion of the rainfall soaks into the ground and a lesser proportion runs off directly to the streams. The monthly average fresh-water discharge at Trenton, N.J., at the head of tide in the Delaware River, shown in figure 11 is based on the 33-year period 1923–55. The greater fresh-water discharge of March and April flushes the salt water seaward, and the

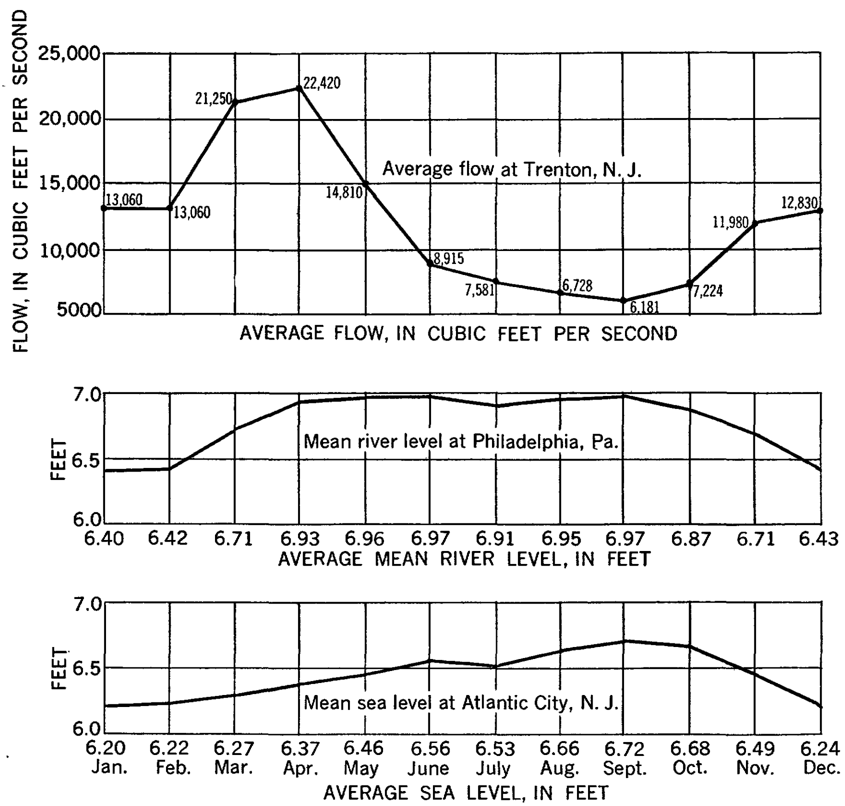

FIGURE 11.—Curves of average flow at Trenton, N.J., mean river level at Philadelphia, Pa., and mean sea level at Atlantic City, N.J. (On the basis of 33 years of record, 1923–55.)

lower flows of June to October provide an opportunity for the salt water to move upstream.

Since the source of the salt water in a tidal river is the ocean, changes in sea level will affect the quantity of sea water in the river. As the sea level rises, increasing amounts of salt water flow upstream. When the sea level falls, the quantity of salt water in the river decreases.

Sea level varies seasonally outside Delaware Bay; sea levels are lower in December, January, and February, and are higher in August, September, and October. Figure 11 shows the monthly average sea levels for the 33-year period 1923–55 at Atlantic City, N.J. The changing sea level outside Delaware Bay favors upstream movement of salt water most in August, September, and October, and least in December, January, and February.

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The competing effects of fresh-water discharge and sea level are reflected in river-level[1] curves. In Delaware Bay the average river level curve (Zeskind and Le Lacheur, 1926) is about the same shape as the average sea level curve at Atlantic City (fig. 11), except in May, when a hump appears which reflects the effect of the peak flows at Trenton, N.J. of March and April. The time lag is due to the water travel time to locations downstream (Ketchum, 1951) Similarly, the average river level curve just below Trenton, N.J. (Zeskind and Le Lacheur, 1926) shows a hump in September, corresponding to the peak sea level for the year. Figure 11 shows the average river level at Philadelphia, Pa., for the 33-year period 1923–55. The average river-level curve at Philadelphia is a function of the fresh-water flow and sea level. It is of interest that in March and April the river level is primarily a function of the fresh-water flow, while in August, September, and October it is mainly a function of sea level.

If sufficient data on salinity were available for the same 33 years, one no doubt could correlate the advance and retreat of salt water with the fresh-water discharge and sea-level changes. Variations from average discharge or sea level in any individual year cause variations from the average salinity. For example, during January 1956 the average sea level at Atlantic City was 6.88 feet (0.68 foot above the long-term average), and the average monthly flow at Trenton was 6,855 cfs (6,145 cfs below the long-term average). For the last 10 days of January 1956 the specific conductance at Reedy Point averaged 13,000 micromhos. In May 1956 the average sea level was 6.68 feet (0.22 foot above the long-term average) and the average monthly flow at Trenton was 18,040 cfs (4,420 cfs below the long-term average). The specific conductance at Reedy Point averaged 801 micromhos. The increased fresh-water discharge and the decrease in sea level in May moved the salt water seaward, and the salinity at Reedy Point and elsewhere decreased.

The movement of salt water and the relative severity of salt-water invasions may be qualitatively predicted from sea level and fresh-water discharge, as shown in table 10.

Prolonged periods of low flows result in high concentrations of chloride in the water at Chester, Pa. If the flow at Trenton drops to less than 4,000 cfs for 30 to 60 days, the chloride concentration increases at Chester. For example, in June 1954 the flow at Trenton decreased and became steady at approximately 2,000 cfs during July and August (fig. 12). During these 2 months the daily maximum

[1] Daily mean river level is defined as the average height of the surface of a river at any point and is usually determined by averaging hourly height readings.

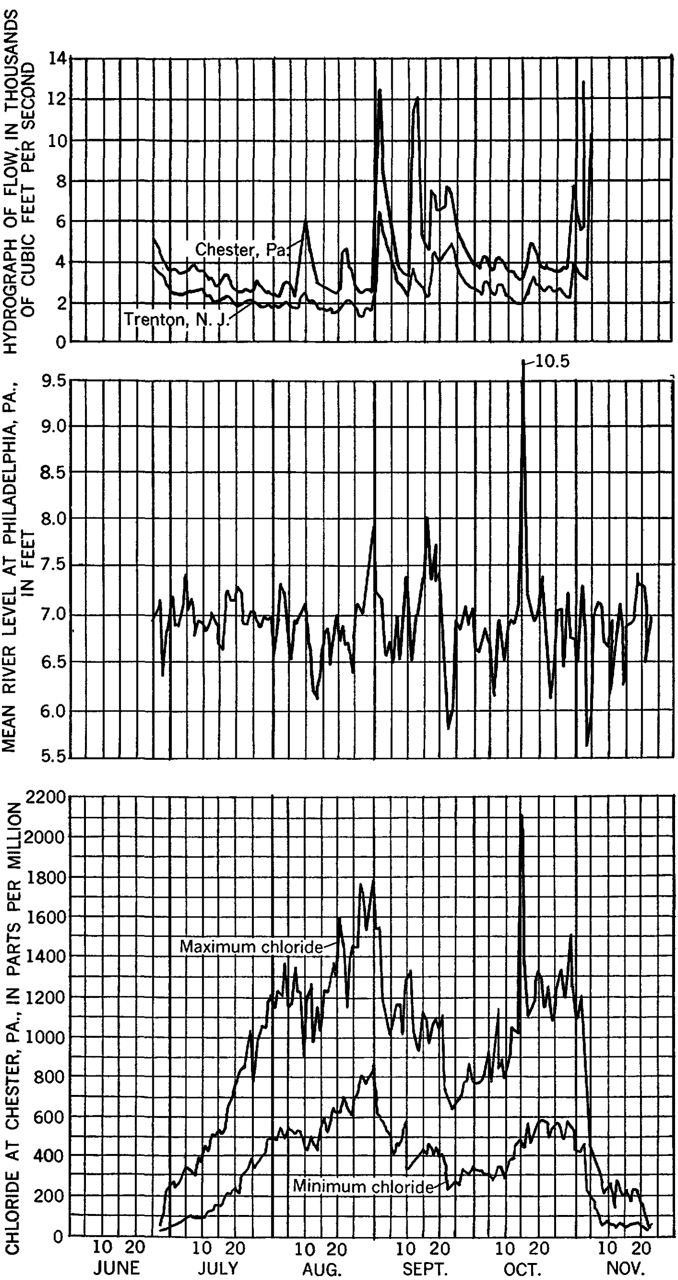

Figure 12.—Time series of maximum and minimum daily chloride concentrations at Chester, Pa. (July–November 1954), with a hydrograph of flow at Trenton, N.J., and Chester, Pa., and the daily mean river level at Philadelphia, Pa.

concentration of chloride at Chester increased steadily from 200 ppm on July 1 to more than 1,500 ppm at the end of August (fig. 12). Similarly in 1949 the chloride concentration increased from 50 to 800 ppm at the same location (fig. 13) after a period of low flow at

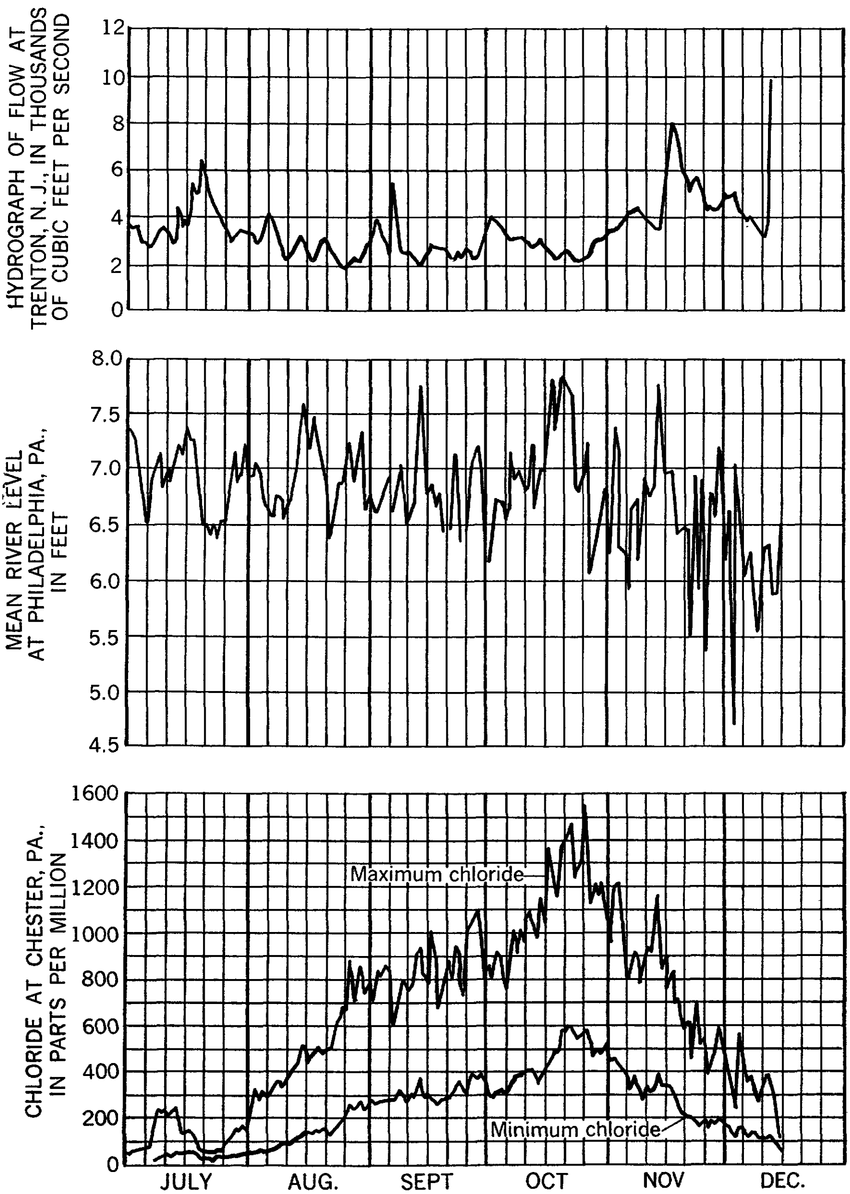

Figure 13.—Time series of maximum and minimum daily chloride concentrations at Chester, Pa. (July–December 1949), with a hydrograph of flow at Trenton, N.J., and the daily mean river level at Philadelphia, Pa.

Trenton. When the chloride concentration has increased to approximately 1,000 ppm, a rapid increase in discharge—even of a few days' duration—is likely to produce a rapid decrease in chloride concentration.

Since the discharge of the Delaware River below Trenton is difficult to measure because the river is tidal, the streamflow discharge at several points south of Trenton has been estimated. All flow figures used at Chester or Marcus Hook, Pa., are a result of these estimates. These evaluations, which were started in August 1953, are based on the record of flow of the Delaware River at Trenton plus the estimated contribution from the drainage area below Trenton. This contribution is estimated from the records at gaging stations on tributaries entering the Delaware River below Trenton. Such gaged tributaries make up 85 percent of the total drainage area above Marcus Hook on the Pennsylvania side, and 28 percent of the drainage area above Marcus Hook on the New Jersey side. Contribution from the ungaged area is determined by use of a drainage area ratio.

In 1954, increases in flow on August 10 and 22 at Chester were followed by decreases in chloride concentration at Chester (fig. 12). During the summer and early fall months of any year, periodic large increases in flow at Chester result in a temporary reduction in chloride concentration which may persist for some time, depending upon the magnitude and duration of the higher flows. However, the increased fresh-water volume is generally rapidly assimilated by the large volume of salt water in the tidal area of the estuary below Chester, and as the flow decreases, the chloride concentration again begins to increase.

The effect of flow on chloride concentration is more apparent when the maximum and minimum chloride concentrations in parts per million are plotted as a moving weighted-average curve (fig. 14). The curve gives a weight of 0.4 ppm to the maximum chloride of day x; 0.3 ppm to the maximum chloride of day $x-1$ (the day before x); 0.2 ppm to the maximum of day $x-2$; and 0.1 ppm to the maximum of day $x-3$. By this method of plotting irregularities are removed and pronounced prolonged effects due to flow can be seen. Major increases in flow at Trenton or Chester are generally followed by a decrease in chloride concentration at Chester.

In addition to the effects of fresh-water flow on chloride concentration at a particular location on the river, the change in sea level, as already pointed out, is a major factor in producing the resulting chloride curve. A combination of decreased daily mean river level and increased flow will produce large decreases in the chloride concentration. The variations in chloride concentrations due to variations

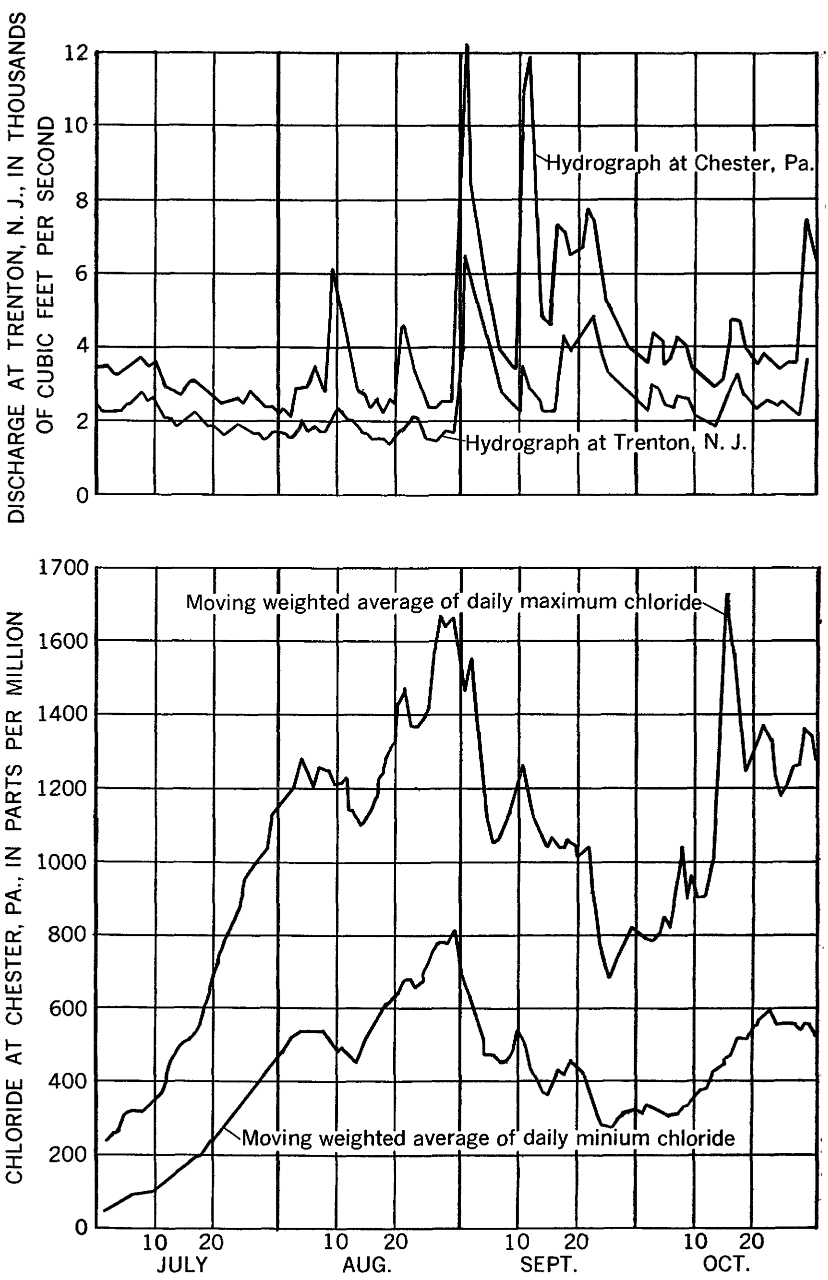

FIGURE 14.—Time series of moving weighted-average of daily maximum and minimum chloride concentrations at Chester, Pa. (July–October 1954), with a hydrograph of flow at Trenton, N.J., and Chester, Pa.

in daily mean river level are more pronounced when the chloride concentration is at least several hundred parts per million. The drop in the daily maximum chloride on September 17, 1954 (fig. 12) was a result of increased flow and decreased mean river level. The lowest chloride concentration for the 1954 salt-water invasion occurred on September 24. This was a result of decreased mean river level. On August 6 and 13, 1954 the fall in mean river level was accompanied by a decrease in chloride concentration. On August 3, 1954 the mean river level began to drop and reached a minimum on August 6. The maximum chloride decreased. On August 13 1954, although the flow decreased, the maximum chloride decreased. The fall in mean river level was the major contributing factor to the decrease.

During 1931–39, the Corps of Engineers, Department of the Army, made measurements of the effects of fresh-water flow on mean river levels at several locations on the Delaware River. At Philadelphia the difference between mean low waters at sustained flows of 6,000 and 11,800 cfs was 0.15 foot. The difference between mean high waters at the same flows was 0.1 foot. For the flows below 6,000 cfs, the difference was less than 0.1 foot. Downstream, the differences between mean highs and mean lows for various flow rates decrease. For example, at New Castle, Del., the difference for sustained flows of 16,400 and 30,700 cfs was 0.1 foot. This decrease for higher flows is the result of the large tidal area below Philadelphia, nullifying the effects of the increased flow. The changes in river level for August 3–6 and 10–13, 1954 were not effectively influenced by the fresh-water flow and the chloride decreases were primarily a result of the sea-level change.

From August 25–31, 1954 there are two peaks in the maximum chloride curve (fig. 12)—one on August 27 and the other August 31. Both peaks are of the same height. There are two corresponding peaks in the daily mean river level curve; however, the one on August 31 is considerably higher than the one on August 27. By comparing the daily mean river level curve and the chloride curve to a hydrograph of flow at Chester, the apparent inconsistency is removed. The higher flow on August 31 was sufficient to offset the effects of the higher daily mean river level. The peak chloride of 2,120 ppm for the summer of 1954 occurred on October 15 and was the result of an abnormally high tide on this day (fig. 12).

Figure 15 is a time-series graph of the maximum and minimum chloride concentrations at Chester, Pa., with a hydrograph at Trenton, N.J., for 1955. The chloride concentrations increased in July as the flow at Trenton decreased. On August 13 Hurricane Connie passed through Pennsylvania and brought heavy rainfall—within 2 days the salt-water invasion at Chester was flushed out. The chloride

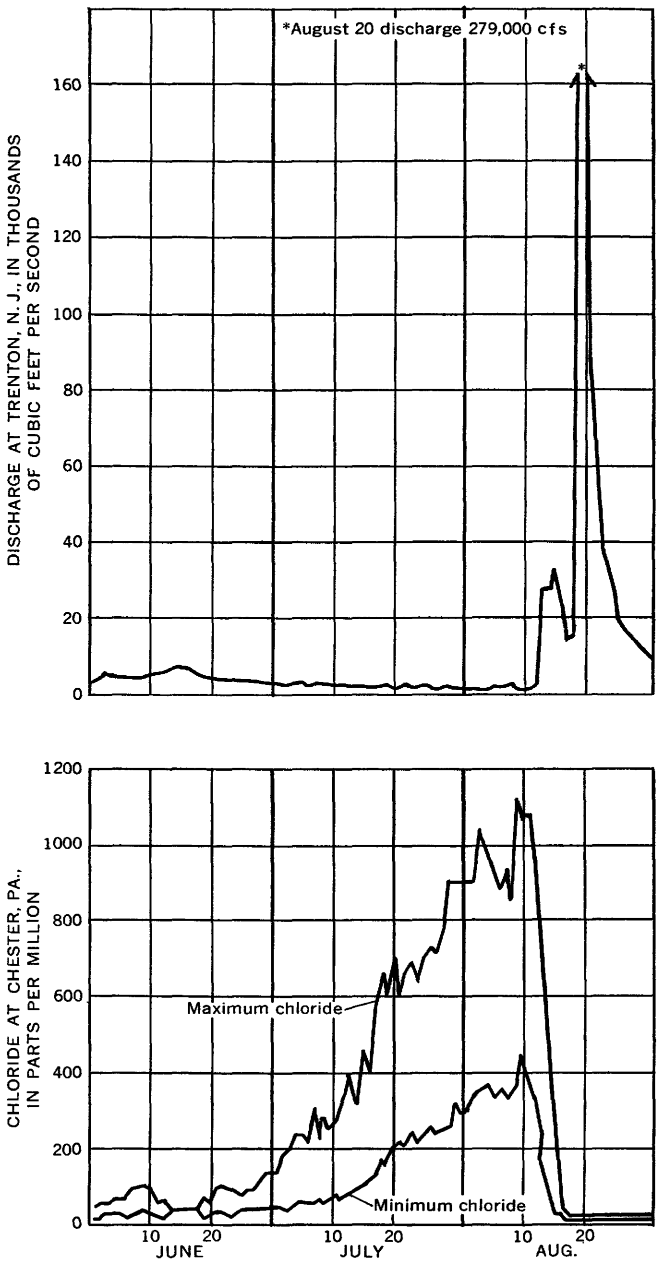

FIGURE 15.—Time series of maximum and minimum daily chloride concentrations at Chester, Pa. (June–October 1955), with a hydrograph of flow at Trenton, N.J.

concentrations at Chester decreased to 30 ppm after the heavy discharge on August 13 and did not drop much below this figure, although some of the highest water discharges ever recorded occurred from August 19 to the first week in November.

The minimum chloride changes in a pattern similar to that of the maximum chloride, but fluctuations in minimum chloride are less than in the maximum. Extreme flow and daily mean river level changes show up readily in the minimum chloride curve. On September 1 and 12, 1954 the flow at Chester increased and the daily mean river level and minimum chloride decreased (fig. 12).

Figure 16 is a time series of maximum and minimum daily specific conductances at Reedy Island Jetty, Del., with a hydrograph of flow at Trenton, N.J., and the daily mean river level at Philadelphia, Pa., for July to November 1957. The plotted data for Chester, Pa., were for conditions of varying flow and mean river level. For July–November 1957 daily flows at Trenton were relatively constant and the specific conductance curves closely follow the mean river level in fluctuation pattern but not in general shape. During July the increasing specific conductance may be explained by prolonged low flow allowing the salt water to move upstream to the point where the combination of river level and fresh-water flow will not permit the salt water to move further upstream. This point was apparently reached in August as the specific conductance did not increase. In September the specific conductance decreased. On the basis of the above explanation this decrease should not occur. Unfortunately, the only flow data available are at the head of tide and these data do not reflect runoff from rain below the gaging station. Heavy rains below Trenton accounted for the decreased specific conductance during September 1957. In October the specific conductance increased to the values of August. The curve for November shows a sudden decrease in specific conductance, much greater than would be expected from the slight increase in fresh-water flow. This decrease again points out the effect of the dropping river level (or sea level).

CROSS-SECTIONAL STUDIES

It has been shown previously that the approximate concentration of dissolved solids is conveniently estimated from the specific conductance of the water. Figure 17 shows the specific conductance of Delaware River water on four dates from September 1 to October 3, 1955 at selected locations between the Delaware Memorial Bridge and Reedy Point, a 10-mile reach of the river. These locations were chosen with reference to the direction of the river channel and are identified by buoys shown on navigation maps (table 4).

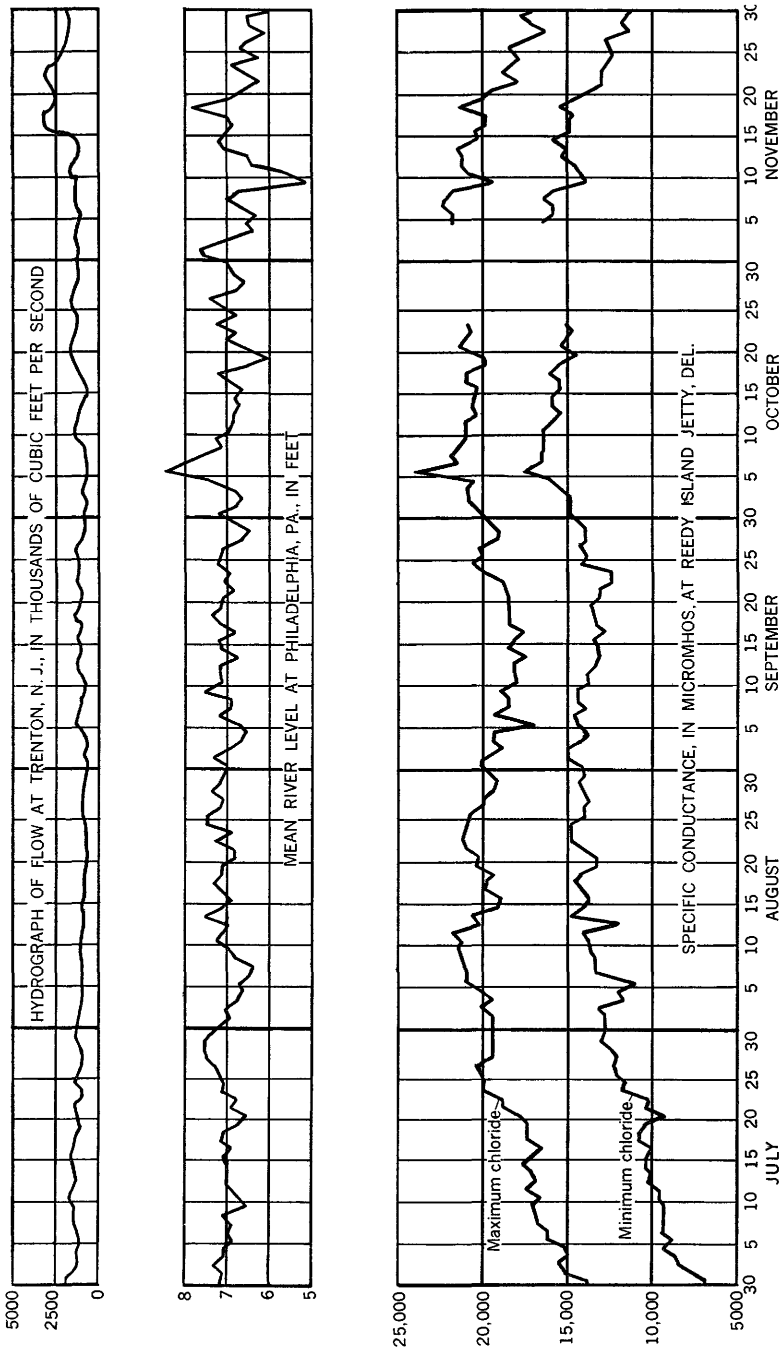

FIGURE 16.—Time series of maximum and minimum daily specific conductances at Reedy Island Jetty, Delaware (July–November 1957), with a hydrograph of flow at Trenton, N.J., and the daily mean river level at Philadelphia, Pa.

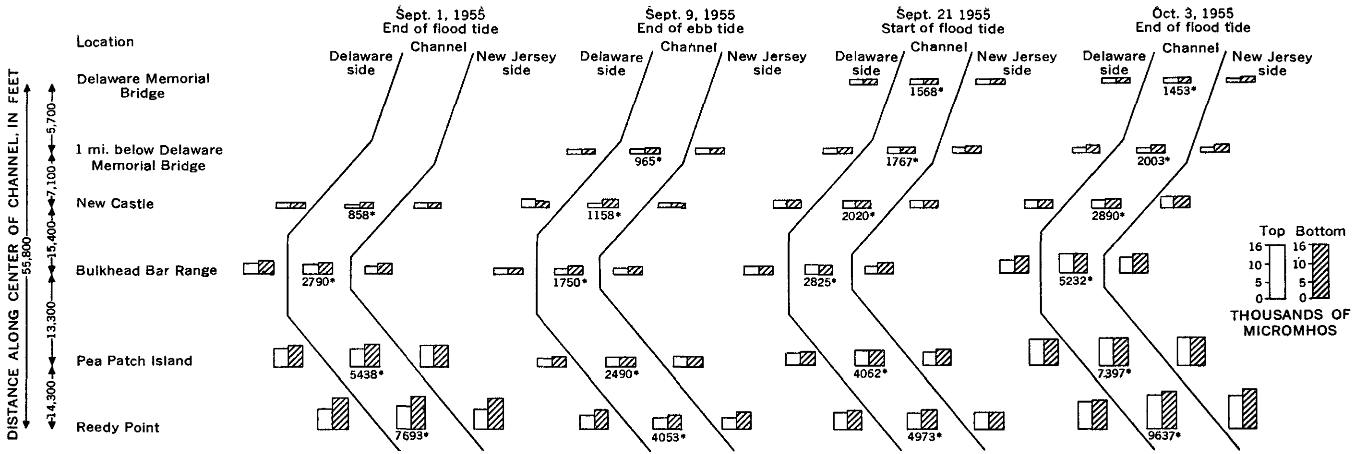

FIGURE 17.—Cross-sectional variation of specific conductance from the Delaware Memorial Bridge to Reedy Point from September to October 1955. (Figures represent average specific conductance, in micromhos, for cross section. See table 4 for location of sampling stations.)

TABLE 4.—*Location of sampling stations for cross-sectional sampling*

	Delaware side of channel	Center of channel	New Jersey side of channel
Delaware Memorial Bridge.	West column	Midway between	East column.
One mile below Delaware Memorial Bridge.	"1C2"	do	N"2c2".
New Castle	"5D"	do	N"6D".
Bulkhead Bar Range	"1B"	do	R"4B".
Pea Patch Island	Bell at Pea Patch.	do	RN"2".
Reedy Point	C"27"	100 yards west of "1N".	N"2N".

Samples were collected 3 feet below the surface, 3 feet above the bottom of the river and from the right side, center, and left side of the channel. The specific conductance, in micromhos, is shown for each sample on the diagram by a bar height proportional to the specific conductance of the water. In addition, a number printed below the bar diagrams gives the average specific conductance of the cross section.

Preceding and during this period of investigation (September to October 1955) the flow of water in the Delaware River was greater than usual for this time of year. Heavy discharge began on August 13, and on August 19 the discharge measured at Trenton was the greatest in 53 years.

The cross-sectional studies of 1955 and 1956 indicate that generally there is little or no variation in salinity across the navigation channel of the river. The salinity of the Delaware River generally varies with depth, and is greater on the bottom. The variations between top and bottom become greater as the salinity of the water increases. This relationship is maintained throughout each tidal cycle.

FREQUENCY OF OCCURRENCE OF CHLORIDE CONCENTRATIONS

Frequency curves for chloride, in parts per million, at Marcus Hook, Pa. (1950–55), Camden, N.J. (1950–55), and Bridesburg, Pa. (1952–55), have been plotted (fig. 18). These curves indicate the frequency of occurrence of various chloride concentrations, irrespective of the chronological sequence, and are based on the chloride concentration of a sample collected each day at Camden, N.J., the maximum chloride concentration each day at Bridesburg, Pa., and the daily average chloride concentration at Marcus Hook, Pa. At least 64 percent of the time at Marcus Hook, 90 percent of the time at

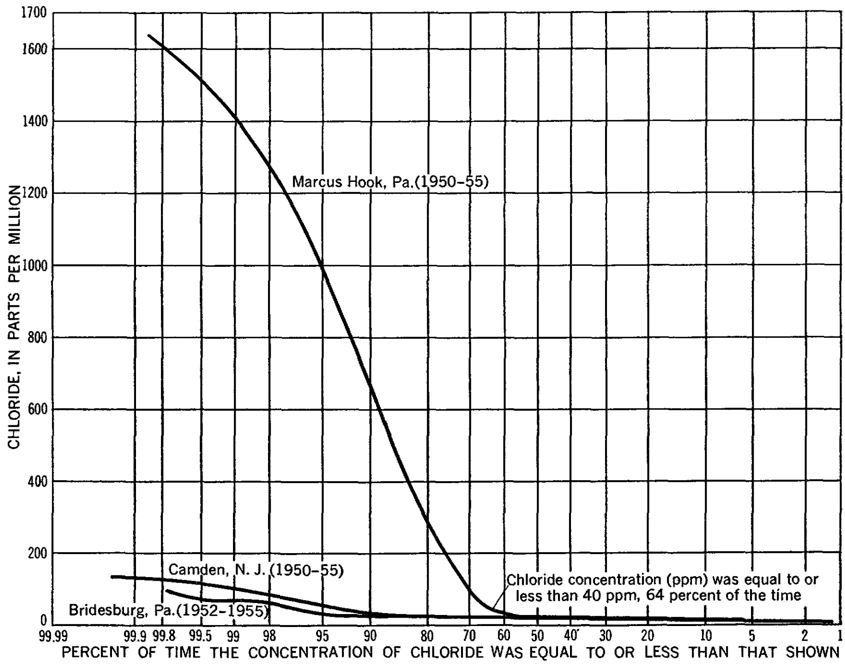

FIGURE 18.—Frequency of occurrence of concentrations of chloride in parts per million, in the Delaware River at Marcus Hook, Pa., Camden, N.J., and Bridesburg, Pa.

Camden and 95 percent of the time at Bridesburg the chloride concentration was equal to or less than 50 ppm. It is interesting to note that between Camden and Bridesburg there is very little change in the chloride concentration or the frequency of occurrence. Only about 5 percent of the time is there an appreciable difference and it usually amounts to no more than about 50 ppm of chloride. The daily sample at Camden 90 percent of the time is within 20 ppm of the maximum chloride at Bridesburg. Between Camden and Marcus Hook 35 percent of the time the difference in chloride concentration is considerable.

EFFECTS OF HURRICANES ON SALINITY

Hurricanes [2] affect the salinity of the Delaware River through three major factors—sea-level changes, wind direction and velocity, and runoff from precipitation. The first major factor is the rise in sea level. This rise is the result of many factors, the two most important of which are the "surge," which is a result of hurricane winds, and

[2] The term "hurricane" is used to describe storms which result from hurricanes, to distinguish these storms from other storms. Most hurricanes when they reach the Delaware River are no longer of sufficient strength to be truly considered as hurricanes. Nevertheless, all references in the literature are made to "hurricane so and so" and thus the terminology has been used.

has not been evaluated quantitatively (a priori), and the barometric pressure effect of the "inverted barometer." Sea level rises about 1 foot for each 1 inch of mercury decrease in atmospheric pressure (Redfield and Miller, 1955; and Hubert and Clark, 1955). The rise caused by these factors can readily be seen from the rise in sea level above the normal values at Atlantic City, N.J., for the hurricanes of 1954: for Hurricane Carol, 2.6 feet; for Hurricane Edna, 1.8 feet; and for Hurricane Hazel, 3.4 feet. (These values are the maximum increases.) The increased sea level causes a rise in river level [3] (table 5) and increases the salinity of the river.

The second major factor affecting the salinity is the hurricane winds on the surface of the water. Since the winds of a hurricane in the Northern Hemisphere circulate counterclockwise around the low pressure area ("eye"), hurricanes passing west of the river (on shore) tend to aggravate the increased river level by blowing ocean water upstream (fig. 19a). Winds from hurricanes passing east of the river (offshore) produce winds which blow water out of the river (fig. 19*B*). In the offshore hurricanes studied the river level increased approximately 0.5 to 0.8 foot. It appears that the wind action on the surface of the water is not able to overcome the increase in river level caused by the increase in sea level but is able to reduce this increase. The effectiveness of winds is dependent upon their strength, duration, and the distance of the hurricane center from the river. For example, Hurricane Carol (1954) and Hurricane Edna (1954) both raised the sea level the same height (0.87 foot-based on the the average sea level increase) and both had winds of the same strength, but the rise in river level was greater for Hurricane Edna. The lower river level for Hurricane Carol was probably a result of the stronger wind action owing to the hurricane being closer to the coast.[4]

The third factor affecting the salinity is the runoff from rains. The increase in river level caused by the increase in sea level and, during onshore hurricanes, by the winds, produces rapid increases in salinity. The increased runoff from rains subsequently causes an equally rapid decrease in salinity.

Since 1954 five hurricanes (Carol 1954, Edna 1954, Hazel 1954, Connie 1955, and Diane 1955) have had a major effect on the salinity of the Delaware River.

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[3] In a few instances the increased runoff contributed to the rise in river level. For an evaluation of the increased runoff see figure 21.

[4] Hurricane Edna was farther east of Cape May than Hurricane Carol.

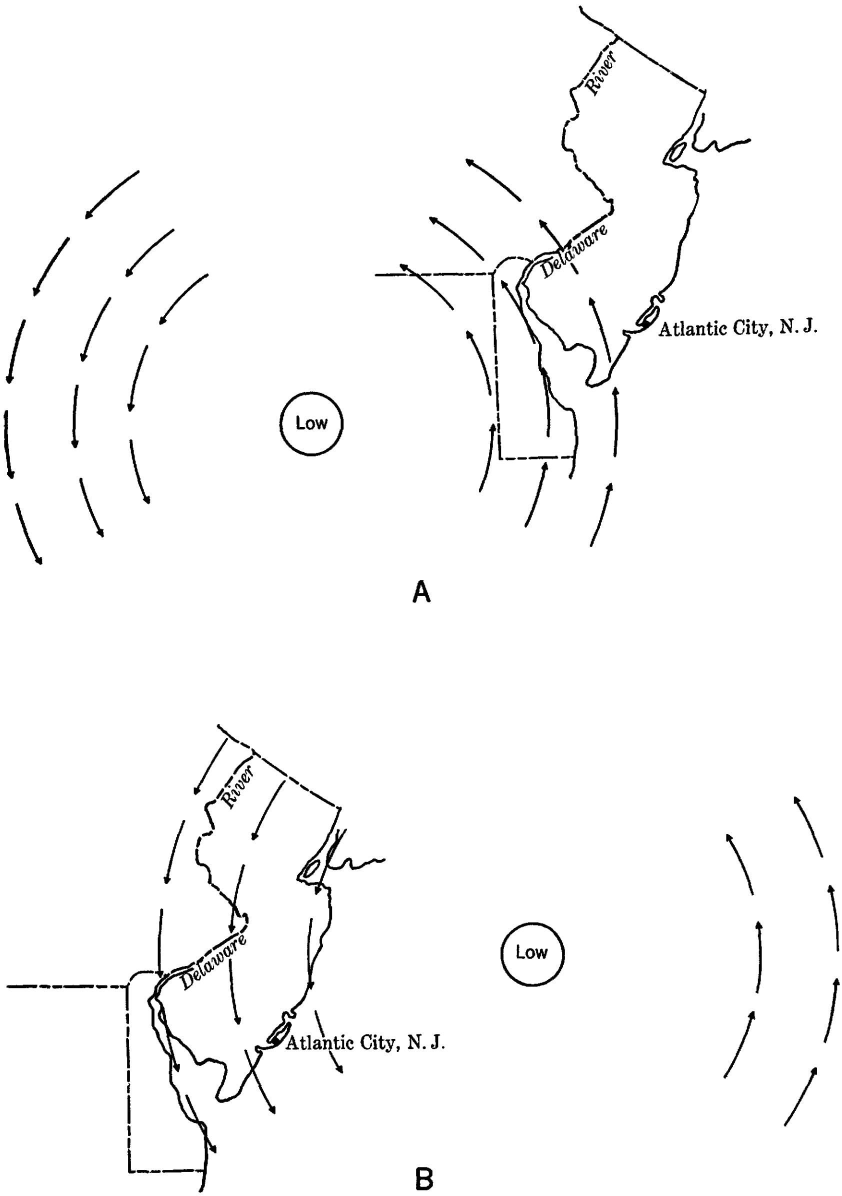

FIGURE 19.—Hurricane wind circulation with respect to the Delaware River. *A*. Hurricanes passing west of the river. *B*. Hurricanes passing east of the river.

TABLE 5.—*Daily mean river level at Philadelphia, Pa.*

Hurricane	Days during which river level was influenced by hurricanes	Daily mean river level at Philadelphia, Pa. (feet)
Carol	Aug. 30, 1954 [1]	7.45
	Aug. 31, 1954 [1]	7.92
	Sept. 1, 1954	7.29
Edna	Sept. 9, 1954	6.72
	Sept. 10, 1954 [1]	7.43
	Sept. 11, 1954	6.97
Hazel	Oct. 14, 1954	7.15
	Oct. 15, 1954 [1]	9.18
	Oct. 16, 1954	7.95
	Oct. 17, 1954	7.20
Connie	Aug. 12, 1955 [1]	7.15
	Aug. 13, 1955 [1]	10.55
	Aug. 14, 1955	8.50
Diane	Aug. 17, 1955	7.83
	Aug. 18, 1955 [1]	8.96
	Aug. 19, 1955 [1]	9.42
	Aug. 20, 1955 [1]	10.73
	Aug. 21, 1955	9.18

[1] Date of hurricane in Philadelphia area.

The path of Hurricane Carol in 1954 was offshore (fig. 20) from SSW. to NNE. Thus, Delaware Bay was west of the hurricane; the prevailing winds in the bay were WNW., and blew water out of Delaware Bay. The river level (table 5) was approximately 0.5 foot higher than usual, and some increase in salinity due to tides was to be expected. On August 31, 1954 the daily mean river level increased and there was a corresponding increase in the chloride concentration at Chester, Pa. This increase in salinity was attributed to salt water moving upstream as a result of the increased sea level. Heavy rainfall (table 6), the wind velocity (40 mph) and direction (N), and the rapidly dropping river level after the hurricane flushed the salt water seaward. These events are presented graphically in figure 21.

Hurricane Edna followed shortly after Hurricane Carol in 1954 and had a path approximately the same as Carol (fig. 20) but farther out to sea. Conditions were very similar to Hurricane Carol and again a salt-water retreat occurred (fig. 21). For 5 days following the hurricane there was essentially no recovery of the chloride concentration at Chester. The path of Hurricane Hazel, in 1954, was approximately parallel to that of Hurricane Carol but inland, so Hazel passed to the west of Delaware Bay (fig. 20). The winds in Delaware Bay were from the southeast and blew ocean water into the bay, which caused higher tides than normal (table 5) and increased salinity. During the high tide on October 15 a 60-mph wind blew for 1 hour, forcing salt water into the estuary. On October 16 the wind shifted

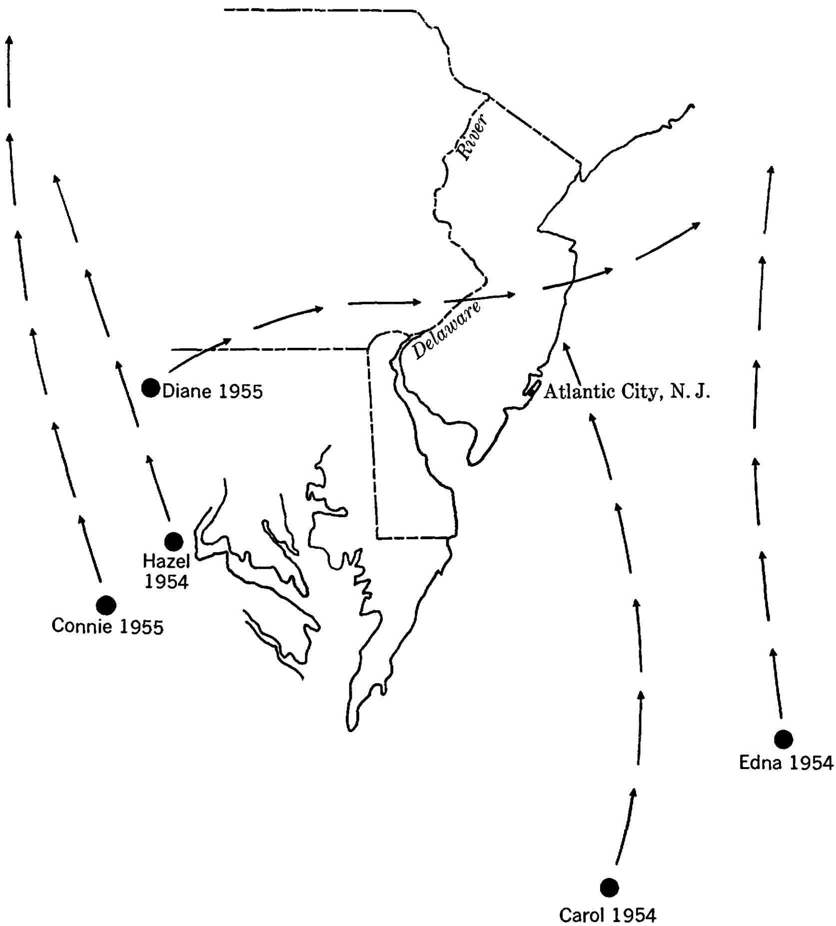

FIGURE 20.—Paths of the hurricanes affecting the Delaware River during 1954 and 1955.

and subsided, and the daily mean tidal elevation dropped. Very little rain accompanied this hurricane (table 6) and the major effects upon salinity were a result of the winds and increased river level which was partly the result of a 3.4-foot increase in sea level. The chloride concentration increased about 1,000 ppm from the 14th to the 15th of October at Chester, and decreased 700 ppm on the 16th. The conditions causing these changes are indicated in figure 21. The chloride concentration recovered immediately and increased after this hurricane.

The path of Hurricane Connie (August 13, 1955) was inland and west of the Delaware River (fig. 20). Maximum wind velocities were 40 to 45 mph SE. on August 12 and 13. The unusually heavy precipitation accompanying this hurricane produced thorough flush-

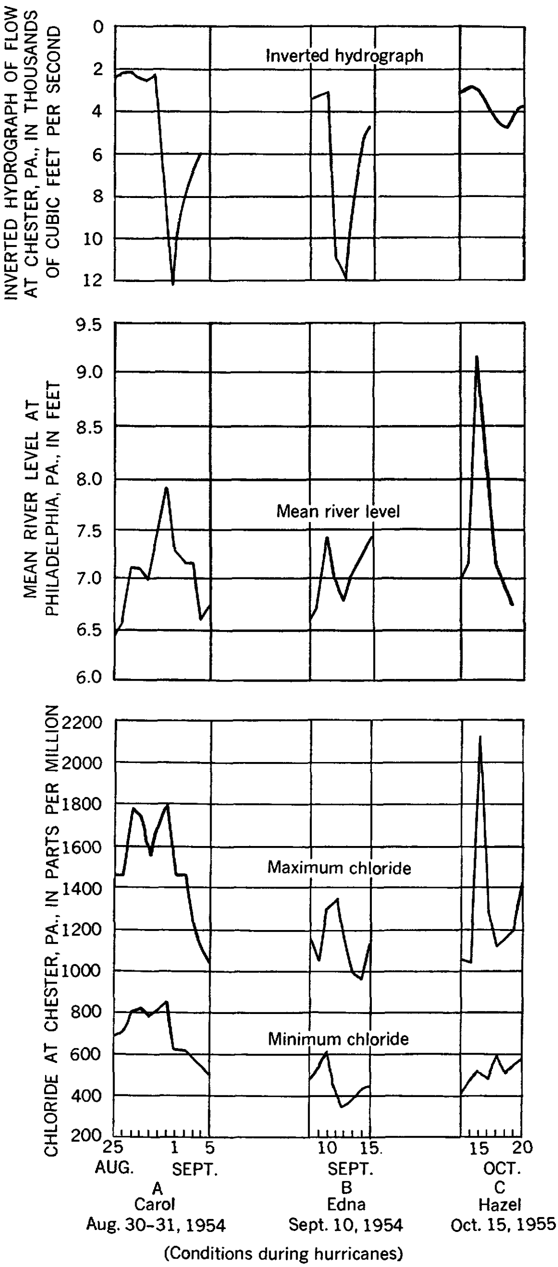

FIGURE 21.—Selected times series of maximum and minimum daily chloride concentrations at Chester, Pa., during hurricanes in 1954, with an inverted hydrograph of flow at Chester, Pa., and mean river level at Philadelphia, Pa.

TABLE 6.—*Rainfall and wind data for the hurricanes of 1954 and 1955*

Hurricane	Period of time in Philadelphia area	Average rainfall for several stations in the catchment area of the river [1] (inches)	Maximum wind velocity and direction at Delaware Bay (mph)	Average wind velocity at Delaware Bay (mph)
Carol	Aug. 30–31, 1954	2.65	40 (N.), Aug. 30	10
			42 (WNW.), Aug. 31	26
Edna	Sept. 10, 1954	.65	26 (E.), Sept. 10	19
			49 (NW.), Sept. 11	32
Hazel	Oct. 15, 1954	.60	75 (S.)	31
Connie	Aug. 12, 1955	.897	40–45 (SE.)	29
	13, 1955	3.72	40–45 (SE.)	30
	14, 1955	1.53	20 (S.)	13
Diane	18, 1955	1.81	35–40 (S. to SW.)	21
	19, 1955	3.99	30 (W.)	17

[1] For more complete information, consult U.S. Department of Commerce Weather Bureau Publ. 26 (17).

ing of the Delaware River. The chloride concentration dropped at Chester from about 1,100 to 30 ppm. Hurricane Diane (August 18–19, 1955) passed inland west of the Delaware River and crossed the river just north of Philadelphia. Maximum wind velocities for this hurricane were 35–40 mph south to southwest at Delaware Bay on August 18. The heaviest runoff in 53 years accompanied this hurricane and resulted in the farthest retreat of the salt water. Hurricane Connie was preceded by the start of a salt-water invasion; this chloride concentration at Chester had been rising for 40 days and was above 1,100 ppm. There was no early recovery from hurricanes Diane or Connie at Chester; the chloride concentration did not rise above 30 ppm at any time during the next few months.

SUMMARY

The salinity of the Delaware River at any time is primarily the resultant of the fresh-water flow of the river and the changes in sea level at the mouth of Delaware Bay. The changes in sea level are reflected in changes in river level and only under conditions of very heavy fresh-water flow does the river level reflect the influence of flow. Therefore, when the mean river level increases, quantities of salt water are moving into the river and generally increase the salinity of the river. The converse is true when the mean river level falls.

The salinity of the Delaware River water increases downstream. There is some difference between top and bottom salinities and this difference increases downstream. There is little variation in salinity across the navigation channel.

The salinity varies with the tide, decreasing on the ebb tide and increasing on the flood tide. Maximum salinity occurs after maximum stage at or near high-water slack, and minimum salinity occurs after minimum stage at or near low-water slack.

The most favorable conditions for salt-water invasion in the Delaware River occur from August to October. During this period the sea level outside Delaware Bay is at its highest and the fresh-water flow at its lowest. Salt-water invasion usually starts in June and continues until early October; from October to December there are marked decreases in salinity. The river water generally contains the least amount of dissolved solids from December to May.

The frequency of occurrence of chloride is equal to or less than 35 ppm at least 64 percent of the time at Marcus Hook, Pa., and 96 percent of the time at Philadelphia, Pa., on the basis of records for 1950 through 1955.

Hurricanes affect salinity through sea-level changes, wind direction and velocity, and runoff from precipitation. A hurricane whose "eye" passes to the west of the Delaware River is usually accompanied by winds that force salt water into the estuary, thereby increasing the salinity. If this phenomenon is followed by heavy rainfall in the upstream reaches, the increased fresh-water runoff quickly forces the salt water seaward. A hurricane passing to the east of the bay and river is accompanied by winds that move water seaward. Subsequent rainfall will also move the salt water seaward.

At the beginning of the summer of 1955 the water from Reedy Point upstream contained less than 2,200 ppm of chloride. On July 19 at high-water slack the chloride concentrations in the center of the navigation channel at Reedy Point and the Delaware Memorial Bridge were 4,950 and 2,420 ppm, respectively; whereas on August 2, the concentrations were 5,380 ppm at Reedy Point and 2,880 ppm at the bridge. Heavy runoff from precipitation accompanying hurricanes in August (Connie, August 12–14; Diane, August 18–19) caused the chloride concentration to decrease to 2,050 ppm at Reedy Point and to 32 ppm at the Delaware Memorial Bridge.

No appreciable salt-water invasion occurred in 1956. The average maximum daily chloride concentration at Chester, Pa., between mid-August and October was 134 ppm. During the summer months, prior to mid-August, the maximum daily chloride concentration was less than 40 ppm.

During 1957 a salt-water invasion occurred in the Delaware River. This invasion was the most severe and prolonged of those studied, as indicated by the various curves in this report. The maximum daily chloride concentration at Chester, Pa., increased from 50 ppm on June 21, 1957 to a high of 2,030 ppm on October 6, 1957.

No appreciable salt-water invasion occurred in 1958 owing to heavy fresh-water flow from rains.

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METHOD OF PREDICTING THE ORDER OF SALT-WATER INVASIONS

The severity of salt-water invasions may be predicted each year from sea level at Atlantic City, N.J., and the river level at Philadelphia, Pa.

The difference between river level at Philadelphia and sea level at Atlantic City (table 7) has been assigned values of 1 to 7 for each month from June to October, depending upon the difference. The year of the largest difference receives a value of 7, the next largest 6, and so on through the years for a given month (table 8). The total value of the 1 to 7 assignments when arranged from the lowest to the highest gives the predicted arrangement.

The predicted and actual orders of salt-water invasions (in order of decreasing severity of the invasion) are given in table 9. Severity is based on average chloride (ppm) at Marcus Hook, Pa.

Other examples of variation effects of yearly sea level and fresh-water flow can be obtained by comparing the sea level and the fresh-water flow curves for a particular year with average curves. Table 10 shows the movement of salt water for 1949 compared with the chloride concentration observed.

Chemical analyses of Delaware River water are presented for the Delaware Memorial Bridge (table 11) and for Reedy Point (table 12).

TABLE 7.—*Differences between river level and sea level, 1949–55, in feet*

Month	1949	1950	1951	1952	1953	1954	1955
June	0.47	0.48	0.37	0.42	0.49	0.43	0.32
July	.37	.34	.32	.47	.30	.28	.29
August	.17	.20	.24	.38	.22	.16	.79
September	.15	.11	.28	.38	.19	.26	.34
October	.07	.11	.20	.11	.02	.20	.62

TABLE 8.—*Arrangement of years on 1-to-7 assignments, by months*

Year	June	July	August	September	October	Total
1949	5	6	2	2	2	17
1950	6	5	3	1	3	18
1951	2	4	5	5	4	20
1952	3	7	6	7	3	26
1953	7	3	4	3	1	18
1954	4	1	1	4	4	14
1955	1	2	7	6	7	23

TABLE 9.—*Order of salt-water invasions*

[Most severe at top of list]

Predicted order of salt-water invasion	Actual order of salt-water invasion based on average chloride at Marcus Hook, Pa.
1954	1954
1949	1949
1953	1953
1950	1955
1951	1950
1955	1951
1952	1952

TABLE 10.—*Estimated conditions of salinity for 1949 from comparison of 1949 sea level and fresh-water flow curves, Marcus Hook, Pa.*

Month	Prediction	Actual conditions of salinity	Monthly average chloride concentration (ppm)
June	Salt water began to move upstream slowly at Marcus Hook.	Chloride concentration began to increase slowly.	22
July	Salt water advanced upstream but at a faster rate than in June.	Chloride concentration continued to increase.	197
August	A greater advance than in July.	Chloride concentration increasing.	512
September	Salt water still advancing	do	839
October	Farthest advance of the salt water for the summer of 1949.	Maximum chloride concentration reached (1,520 ppm).	1, 140
November	Some evidence remains of salt-water invasion at Marcus Hook, but retreat of salt water started.	Large decrease in chloride concentration but still considerable evidence of a salt-water invasion.	762
December	No evidence of salt-water invasion at Marcus Hook.	Chloride concentration decreased to 48 ppm on Dec. 18 and continued to decrease to about 18 ppm.	215

TABLE 11.—*Chemical analyses of water of the Delaware River at the Delaware Memorial Bridge, Wilmington, Del., July 1955 to December 1958*

Location.—Center of the navigation channel at the center of the Delaware Memorial Bridge, 1.9 miles downstream from the mouth of the Christina River.
Drainage area.—11,030 square miles.
Records available.—Chemical analyses: July 1955 to December 1958. Water temperatures: October 1955 to December 1958.
Extremes, 1955–58.—Dissolved solids: Maximum, 6,060 ppm September 5, 1957; minimum, 121 ppm May 19, 1958.
Hardness: Maximum, 1,120 ppm September 5, 1957; minimum, 59 ppm May 19, 1958.
Specific conductance: Maximum, 9,730 micromhos September 5, 1957; minimum, 183 micromhos May 19, 1958.
Water temperatures: Maximum, 82°F June 25, 1957; minimum, 34°F December 17, 1958.

[Chemical analyses in parts per million]

Date of collection	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (residue on evaporation at 180° C)	Hardness as $CaCO_3$		Specific conductance (micromhos at 25°C)	pH	Color
													Calcium, magnesium	Noncarbonate			
1955																	
July 13	3.6	0.22	51	75		750	9	318	1,220	0.8	5.6	2,530	436	428	4,410	6.6	8
Aug. 2	2.8	.25	87	212		1,760	18	497	3,100	.8	2.2	5,910	1,090	1,070	9,690	6.8	8
Sept. 1	7.6	.16	21	26		222	14	94	375	.4	4.0	789	159	148	1,400	6.8	14
Oct. 3	7.3	.26	55	88		632	14	226	1,140	.6	4.7	2,310	499	488	3,960	6.7	8
1956																	
Jan. 11	6.2	.12	67	170		1,370	32	414	2,400	.6	.4	5,120	866	840	8,250	6.9	10
Mar. 2	6.8	.00	17	6.5		16	14	55	14	.3	9.4	134	70	58	223	6.0	4
July 12	6.3	.00	19	7.9		47	7	73	66	.5	7.2	255	80	74	495	6.6	5
Aug. 7	5.8	.03	41	82		621	19	212	1,100	.7	1.7	2,260	440	424	3,790	7.1	6
Sept. 6	2.6	.00	56	131		1,010	20	317	1,790	.7	3.0	3,530	678	666	5,950	6.3	7
Oct. 3	2.2	.00	60	129		1,130	25	344	1,950	.7	3.1	3,870	680	660	6,440	7.3	6
Oct. 16	2.2	.00	52	83		766	15	257	1,310	.7	5.0	2,620	471	459	4,580	6.8	5
Nov. 2	1.9	.02	52	85		818	16	267	1,390	.7	5.8	2,900	479	466	4,790	6.1	6
Nov. 20	4.6	.04	27	27		208	13	142	332	.5	3.2	771	178	168	1,350	6.5	3
Dec. 19	6.6	.05	21	5.8		20	10	62	22	.5	6.9	187	76	60	302	6.6	2
1957																	
Jan. 8	7.1	.14	16	8.2		24	11	55	35	.4	7.2	187	74	65	291	7.1	5
Jan. 24	8.7	.13	21	10		64	4	82	98	.5	7.2	348	94	90	553	5.4	5
Feb. 15	6.3	.20	29	22		242	16	150	365	.5	4.0	827	163	150	1,490	6.3	4
Mar. 20	7.1	.03	17	4.8		14	12	51	16	.3	8.5	137	62	52	226	6.0	6
May 14	6.3	.08	27	32		223	16	111	390	.4	4.6	911	199	186	1,590	6.4	7
June 4	4.1	.05	32	17	104	6.3	10	113	165	.5	8.1	463	150	142	811	5.6	6
June 25	3.8	.01	48	54	466	20	8	198	790	.7	4.6	1,700	342	336	2,880	5.5	5
July 30	4.1	.04	71	137	1,390	51	14	444	2,380	.9	5.2	4,700	741	730	7,680	5.8	5
Sept. 5	2.4	.02	91	217	1,800	75	13	553	3,080	1.0	4.5	6,060	1,120	1,110	9,730	5.7	
Oct. 17	2.8	....	89	214	1,690	75	12	543	2,950	1.2	5.2	6,000	1,100	1,090	9,500	5.6	

1958																	
Jan. 23	7.5	--------	18	5.2	18	2.5	5	65	24	.4	8.4	164	67	63	269	5.4	6
Mar. 5	7.1	--------	17	5.5	12	2.4	23	46	15	.4	8.1	129	66	47	208	6.3	7
May 19	7.0	--------	16	4.6	9.0	2.0	17	47	11	.1	5.5	121	59	45	183	6.9	8
June 12	7.6	--------	20	5.7	20	2.7	10	68	26	--------	6.9	180	74	66	272	6.5	8
Sept. 22	2.0	--------	50	68	446	39	29	211	875	.6	1.4	1,900	405	381	3,200	6.4	5
Sept. 22	2.7	--------	42	63	430	35	10	199	790	.7	1.8	1,690	364	356	2,890	6.4	5
Oct. 21	3.7	--------	52	78	632	43	19	239	1,100	.7	1.5	2,300	450	435	3,870	6.2	8
Nov. 13	5.4	--------	26	28	194	9.0	23	112	320	.4	4.5	736	180	161	1,330	6.5	12
Dec. 17	6.2	--------	19	5.8	16	2.7	10	63	19	6	7.7	149	72	64	252	6.2	7

Table 12.—*Chemical analyses of water of the Delaware River at Reedy Point, Del., July 1955 to December 1958*

Location.—One hundred yards west of buoy "IN", 0.8 mile southeast of the Chesapeake and Delaware Canal, and 2.1 miles south of Pea Patch Island.
Drainage area.—11,220 square miles.
Records available.—Chemical analyses: July 1955 to December 1958. Water temperatures: October 1955 to December 1958.
Extremes, 1955–58.—Dissolved solids: Maximum, 12,600 ppm November 6–9, 1957; minimum, 117 ppm May 11–14, 1958.
Hardness: Maximum, 1,960 ppm October 1, 5–7, 9, 10; minimum, 60 ppm May 11–14, 1958.
Specific conductance: Maximum daily, 20,800 micromhos October 7, 1957; minimum daily, 154 micromhos April 14, 1958.
Water temperatures: Maximum daily, 85°F June 17, 1957 and August 4, 1958; minimum daily, freezing point on many days during winter months.

[Chemical analyses in parts per million]

Date of collection	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (residue on evaporation at 180° C)	Hardness as $CaCO_3$		Specific conductance (micromhos at 25°C)	pH	Color
													Calcium, magnesium	Noncarbonate			
1955																	
July 13	3.2	0.22	85	216	1,860		27	510	3,250	0.6	1.7	6,310	1,100	1,080	10,200	6.9	7
Aug. 2	3.0	.22	131	340	2,570		42	820	4,650	.6	.2	10,600	1,720	1,690	16,500	7.2	9
Sept. 1	6.2	.18	67	214	1,680		33	430	3,000	.4	1.2	5,720	1,050	1,020	9,360	7.1	12
Oct. 3	6.2	.22	85	240	1,880		36	515	3,350	.6	1.3	6,660	1,200	1,170	10,800	6.9	10
Nov. 1–4, 7–10	11	.07	25	35	413		22	125	675	.3	3.7	1,120	206	188	2,020	7.1	
Dec. 1–10	6.9	.11	44	90	874		22	233	1,500	.4	2.8	2,590	480	462	4,580	7.0	
1956																	
Jan. 12, 16, 19, 20	6.5	.06	119	340	3,170		50	762	5,500	.6	.1	9,820	1,700	1,650	15,400	7.1	
Feb. 1, 2, 4, 6–10	13	.03	78	157	1,590		24	401	2,730	.5	1.3	5,420	840	820	8,860	7.2	2
Mar. 1, 3, 5–8, 10	12	.02	71	18	333		23	143	570	.3	3.5	1,250	251	232	2,180	7.2	4
Apr. 1–10	13	.02	27	38	291		17	115	510	.3	3.5	1,090	224	210	1,930	7.2	3
May, 1, 3–5, 7–10	14	.01	13	7.6	33		11	43	54	.3	4.8	204	64	55	334	7.2	3
June 1–10	10	.17	33	44	360		14	138	630	.4	2.4	1,380	263	252	2,330	6.9	4
June 21	3.5	.00	55	122	864		5	264	1,580	.3	2.0	3,270	639	635	5,330	6.7	5
Aug. 1–10	5.0	.02	60	134	1,280		30	361	2,180	.5	2.3	4,220	701	676	7,160	7.3	6
Sept. 6	2.6	.01	100	261	2,300		41	614	4,000	.6	.9	7,540	1,320	1,290	12,300	6.7	7
Oct. 3–10	6.2	--------	93	235	2,060		39	553	3,600	.6	.9	6,820	1,200	1,170	11,200	6.8	7
Oct. 16	2.6	--------	112	299	2,640		46	684	4,600	.7	.9	8,670	1,510	1,470	13,800	7.4	6
Nov. 1–10	4.0	--------	66	149	1,230		25	371	2,160	.5	1.7	4,380	780	762	7,180	6.8	7
Nov. 20	3.8	.41	81	187	1,590		36	434	2,790	.5	1.0	5,380	971	942	8,830	6.8	4
Dec. 11–20	6.4	--------	52	89	750		20	248	1,310	.5	3.0	2,590	496	479	4,470	6.8	2
Dec. 19	6.1	1.2	31	37	296		16	156	490	.5	5.9	1,130	230	216	1,940	6.5	4

1957																	
Feb. 15	7.7	.76	66	154		1,390		39	386	2,400	.4	1.0	4,580	798	766	7,850	6.9	2
Mar. 20	7.2	.65	56	107		912		25	271	1,600	.3	2.9	3,260	580	559	5,350	6.4	8
Apr. 1-3, 5-10	7.5	-----	32	49	450		24	22	155	755	.4	5.8	1,580	282	264	2,850	6.4	2
May 5-9	7.9	-----	38	67	600		24	20	193	1,010	.4	4.5	2,060	370	354	3,580	6.3	3
May 14	4.9	-----	62	159		1,370		33	365	2,400	.3	.6	4,770	810	782	7,890	6.8	8
June 4-9	-----	-----	-----	-----		1,200		26	348	2,150	-----	3.4	-----	820	799	6,950	6.1	8
June 25	-----	-----	79	200	1,780		70	32	482	3,150	.7	-----	-----	1,020	994	10,000	6.1	
July 1-10	-----	-----	-----	-----		1,880		34	522	3,280	-----	1.4	-----	1,100	1,070	10,100	6.3	8
July 30	9.4	-----	111	293	2,710		105	33	735	4,690	.7	1.8	8,960	1,480	1,460	14,200	7.3	5
Aug. 2-5, 7-10	4.3	-----	123	300	2,710		108	44	700	4,780	.7	.8	9,240	1,540	1,510	14,400	7.5	3
Sept. 1-3, 5-10	6.0	-----	142	374	3,390		129	46	871	5,680	.7	.7	10,800	1,890	1,850	17,100	6.6	5
Oct. 1, 5-7, 9, 10	-----	-----	-----	-----		3,610		46	991	6,200	.8	-----	-----	1,960	1,920	18,800	7.4	5
Nov. 6-9	8.6	-----	153	379	3,730		134	45	973	6,610	.9	.9	12,600	1,940	1,900	19,100	6.7	3
Dec. 3, 4, 6, 7	5.2	-----	131	298	2,770		100	41	766	4,740	.8	1.7	9,410	1,550	1,520	14,700	6.3	3
1958																	
Jan. 6, 7	6.6	-----	51	110	1,060		46	27	314	1,950	.3	3.1	3,850	580	558	6,390	6.4	2
Feb. 11-13	5.6	-----	61	160	1,300		54	30	381	2,350	.3	2.5	4,640	810	786	7,520	6.6	2
Mar. 4-6	7.5	-----	28	34	220		16	27	112	415	.4	7.2	920	210	188	1,650	6.7	3
Apr. 3-5	7.9	-----	33	2.6	28		7.5	19	44	77	.4	3.4	237	94	78	437	6.3	8
May 11-14	12	-----	16	4.9		7.1		22	35	12	.5	3.4	117	60	42	183	6.4	8
July 2-6	5.2	-----	69	141	1,170		50	28	360	2,020	.5	2.6	4,240	753	730	6,820	6.8	10
Aug. 1-4	3.7	-----	80	151	1,250		114	25	305	2,250	.7	.9	4,610	821	801	7,360	6.2	2
Sept. 1-4	-----	-----	-----	-----		1,380		34	444	2,400	-----	1.4	-----	880	853	7,830	6.6	3
Oct. 1-4	3.9	-----	76	197	1,600		42	34	489	2,820	.7	.9	5,540	1,000	972	8,980	6.9	7
Nov. 4-7	6.0	-----	72	149	1,340		48	33	386	2,240	.8	3.7	4,450	793	766	7,300	6.8	7

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