DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

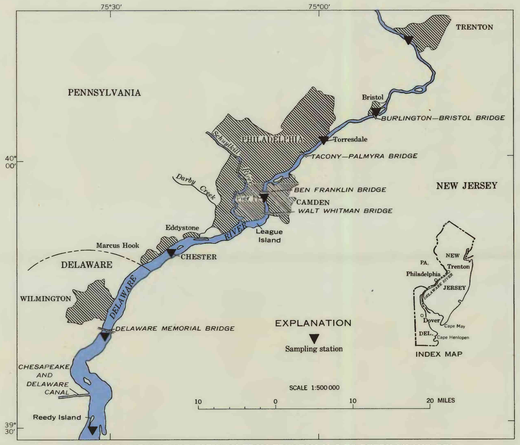
PREPARED IN COOPERATION WITH THE
WATER DEPARTMENT, CITY OF PHILADELPHIA
AND THE
DELAWARE GEOLOGICAL SURVEY

HYDROLOGIC INVESTIGATIONS
ATLAS HA-335(SHEET 1 OF 2)

CONDITIONS IN 1965

INTRODUCTION

This report describes the effects of a drought on water quality in an estuary and calls attention to the factors responsible for variations in the water quality of the estuary. The estuary used as an example is that of the Delaware River, which extends 133 miles from the head of tide at Trenton, N.J., to the Atlantic Ocean at Capes May and Henlopen (see map below). The estuary is that part of the river where the ebb and flood of the tide mixes salt water with the fresh water. This water is of increasing importance to the many great urban and industrial centers adjacent to the estuary, especially that part of the estuary from Wilmington, Del., north to Trenton which is discussed in this report. In time of drought the estuary water increases in salinity owing to the influx of ocean water. Water quality also deteriorates because there is a decrease in fresh water to flush pollution seaward. This report shows the effects of the drought of 1961 to 1966, with emphasis on the last 2 years, 1965 and 1966.

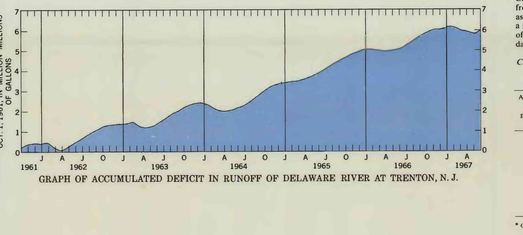


MAP OF THE DELAWARE ESTUARY FROM TRENTON, N. J. TO REEDY ISLAND, DEL.

THE DROUGHT

During the period 1961 to 1966 precipitation in the Delaware River basin was deficient, and streamflow decreased until record low flows were experienced for many streams. The major source of fresh-water flow into the estuary is the Delaware River at Trenton. Over a 50-year period the average flow of fresh water at Trenton was 7,642 mgd (million gallons per day). During most of the drought the flow at Trenton was less than normal. The deficit in flow is shown in the graph below, where the monthly departures from normal flow are cumulated from October 1, 1961. An increase in slope in this plot indicates an increase in the total deficit, and a downward slope shows a decrease in the deficit because of flow greater than normal. There was a decrease in the deficit in February and March of each year and in April of each year except 1965. At that time of year flows are often larger than average because melting snow or rainfall does not infiltrate frozen ground but runs off immediately to the streams.

The streamflow deficit was 3.4 million million gallons by January 1965. This is equivalent to about 14 months of normal runoff. On August 18, 1965 the President declared an emergency and restricted water use in the Delaware River basin. Federal agencies were directed to assist communities with their water-supply problems and to locate sources of emergency supplies. By January 1, 1967 the deficit was 6.1 million million gallons. However, a year of normal rainfall would end the drought. A drought of this magnitude is rare, as explained in a report by the River Master of the Delaware River for the period December 1, 1964 to November 30, 1965. "Weather and streamflow records indicate that a drought of this severity over a 4-year period has not occurred since at least 1820 and probably even long before that date. It has been estimated to be an event that might be expected on the average of only once in a 200 - 1,000 years." Consequently, salinity intrusion, to the extent that it occurred from 1961 to 1966, is not expected frequently.



GRAPH OF ACCUMULATED DEFICIT IN RUNOFF OF DELAWARE RIVER AT TRENTON, N. J.

SALINITY

The salinity or salt concentration of the Delaware estuary has been observed to be greatest when the flow of fresh water into the estuary is low, and smallest when flushed out by large fresh-water flows. During the drought of 1961–66 salt water advanced farther upstream than at any time on record. High salinity is objectionable because it limits the usefulness of the water for municipal and industrial supply. Concentrations in excess of 250 mg/l (milligrams per liter) of chloride are undesirable in domestic water supplies, and concentrations greater than 50 mg/l are unsatisfactory for some industrial uses. In the summer of 1965 it was anticipated that salt water might intrude upstream as far as the Torresdale intake for Philadelphia's city water supply, and arrangements were made to pipe water from farther upstream to the water purification plant, if it became necessary. Salinity did not intrude so far, and the water at Torresdale remained sufficiently fresh for use. At some locations and under certain conditions water from the Delaware River infiltrates into ground-water storage, and it is possible that water of high salinity in the estuary could affect some ground-water supplies.

Those responsible for the management of water resources in the basin need to know the conditions which cause the salinity to advance or retreat so that they may assess the need for fresh-water releases from upstream reservoirs, for restricting pumpage from wells, or for the timing of other actions or regulations to minimize the effects of salt-water intrusion. Two principal factors responsible for fluctuations in the salinity of the estuary are change in the quantity of fresh-water flow and change in the tidal conditions.

For a 50-year period the average yearly flow of the Delaware River at Trenton was 11,830 cfs (cubic feet per second) or 7,642 mgd. A flow of 1 cfs for 1 day is equivalent to 646,317 gallons. In the period 1913 to 1960 the flow was less than 8,300 cfs 50 percent of the time and less than 2,750 cfs 10 percent of the time. The Schuylkill River also contributes fresh water and converges with the Delaware estuary between Pier 11, Philadelphia, and Chester, Pa. The flow of the Schuylkill River, measured 8 miles above its mouth, was less than 1,600 cfs 50 percent of the time and less than 360 cfs 10 percent of the time. Sea water, with approximately 19,000 mg/l of chloride is present at the mouth of Delaware Bay. It tends to move upstream because of its greater density and by turbulent diffusion generated by tidal action. Fresh water from the Delaware River at Trenton, from the Schuylkill River at Philadelphia, and, to a smaller extent, from other tributary streamflow and from overland runoff, dilutes the saline water and pushes it seaward. Thus, the chloride concentration, which is a measure of the salinity, ranges from less than 10-mg/l chloride at Trenton to 19,000 mg/l at the mouth of the estuary. The salinity increases in the downstream direction at a rate determined largely by the quantity of fresh-water flow.

The chloride concentrations of the Delaware River water at League Island, Eddystone, and Marcus Hook may be estimated from the average flow of the river during the preceding month, as in the table below. These estimates apply when the river is at a steady state and fail when there are strong winds at the mouth of the estuary, or heavy rainfall in the basin a few days before the day for which salinity is estimated.

Chloride concentration at League Island, Eddystone, and Marcus Hook, Pa., for various discharge rates of Delaware River at Trenton, N.J.

Average discharge at Trenton for preceding month (cfs)*	Chloride concentration (mg/l)								
	League Island			Eddystone			Marcus Hook		
	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min
2,000	194	164	141	572	452	375	1172	861	672
3,000	80	68	58	333	262	217	763	561	438
4,000	30	25	22	112	88	73	441	324	252
5,000	25	21	18	34	27	22	82	60	47
6,000	21	18	16	28	22	18	52	38	30
7,000	16	14	12	24	19	16	34	25	20
8,000	14	12	10	20	16	13	26	19	15
9,000	12	10	8.6	15	12	10	16	12	9.3
10,000	8.5	7.2	6.2	13	10	8.3	14	10	7.8

* one cfs (cubic foot per second) for 24 hours equals 646,317 million gallons.

SALINITY – 1965

Salinity changes during 1965 from Trenton, N.J., to Reedy Island, Del., are shown in the upper strip of eight river maps. Trenton is 133 river miles upstream from the mouth of the Delaware Bay, and Reedy Island is 55 miles upstream. Below the eight chloride concentration maps is a hydrograph which shows the flow of the Delaware River at Trenton and of the Schuylkill River at Philadelphia for each day of 1965.

At the beginning of 1965 the Delaware River basin had undergone a 3-year drought. From August 1961 to January 1965 precipitation in the basin above Trenton had been 32 inches less than normal, a deficiency of three-quarters of a normal year's rainfall. During those 3 years ocean salts had intruded into the estuary as far as the Wilmington–Chester–Philadelphia–Camden region, where the water is used by industries as process water and as cooling water. Rainfall and increased runoff in December 1964 and January 1965 decreased the salinity in the estuary. At the beginning of February the salinity was 50-mg/l chloride between Chester and Philadelphia, 250 mg/l near the Pennsylvania–Delaware State line, and 1,000 mg/l near Wilmington (map of February 2–4).

Rain on February 8 and an air temperature of 10°C melted most of the snow cover and river ice in the upper part of the basin. The streamflow at Trenton increased from 3,700 cfs on February 5 to 32,800 cfs on February 8 and remained in excess of 20,000 cfs for the following 5 days. This increase in river flow flushed the saline water still farther seaward, as shown in the map for February 22–24. The 50-mg/l boundary line for chloride concentration receded to Wilmington, and the 250-mg/l and 1,000-mg/l lines receded to just north of Reedy Island.

In March and early April increased salinity again moved upstream while the discharge at Trenton varied between 13,600 and 6,180 cfs. In April the 250-mg/l boundary line moved through a 6-mile reach near Wilmington. On April 18, the streamflow at Trenton was 14,100 cfs and for the next 4 days the flow was 12,000 cfs or more. On April 19–21 the estuary above the Delaware—Pennsylvania State line was rather low in chloride concentration, ranging from 50-mg/l chloride at the State line to 250 mg/l 3 miles below the Delaware Memorial Bridge (see map of April 19–21).

In May and June the streamflow at Trenton decreased. In May the average flow was 5,209 cfs, with a maximum flow of 3,880 cfs during the last 10 days of the month. The reduced flow permitted the salt front to advance farther up the estuary. By June 1 the 50-, 250-, and 1,000-mg/l boundary lines had advanced 13, 7, and 10 miles beyond their positions on April 20 (see map of June 1–3).

During May, June, and July of 1965, the streamflow in the Delaware River at Trenton and in the Schuylkill River at Philadelphia was the lowest of record for each of these months. The average flow at Trenton during July was 1,548 cfs, the lowest for any month since the record began in 1912. The salinity invasion, which started in May, continued through June, July, August, and September. During June the 50-, 250-, and 1,000-mg/l lines moved up the estuary 16, 13, and 9 miles, respectively. At the end of June 1965 salt water had advanced beyond any June advance since 1930 (see map of July 1–3).

In July salt water advanced at about half the rate for June, and in August and September the chloride lines continued to advance, but at a rate of only 2–4 miles each month. The average flow at Trenton was 1,808 cfs in August and 2,088 cfs in September. By August 8 the 50-mg/l line was at the Tacony – Palmyra Bridge and the 250-mg/l line at the mouth of the Schuylkill River. Between August 20 and September 1 there was little change in flow, and the salinity advanced farther up the estuary, especially the 250- and 1,000-mg/l lines (see map of August 19–20).

At the end of September the 50-mg/l line was about 1 mile below the Torresdale intake. This was the farthest upstream advance of the 50-mg/l line during the drought (see map of September 30–October 2).

On October 7 heavy winds from the south pushed salty water into the estuary and raised the high-tide level 3 feet above normal. When the wind ceased, the excess water in the estuary moved seaward, and the salinity of the estuary decreased. On October 8 the 250-mg/l line approached Pier 11, 10 miles below Torresdale. An interval of precipitation and below-normal tides, resulting from strong winds from the northwest, caused a 6–7 mile recession of the 50- and 250-mg/l lines. By November 20, however, in response to reduced streamflow, the 250-mg/l line had returned to within 2 miles of Pier 11 and the 1,000-mg/l line to 3 miles up the estuary from Chester (see map of November 19–21).

In late December the salinity advance was halted by a release of 3 billion gallons of water from the Francis E. Walter Reservoir on December 21–22 and from rains on December 24–25. This reservoir is in the headwaters of the Lehigh River, a tributary of the Delaware River. The streamflow at Trenton averaged 5,810 cfs from December 20 to the end of the month, and on December 22 and 27 there were peak flows in excess of 7,000 cfs. The 250-mg/l line moved down the estuary 9 miles from Walt Whitman Bridge to Darby Creek.

DISSOLVED OXYGEN

Water acquires dissolved oxygen chiefly by its contact with the atmosphere. Oxygen passes through the air-water interface into the water. The process is most efficient when the surface is agitated, as by wind or by shipping. Because aeration takes place at the surface, it is favored in water bodies with a high ratio of surface to volume. For example, aeration is often more rapid in shallow marshes than in deeper water bodies. Oxygen is liberated by plants in photosynthesis. Most organic pollutants are oxidizable; they consume oxygen and are converted to carbon dioxide and water. Warm water dissolves less oxygen from air than does cold water (9.1 mg/l at 21°C, 12.8 mg/l at 4°C), and the oxidation process consumes oxygen more rapidly at higher temperatures. Both the fresh water flowing into the estuary at Trenton and the sea water entering the estuary from the ocean have relatively high concentrations of dissolved oxygen. These inflows help replenish oxygen in the reaches of the stream where it has been depleted by oxidation. A low DO concentration may therefore be an indication of pollution. In the winter and early spring the water temperature is low, and the capacity for dissolving oxygen is increased, the rate of oxidation is slow, and the oxygen concentration of the water is increased. Consequently the dissolved-oxygen concentrations are greatest in the winter and early spring and lowest in the summer and early autumn.

When streamflows at Trenton decrease to 7,000 – 9,000 cfs and water temperatures rise to 11–14°C, dissolved-oxygen concentrations at Pier 11 Philadelphia, often decrease at rates of 1 mg/l per day. This usually occurs between mid-April and mid-May.

Natural waters with a deficiency of dissolved oxygen fail to support fish life, are of limited value for the disposal of sewage and other pollutants, and may be odorous and aesthetically unsatisfactory in the extreme case.

Jess W. Malcolm of the Delaware River Basin Commission reported some studies of fish population in the estuary in the late summer of 1964 (Malcolm, 1964). The dissolved-oxygen concentration decreased from 7 mg/l at Torresdale to about 1 mg/l near Marcus Hook and then the dissolved oxygen increased rapidly downstream. A greater number of fish species were found north of Torresdale than between Torresdale and Marcus Hook and the number of species increased again below Marcus Hook to Delaware Bay. The fish population corresponds to the increase in dissolved oxygen. Eels and killifish appear to tolerate some pollution and low concentrations of dissolved oxygen, while other species move up or down the estuary from regions of low dissolved-oxygen. An example of sensitivity to oxygen deficiency is the fry of white perch which require 5 mg/l or more of dissolved oxygen.

Some quality standards proposed for Delaware River water include a minimum daily average dissolved-oxygen concentration of 3.5 mg/l for water near Philadelphia, 5.0 mg/l for water upstream from Philadelphia, and a minimum of 6.5 mg/l for water upstream from Philadelphia, and a minimum of 6.5 mg/l during that part of the year when fish migrate up or down the river. In 1965 and 1966 dissolved-oxygen levels approached zero and were the lowest recorded in the estuary. The lower levels should be expected because of the present pollution loads, but increased river flow can dilute the pollution and provide more dissolved oxygen. Nevertheless, the anticipated increases in population and in industry for the area adjacent to the estuary can result in an increase in the pollution and in recurring low levels of dissolved oxygen.

DISSOLVED OXYGEN – 1965

Variations in concentrations during 1965 are shown in the lower strip of eight river maps. The daily average river temperatures are plotted below these maps.

The large flows in the river during February flushed out the estuary and filled it with water of relatively high dissolved-oxygen concentration, but the concentrations were less downstream from Philadelphia. The minimum daily dissolved-oxygen concentration on February 22–24, 1965 is shown in the first map at the left of the strip. At these minimum concentrations the water was 100, 97, 90, 70, 60, and 65 percent saturated at Trenton, Bristol, Torresdale, Pier 11, Chester, and the Delaware Memorial Bridge, respectively. This shows that oxygen is consumed more rapidly in reaction with pollutants from the more heavily populated and industrialized Philadelphia and downstream areas.

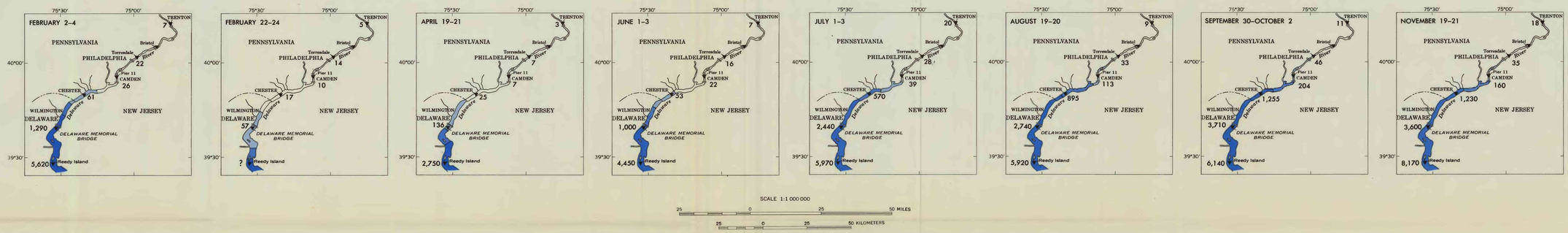
Delaware River water was 8°C warmer on April 19 than it had been on February 22–24. Dissolved oxygen was depleted rapidly because of oxidation and by April 19–21 the minimum dissolved-oxygen concentrations at Trenton, Bristol, Torresdale, Pier 11, and Chester corresponded to 100, 90, 80, 50, and 25 percent saturation, respectively (see map of April 19–21). The dissolved-oxygen concentration was lowest in that part of the river from the mouth of the Schuylkill River to the Delaware Memorial Bridge. The rate at which oxygen was restored to the water by aeration was less than the rate at which it was consumed by the high pollution load. This imbalance in rates resulted in a dissolved-oxygen sag near the source of pollution. Downstream from Delaware Memorial Bridge the remaining pollutants were at a lower concentration, and oxygen was consumed less rapidly so that the dissolved-oxygen concentration increased. A dissolved-oxygen sag is often observed in the summer months.

During the next 10 days the flow at Trenton decreased slightly, and the water temperature remained 12°C. The dissolved-oxygen concentrations decreased to less than 1.0 mg/l from the Delaware Memorial Bridge to north of Chester and to less than 4.0 mg/l upstream from Pier 11 (see map of May 1–3). Thus, the dissolved-oxygen concentration deteriorated from fair to poor along an extensive reach of the river, and this is not attributable to changes in streamflow or water temperature; it is probably a continuation of the dissolved-oxygen sag prior to recovery.

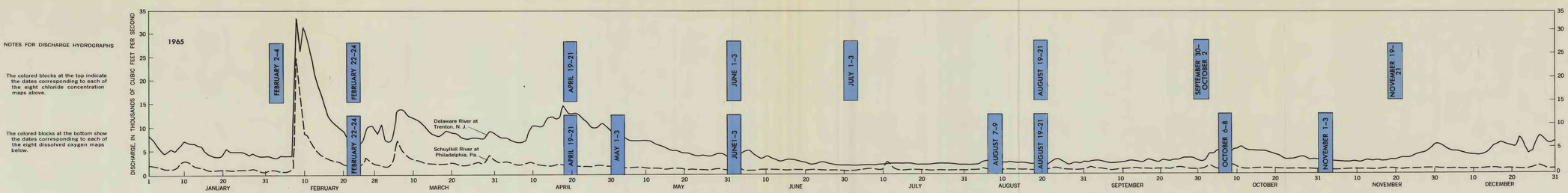
As fresh-water flow decreased and water temperatures increased to 22°C on June 1 the dissolved-oxygen sag developed both in amount of degradation and in longitudinal extent during May. In the warmer water oxygen was used up faster, and less was left dissolved in the water. About May 15 numerous dead fish were found near Pier 11 and between the mouth of the Schuylkill River and Marcus Hook. By June 1 the dissolved-oxygen concentration in the estuary was less than 1 mg/l between Wilmington and the Tacony – Palmyra Bridge (see map of June 1–3). Although fresh-water flows remained low and temperatures high, there was continued improvement for June and July. The dissolved-oxygen concentration on August 8 exceeded 1 mg/l, but was less than 4 mg/l, between Wilmington and north of Bristol, although the river flow at Trenton was less than 1,900 cfs for all of July (see map of August 7–9).

Although there was little change in fresh-water flow or in temperature from August 9 to 19, the dissolved-oxygen concentrations again decreased to less than 1 mg/l from Philadelphia to south of Marcus Hook by August 19 (see map for August 19–21). The flow rate, the temperature, and the dissolved-oxygen concentrations were stable through most of September.

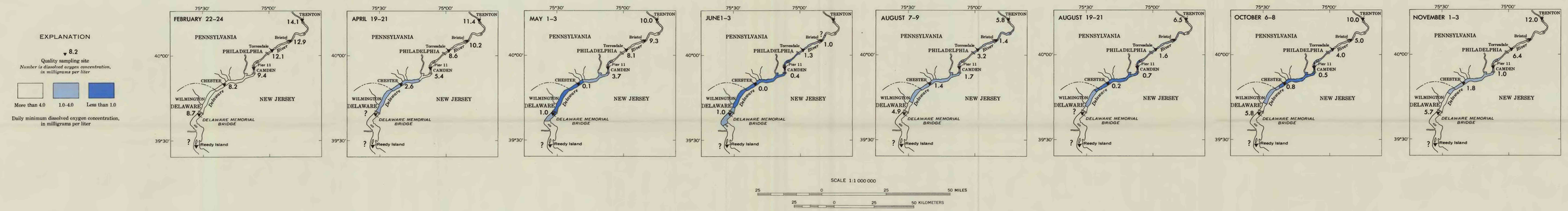
By October 6 the temperature had decreased to 21°C. The lower temperature and a small increase in fresh-water flow reduced the extent of the dissolved-oxygen sag in the estuary (see map of October 6–8). Further improvement was forthcoming when the temperature dropped to 14°C by the end of the month. During November 1–3 the dissolved-oxygen concentration exceeded 1 mg/l, and a dissolved-oxygen sag of less than 4 mg/l extended from the Tacony – Palmyra Bridge to south of Marcus Hook, nearly as extensive as on August 8 (see map of November 1–3).



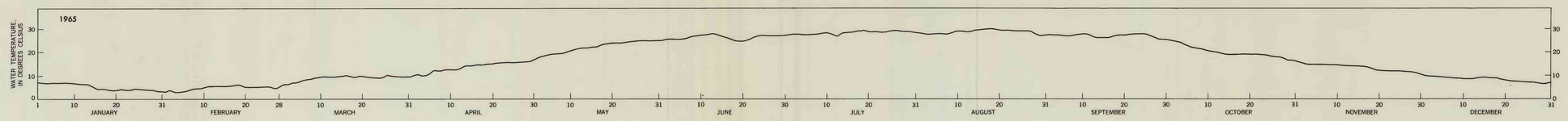
MAPS SHOWING MAXIMUM CHLORIDE CONCENTRATION FOR SELECTED DATES, 1965



HYDROGRAPH OF DISCHARGE OF DELAWARE RIVER AT TRENTON, N.J. AND OF SCHUYLKILL RIVER AT PHILADELPHIA, PA., 1965



MAPS SHOWING MINIMUM DISSOLVED OXYGEN CONCENTRATION FOR SELECTED DATES, 1965



GRAPH OF DAILY AVERAGE RIVER WATER TEMPERATURE AT PIER 11, PHILADELPHIA, PA., 1965

INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D.C.—1969—M-61008

WATER QUALITY IN THE DELAWARE ESTUARY FOR TWO YEARS OF DROUGHT: 1965 AND 1966 FROM TRENTON, NEW JERSEY TO REEDY ISLAND, DELAWARE

By
Walter B. Keighton

1969

For sale by U.S. Geological Survey, price $1.00 per set