Record Low Tide of December 31, 1962 On the Delaware River

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1586-E

Prepared in cooperation with the City of Philadelphia Water Department, the Corps of Engineers, Department of the Army, and the New Jersey Department of Conservation and Economic Development

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By A. C. LENDO

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By A. C. Lendo

ABSTRACT

The lowest known low tide in the recorded history of the Delaware River estuary occurred on December 31, 1962. The primary cause for this low tide was the strong, persistent wind from the northwest which resulted from a stationary low-pressure area over Maine and the Maritime Provinces and a high-pressure area over the Great Lakes. The direction of the wind, blowing downstream on the Delaware Bay forced huge volumes of water out of the Delaware Bay and, at the same time, lowered the ocean tide levels offshore along the coast of the Atlantic Ocean; these effects combined to produce the lowest known low tide in the Delaware estuary. The magnitude of this tide was particularly significant. At the Chestnut Street pier, Philadelphia, Pa., where records have been collected since 1899, the low tide of December 31 was 1.7 feet lower than the previous minimum low tide.

This report presents the data that were collected on this phenomenally low low tide, discusses its causes, and describes its effects on navigation, water supply, and quality of the estuarine water. The frequency of abnormally low tides is evaluated for different degrees of severity at Philadelphia.

INTRODUCTION

Persistent northwest wind on December 30–31, 1962, swept down the Delaware River and Bay (see fig. 1) and offshore over the Atlantic Ocean The wind averaged 23 miles per hour for the 48-hour period at Philadelphia, Pa., and 26 mph at Wilmington, Del. The full strength of this wind in the direction of flow during ebbtide in the Delaware Bay and against the return flow during floodtide caused large amounts of water to flow out to sea during each tide cycle. Meanwhile, wind blowing from offshore lowered ocean tide levels to near record low. The combined effects of the wind caused huge volumes of water to drain out of the Delaware estuary. Before this northwest wind subsided, the Delaware estuary had a low tide on December 31 that was considerably lower than any previously recorded.

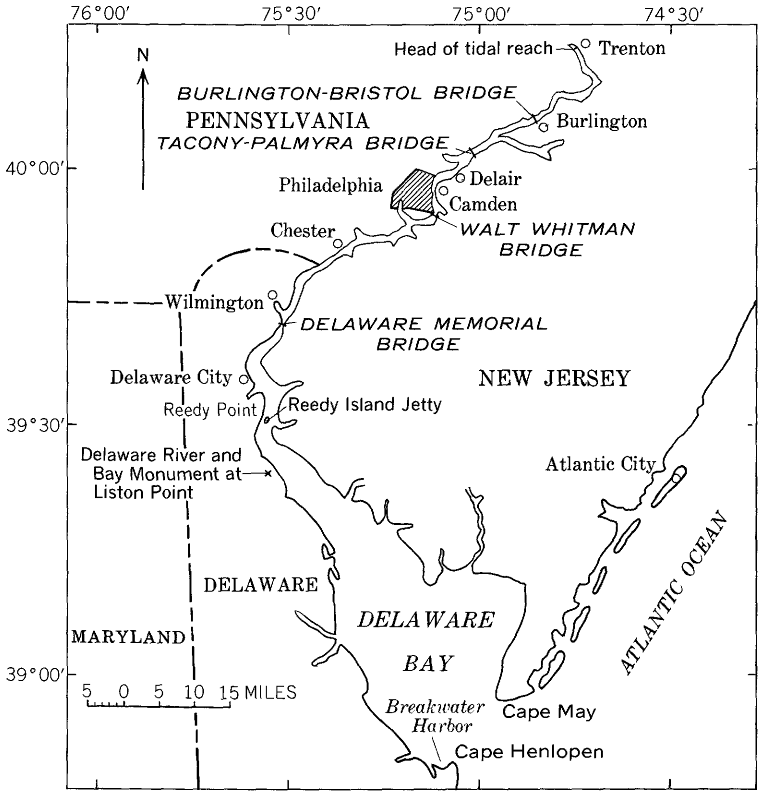

FIGURE 1.—Tidal reach of Delaware River.

The bed of the Delaware River was exposed, for the first time known, as much as 200 feet from the river banks (fig. 2). Channel and berthing depths were reduced sufficiently in some places to affect navigation, and many boats were stranded on the mud. Water-supply intakes for industries, powerplants, and municipalities were unexpectedly out of water for as long as 6 hours. The loss of water supply caused shutdowns, posed a fire hazard, and caused deep concern wherever uninterrupted operations had to be maintained. Arrangements for use of standby water supply were necessary. Some plants managed to continue operations, with lower efficiency, by reuse of the effluent water which was fortunately pooled near the outfall of their water-supply intake.

The effect of the record low tide on the quality of the tidal waters was noteworthy. A significant decrease in salinity was recorded as the huge volume of brackish water moved out of the Delaware River estuary and was replaced by the fresher water flowing from the upper tidal reach. When the wind subsided there was a surge of highly saline water from the ocean and bay, and the chloride concentration in the lower tidal reaches of the river continued abnormally high for 2 or 3 weeks.

The wind from the north brought the first severe cold weather of that winter. The freezing weather, 18°F average for December 30 and 8°F average for December 31, caused many of the recording tide gages and water-quality monitoring instruments to be inoperative because of frozen intake lines or float chambers. Other instruments failed because the tide level dropped below their operating range. The low tide left no marks of the elevation that it reached, in contrast to many high-water marks observed following major floods or maximum high tides. Thus, to better document this rare occurence, visits were made by Geological Survey personnel to many Federal, municipal, and industrial establishments along the Delaware estuary. The information and data that were collected on the record low tide of December 31, 1962, are presented in this report. In addition, comparative data on previous abnormally low tides and annual minimum tides since 1899 at Philadelphia, Pa., are included in the report. These data will be useful for various studies; particularly, they show that the December 31, 1962, low tide was a very rare occurrence.

This work is a special extension of cooperative studies of the Delaware estuary by the U.S. Geological Survey with joint participation by the City of Philadelphia Water Department, the U.S. Army Corps of Engineers, and the Division of Water Policy and Supply of the New Jersey Department of Conservation and Economic Development. The field investigations and preparation of this report were under the general direction of J. E. McCall, district engineer. The Philadelphia office of the U.S. Geological Survey Quality of Water Branch, N. H. Beamer, district chemist, assisted in the investigations and furnished the information and data on the quality of the water. Acknowledgment is also made to the many industries and municipal agencies that provided valuable assistance, data, and information.

DATA AVAILABLE

DATA ON RECORD LOW TIDE

A continuous record of the tidal stages on December 31 was not available for most of the recording gages along the Delaware estuary. Three days after the occurrence of the abnormally low tides on December 31, preliminary data on the minimum tide were available at only a few locations in the vicinity of Philadelphia, Pa. Of the four recording gages on the estuary operated at that time by the U.S. Geological Survey and cooperating agencies, only one, opposite Delair, N.J., operated satisfactorily throughout the period of the record low

FIGURE 2.—Delaware River near Wilmington,

tide. The other gages, at Marine Terminal, Trenton, N.J.; Palmyra, N.J.; and Toresdale, Pa., failed to record the low tide. Similarly, for several locations elsewhere on the Delaware estuary where records were collected by other agencies, the data were incomplete.

The minimum water level which occurred on December 31 was below the recording limit of many of the gages, even though most were designed to record well below the lowest low tide that had previously been known. The extreme cold, which caused gage wells to freeze or recorders to be inoperative, was also a factor in the loss of record. At most places where the stage of the low tide was determined, the measurement was obtained by outside staff or reference point readings, which were obtained under extremely difficult and hazardous conditions. It was impossible to observe or obtain outside readings to define the minimum stage at a few locations because surface ice had settled, as the water receded, until it rested on the river bottom.

Del., during low tide of December 31, 1962.

In spite of the difficult conditions, later visits disclosed that data on the record low tide were collected by several private companies and at municipal installations. At three of these locations, a continuous record of the abnormally low tides was collected by use of a pressure-type gage. For these locations, the inside-outside stage relationship had to be investigated for possible errors in the recorded minimum stage. At other locations where the water level fell below the recording limit of the continuous gages, readings were taken from reference points by company employees at or about the time of the low tide. Additional data were thus available wherever the elevation of the reference point was known or could be determined.

Many different local datums were used in determining the stages of the low tide. The stage of the tide at each location was converted to feet above or below mean sea level datum of 1929, for this report. Verification or determination of the local datum in use was difficult in places. Some of the more commonly used datums and their conversion to sea level are as follows:

Datum	*Above (+) or below (−) mean sea level (feet)*
Delaware River (Corps of Engineers)	−2.9
City of Philadelphia	+5.6
Mean low water of—	
Trenton, N.J	−1.6
Burlington, N.J	−1.8
Philadelphia, Pa	−2.1
Wilmington, Del	−2.0
Delaware City, Del	−2.1

Many different systems have been used to identify the locations on the Delaware River to which the data refer. The Delaware River Basin Commission recently promoted the adoption of a uniform river-mile system, which was reviewed and approved by the U.S. Army Corps of Engineers and other government agencies.

Mile 0 for the adopted mileage system is the intersection of a line between Cape May Light and the tip of Cape Henlopen with the centerline of the navigation channel. Distances from mile 0 are measured along the centerline of the main navigation channel from Delaware Bay to Bridge Street Bridge at Trenton, N.J. Thence, to the head of the main stem of the Delaware River, the river mileages correspond to distances measured along the State boundaries which approximate the centerline of the Delaware River.

The elevations of the December 31 low tide and the stationing of the locations, which were referenced to the adopted mileage system, are given in table 1. The stationing to a point not on the line of measurement was determined by the mileage to the point of intersection of a line through the point perpendicular to the line of measurement.

The lowest water level that was reached on December 31 was an instantaneous minimum because the river level was continuously changing, due to the tidal fluctuations in the estuary. To illustrate the length of time that the river level was at the lowest elevation, or below various elevations, and the time of occurrence of the minimum water level along the estuary, graphs of the tide levels that occurred at two locations during the 3-day period, December 30, 1962, to January 1, 1963, are shown in figure 3.

One of these locations is on the Delaware River opposite Delair, N.J., where the U.S. Geological Survey operates a gage at the Richmond Station of the Philadelphia Electric Co. The other is at Delaware City, Del., where the Tidewater Oil Co. collected and furnished the record. Note that even the high tides of December 31 failed to reach the normal or mean low water level.

TABLE 1.—*Elevations of low tide on December 31, 1962, on the Delaware River*

[Stationing: Mile 0, intersection of the line between Cape May Light and tip of Cape Henlopen with the centerline of navigation channel]

Location	Stationing (miles)	Feet below mean sea level	Time (24 hour)
Public Service Electric & Gas Co., Hamilton Township, N.J	130.4	8.6	1500
U.S. Steel Corp., Falls Township, Pa	127.8	11.0	1500
Colorado Fuel & Iron Corp., Roebling, N.J	125.1	9.0	1500
Lower Bucks Municipal Authority, Tullytown, Pa	122.3	10.9	1445
Public Service Electric & Gas Co., Burlington, N.J	117.5	9.1	1445
Schute & Koerting, Cornwells Heights, Pa	113.8	10.0	--------
Weyerhauser Co., Delair, N.J	104.4	8.4	--------
U.S.G.S. gage at Phila. Elec. Co. (Richmond Sta.) opposite Delair, N.J	104.2	8.6	1430
Pier 9 North, Philadelphia, Pa	100.1	8.8	--------
Pier 4 South, Philadelphia, Pa	99.8	8.5	--------
Texaco, Inc., Westville, N.J	94.4	9.6	--------
Phila. Elec. Co. (Schuylkill Sta.), Philadelphia, Pa	(1)	9.0	1215
Fort Mifflin, Philadelphia, Pa	91.3	8.7	--------
Phila. Elec. Co. (Eddystone Sta.), Philadelphia, Pa	84.9	9.5	1200
Phila. Elec. Co. (Chester Sta.), Chester, Pa	81.3	9.0	1145
Wilmington Marine Terminal, Wilmington, Del	70.7	9.1	--------
Atlantic City Power & Light Co., Deepwater, N.J	68.6	9.1	1130
Tidewater Oil Co., Delaware City, Del	60.7	8.5	1000
Reedy Point, Del	58.9	8.6	--------
Lewes (Fort Miles), Del	(2)	4.5	0600
Atlantic City, N.J	(3)	4.6	0400

[1] On Schuylkill River, 6.5 miles upstream from mouth.
[2] On Breakwater Harbor.
[3] On Atlantic Ocean.

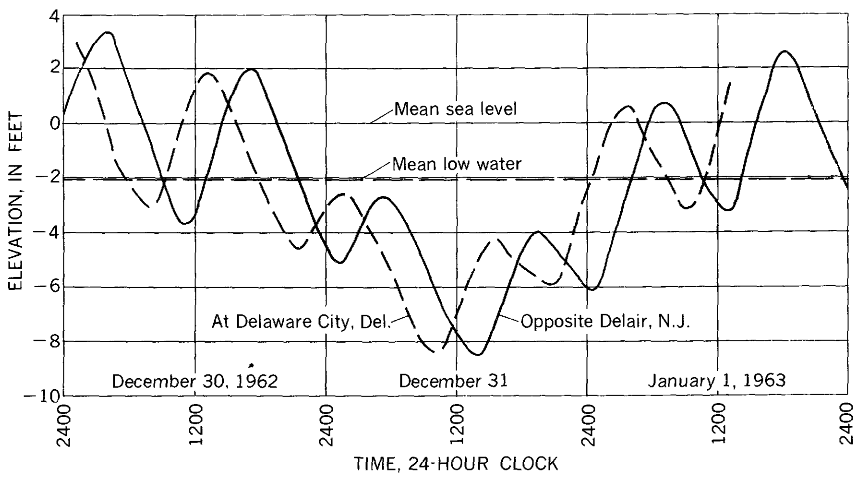

FIGURE 3.—Tidal elevations of Delaware River at Delaware City, Del., and opposite Delair, N.J., during period December 30, 1962, to January 1, 1963.

QUALITY-OF-WATER DATA

Records of chloride concentrations, dissolved-oxygen content, and temperature have been collected since 1949 at several sites along the estuary in cooperation with the City of Philadelphia Water Department and the Delaware Geological Survey. Analysis of these records indicated the changes in water quality which occurred during and after the record low tide.

The daily maximum chloride concentrations and minimum dissolved-oxygen concentrations for December 1962 and January 1963 are shown in figures 7 and 8. The dissolved-oxygen recorders were inoperative December 31, 1962, to January 2, 1963, because of the low water and the freezing temperatures. The changes in dissolved oxygen however can be estimated by observing the records before and after the event.

LONG-TERM RECORDS

In addition to inquiries for facts on the December 31 low tide, a search for past records of low tides was successful. Thus, the magnitude and frequency of occurrence of the December 31 low tide can be compared with low tides of previous periods.

Most of the recording-gage records are of short term. Data on past abnormally low tides are unfortunately incomplete for some of the longer records because measuring gages have frozen or otherwise malfunctioned. The earliest records were collected on the Delaware River at Philadelphia, Pa. An unusually long record, since 1899, has been collected by the Port Division, City of Philadelphia, at the Chestnut Street pier, which is also known as pier 4 South. The annual minimum low tide at this gage is given in table 2. In addition, a tabulation of the low low tides each day for the calendar years 1932–62 was furnished by the Port Division for study and analysis.

For the occasional periods of no record at pier 4 South, the records collected by the U.S. Coast and Geodetic Survey at pier 9 North, Philadelphia, Pa., since 1922, were used. The 1922 minimum low tide was not available at either gage, but other nearby tide-gage records were used for a fairly accurate estimate.

ANALYSIS OF DATA ON RECORD LOW TIDE

The low tide data given in table 1 are plotted in figure 4. The profiles along each bank of the river were drawn from the plotted data, and the lower elevations were overaged wherever there was wide variation.

Field checks indicated that the variation was mostly due to local conditions in the vicinity of the point of observation—that is, whether the site was in a sheltered or open reach of the river, on the windward or leeward side of a bridge or pier, or on a particular bank of the river. A significant difference resulting from local conditions can be demonstrated by comparing the elevations at the Pennsylvania bank of the river with those on the New Jersey side of the river in the reach from Burlington-Bristol Bridge to Trenton, N.J. (fig. 4). The wind blew across the flat and open spaces on the windward (Pennsylvania) side of the river, and thence, its force undiminished, directly across the river in this reach. The force of the wind caused the water to pile up as much as 2 feet on the lee shore, and this situation resulting in these pronounced differences in elevation.

TABLE 2.—*Annual minimum low tides on Delaware River at Chestnut Street pier, Philadelphia, Pa.*

Calendar year	Date	Feet below mean sea level	Calendar year	Date	Feet below mean sea level
1899	Sept. 21	5. 9	1931	Dec. 26	5. 5
1900	Nov. 10	4. 7	1932	Mar. 8	6. 4
1901	Feb. 6	5. 3	1933	Dec. 29	4. 9
1902	Jan. 5	4. 6	1934	Jan. 30	5. 0
1903	Jan. 11	4. 9	1935	Jan. 14	4. 3
1904	Nov. 14	4. 1			
1905	Nov. 13	3. 2	1936	Jan. 25	4. 4
			1937	Feb. 3	3. 6
1906	Apr. 22	4. 5	1938	Feb. 28	[2] 5. 9
1907	Apr. 15	3. 8	1939	Jan. 26	6. 8
1908	Nov. 5	4. 0	1940	Feb. 15, Mar. 26	4. 6
1909	Feb. 1	4. 6			
1910	Dec. 17	5. 6	1941	Mar. 19	[2] 5. 7
			1942	Feb. 22	5. 4
1911	Mar. 16	4. 4	1943	Dec. 11	5. 8
1912	Dec. 1	4. 2	1944	Feb. 1	5. 6
1913	Mar. 7	5. 4	1945	Jan. 25	6. 8
1914	Jan. 12	6. 4			
1915	Dec. 15	4. 8	1946	Dec. 2	6. 6
			1947	Feb. 11	6. 7
1916	Apr. 15	4. 2	1948	Jan. 28	4. 8
1917	Mar. 19	4. 6	1949	Mar. 1	4. 3
1918	July 21	3. 6	1950	Mar. 10	5. 0
1919	Mar. 29	6. 4			
1920	Feb. 27	5. 1	1951	Dec. 16	4. 2
			1952	Feb. 12	4. 2
1921	Jan. 26	4. 2	1953	Feb. 10	4. 1
1922	Jan. 16	[1] 4. 5	1954	Jan. 28, Dec. 23	4. 0
1923	Feb. 15	[2] 5. 4	1955	Mar. 28	5. 3
1924	Nov. 17	5. 5			
1925	Dec. 28	5. 9	1956	Dec. 30	5. 0
			1957	Jan. 24	4. 3
1926	Jan. 4	5. 9	1958	Nov. 30	5. 3
1927	Jan. 16	4. 7	1959	Jan. 6	6. 7
1928	Jan. 21	4. 8	1960	Jan. 21	4. 6
1929	Mar. 8	5. 8	1961	Dec. 15	4. 7
1930	Dec. 2	5. 0	1962	Dec. 31	8. 5

[1] Estimated.
[2] At pier 9 North.

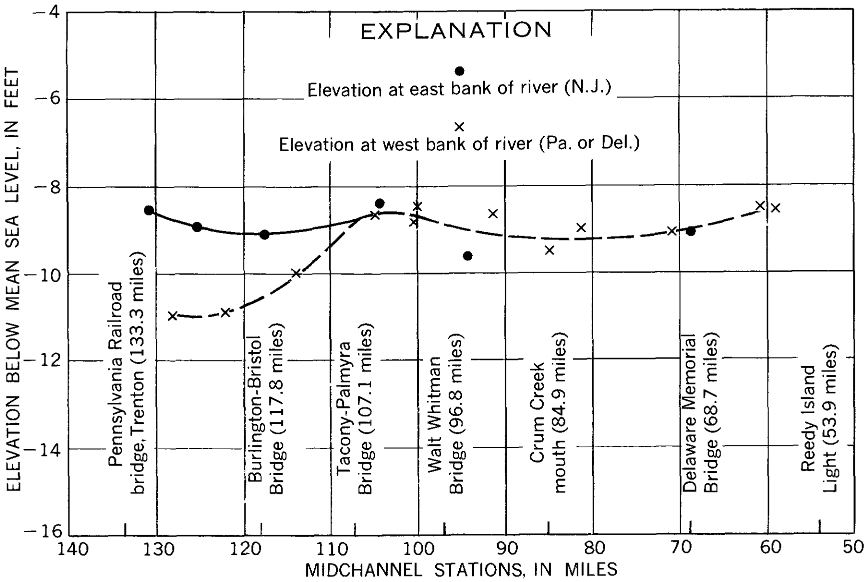

FIGURE 4.—Profile of low tide of December 31, 1962, on the Delaware estuary.

On the average, the low tide was about 9 feet below mean sea level, datum of 1929, or 7 feet below normal (mean low water) from Trenton, N.J., to Reedy Point, Del., except along the Pennsylvania bank in the reach upstream from the Tacony-Palmyra Bridge where it was as much as 11 feet below mean sea level. No data on the minimum tide on the Delaware Bay have been found except for that at Breakwater Harbor, Del.; however, this tide may be approximated on the basis that the minimum tide was 8.6 feet below mean sea level at Reedy Point, Del., and about 4.5 feet below mean sea level at Breakwater Harbor, Del.

EFFECT OF WIND ON TIDE

The principal factors which upset the normal tidal variations in the Delaware estuary are wind and floods on the inflow streams. The most significant effect of the flood was to cause high inflows on the Delaware River at Trenton, N.J. As this flood discharge and the inflow from streams downstream moves seaward, the effect of the volume of water is less noticeable as the tides moving up and down the estuary become greater. From the vicinity of Philadelphia, Pa., to the sea, flood discharges into the estuary are soon dwarfed by the huge tidal volumes of flow.

During the period December 30, 1962, to January 1, 1963, the inflow was low; for example, the flows of the Delaware River at Trenton, N.J., averaged 3,900 cubic feet per second for the 3-day period. These low inflows had no significant effect on the tidal variations. The major cause of the record low tide in the estuary was the unusual strength of the northwest wind and its direction which concides with the ebb flow and these opposed the floodflow during each tide cycle.

Figure 1 shows that the ebb or downstream flow in the Delaware estuary from Trenton, N.J., to the Atlantic Ocean is in a southeasterly direction for about 5 miles, thence in a generally southwesterly direction to the vicinity of Delaware City, Del., where it again changes nearly 90° to flow in a southeasterly direction in the lower Delaware River and Bay.

The sweep of the wind directly down the widest part of the estuary and bay in the 60-mile reach from Delaware City, Del., to the sea is probably the dominant cause of the record low tides in the Delaware River. An important contributing factor was the abnormally low, but not record low, tide levels that were occurring along the Atlantic coast, also as a result of the northwest wind.

At Atlantic City, N.J., the low tide elevation of December 31 was 4.6 feet below mean sea level; however, the record low tide at this location was 0.8 foot lower in March 1932. At Breakwater Harbor, Del., opposite the mouth of Delaware Bay, the low tide elevation was 4.5 feet below mean sea level on December 31. Low tides as much as 0.3 foot lower have been recorded at Breakwater Harbor during 5 years of the 24 years of records, 1919–23, 1936–39, 1947–50, and 1952–62, collected by the U.S. Coast and Geodetic Survey.

As the floodtide began, following the minimum low tide at 0400 hours on December 31 at Breakwater Harbor, the sharply increasing northwest wind caused an additional drag force which retarded the return flow into the bay. Also, as the wind increased to its maximum speed, it blew huge additional volume of water down the bay toward the incoming tide. As a result of the momentum of the body of water, augmented by the wind, the receding tide levels in the upper bay fell considerably lower than those in the vicinity of the mouth of the bay. This effect became even more pronounced farther up the estuary, and the lowest tides, nearly 11 feet below mean sea level, occurred below Trenton near the head of tide.

In figure 5, the successive 6-hour average wind speed at Wilmington, Del., and the low tides at Delaware City, Del., are shown for the period December 29, 1962, to January 1, 1963. The wind was variable and light for the first 17 hours of December 29, and the tides were normal. Thereafter, for the period shown, the wind was persistently from the northwest. As the wind speed increased, the tide levels became progressively lower, and similarly, as the speed diminished, the tides returned gradually to normal.

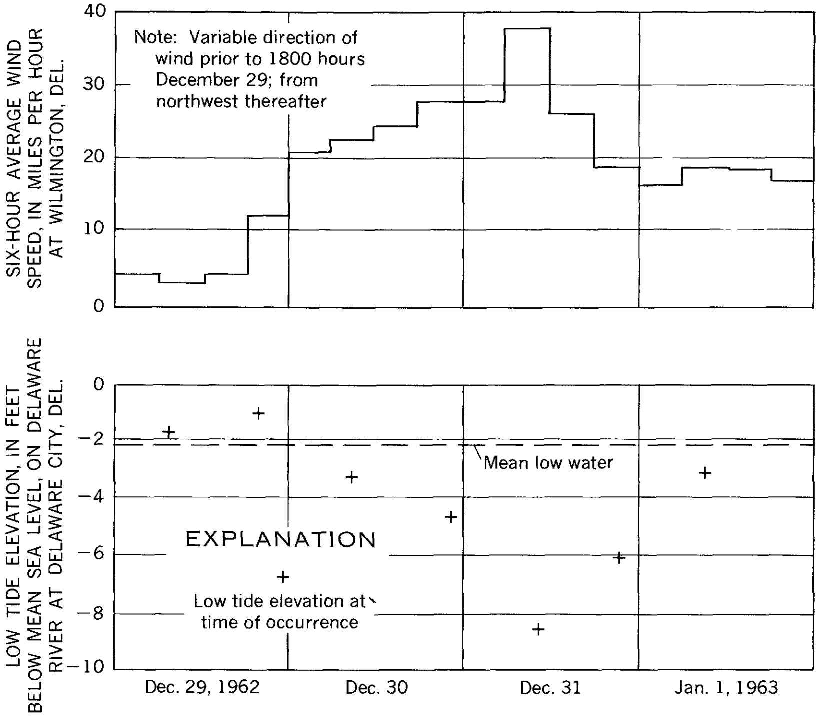

FIGURE 5.—Comparison of wind speed and low tide elevation, December 29, 1962, to January 1, 1963.

Figure 5 shows that wind speeds of 20 mph before and after minimum tide resulted in low tides about 1 foot below normal or mean low water. As the wind speeds increased above the 20-mph average on December 30 and 31, the effect on the tide levels became more significant. The increase in the average wind speed from 28 to 38 mph on December 31 resulted in the record low tide, which was 6.4 feet below normal at Delaware City, Del., and about 4 feet lower than the previous low tide during the latter part of December 30. The effects were apparently cumulative, with more water flowing into the ocean on each ebb tide than returned on the floodtide until the afternoon of December 31, as shown in figure 3.

The wind thus caused an unusual and huge volume of brackish water to drain from the bay into the ocean. At the time of the minimum low tide at 0400 hours on December 31 at Breakwater Harbor, the water level was about 4 feet below mean sea level and falling at Delaware City (see fig. 3), 60 miles upstream. At this time, just before return flow into the bay in floodtide, there had been a drainage of approximately 80 billion cubic feet more in this reach of the bay than at normal mean low water. Similarly, as the tide levels fell to a record low in the upper bay, billions of cubic feet of the fresher water in the upper estuary flowed into the Delaware Bay.

The 25-mile reach from Tacony-Palmyra Bridge to Trenton, N.J., which may be described as a "fresh-water lake," has a capacity of about 3 billion cubic feet at mean low water. At the time of the record low tide at Tacony-Palmyra Bridge, there was a depletion of approximately 1¼ billion cubic feet of water in the reach, or nearly a one-half reduction in the usual contents of this "lake" at normal low tide.

In the 65-mile reach from Delaware Memorial Bridge to Trenton, N.J., the mean low water capacity is about 11 billion cubic feet. This volume was reduced to about 7 billion cubic feet at the time of the minimum low tide on December 31. The depletion of approximately 4 billion cubic feet in this reach was nearly equal to the volume required to fill Neversink Reservoir in the upper Delaware River basin.

ANALYSIS OF LONG-TERM RECORDS OF LOW TIDES ON DELAWARE RIVER AT PHILADELPHIA, PA.

A study of the annual (calendar year) minimum low tides given in table 2 shows that the December 31 low tide was 1.7 feet lower than the previous minimum that occurred on January 26, 1939, and January 25, 1945, and the lowest in 64 years of record. The magnitude of this low tide compared to the previous minimum indicates that its recurrence interval may be considerably greater than a 64-year period.

The frequency was based on 64 years of record at Philadelphia, Pa., and plotted in figure 6. A straight-line extension of the graph indicates that the minimum low tide that occurred on December 31 might be expected, on the average, to recur about once every 150 years. This extrapolation is, of course, highly speculative and could be considerably in error. The tendency toward rising sea levels in recent decades, and possible changes in wind patterns, could easily upset the extrapolation, which also depends on the unproven validity of a straight-line extension.

In addition to the yearly minimums, the daily low low tides for the calendar years 1936–62 were available. There are usually two low tides each day; however, only the lower of these, that is, the low low tide, was included in table 3. The other, or high low tide, was usually less than 0.5 foot higher.

Table 3 was compiled from these records to show the occurrence, by months, of the low tides which reached or exceeded mean low water, which was 2.1 feet below mean sea level at Philadelphia, Pa. Mean low water is the average elevation of the daily low tides for a period of record. At Philadelphia, Pa., it is based on 19 years of record, 1940–58, as furnished by the U.S. Department of Commerce, Coast and Geodetic Survey. In explanation of table 3, it was found that a low low tide at elevations 6.6–7.0 feet (class range) had occurred three times during January for the period 1932–62. Thus, on the average, a low low tide of 6.6–7.0 feet below mean sea level occurred about once in every 10 years in January. Similarly, by adding the total number of days having low tides in class ranges 4.1–4.5 and those farther below mean sea level for March, it was found that there were 30 days during 1932–62 when the low tide was lower than 4.1 feet below mean sea level, or about once every year in March.

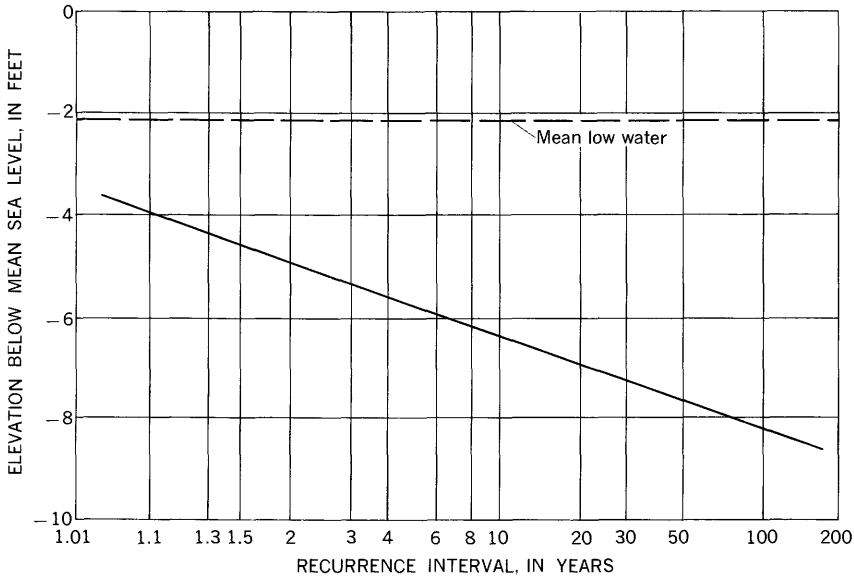

FIGURE 6.—Minimum low tide frequency curve for Delaware River at Philadelphia, Pa.

TABLE 3.—*Total number of days in each month for period 1932–62, when low low tide reached indicated elevation on Delaware River at Chestnut Street pier, Philadelphia, Pa.*

Feet below mean sea level	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
2.1–2.5	214	227	230	235	271	352	333	328	298	269	231	188
2.6–3.0	200	195	161	159	150	143	207	167	137	149	167	227
3.1–3.5	133	121	75	58	43	15	16	29	32	55	69	140
3.6–4.0	95	60	38	18	7	3		1	1	13	33	78
4.1–4.5	33	30	14	4	2	1			1	1	11	44
4.6–5.0	10	13	11		1							13
5.1–5.5	2	7	3	1							3	
5.6–6.0	2	4	1									2
6.1–6.5	1		1									
6.6–7.0	3	1										1
7.1–7.5												
7.6–8.0												
8.1–8.5												1

The tabulation by months in table 3 disclosed some interesting facts relative to the occurrence of the abnormal low tides each month. For example, the lowest tides, 5.6 feet below mean sea level or lower, have occurred during the winter months. The occurrence of the lowest tides in winter may be due to the prevailing direction of the wind, which is from the northwest; tide levels at this time in the Atlantic Ocean in this vicinity are usually about 0.6 foot lower than in the summer, because of the changing declination of the moon. Also, because the prevailing direction of the wind during the summer months is from the southwest or in the upstream direction relative to the middle and upper reaches of the Delaware estuary, tides may be higher than in winter in part, at least, from this cause. In any event, it can be seen by table 3 that the low tides which have occurred during the summer months have not been significantly below mean sea level.

EFFECT OF THE RECORD LOW TIDE ON WATER QUALITY

Figure 7 shows daily maximum chloride concentrations during December 1962 and January 1963 that were recorded at three water-quality monitoring stations in the lower estuary. Concentrations were slightly higher than normal during December, a condition attributable to below normal fresh-water flow. Daily maximum chloride concentrations occurring at or near high-water slack ranged from approximately 3,000 to 5,000 parts per million at Reedy Island Jetty, and from 200 to 1,200 ppm at the Delaware Memorial Bridge from December 1 to 30.

On December 31, the salinity was affected markedly by the record low tide. The daily maximum chloride concentration at Reedy Island Jetty decreased from 4,080 ppm on December 30 to 1,770 ppm on December 31. The decrease noted at the Delaware Memorial Bridge station was from 780 to 110 ppm. This significant decrease in salinity was caused by the huge downstream flow of fresh water driven by the strong, sustained wind. On January 1, 1963, as the tides returned to normal, the quantity of fresh water flowing into the estuary was not sufficient to replace that which was lost into the bay and the ocean during the previous day. As a result, the fresh water was replaced by a surge of highly saline water from the Delaware Bay and the Atlantic Ocean.

Daily maximum chloride concentrations at Reedy Island Jetty, which is 5.7 miles above Delaware Bay, increased to 8,510 ppm on January 2, and remained well above 7,000 ppm until January 13. In comparison, ocean water contains about 19,000 ppm chloride. Concentrations of chloride on January 2 and 3 at the Reedy Island Jetty were the highest recorded since the station was installed in June 1956.

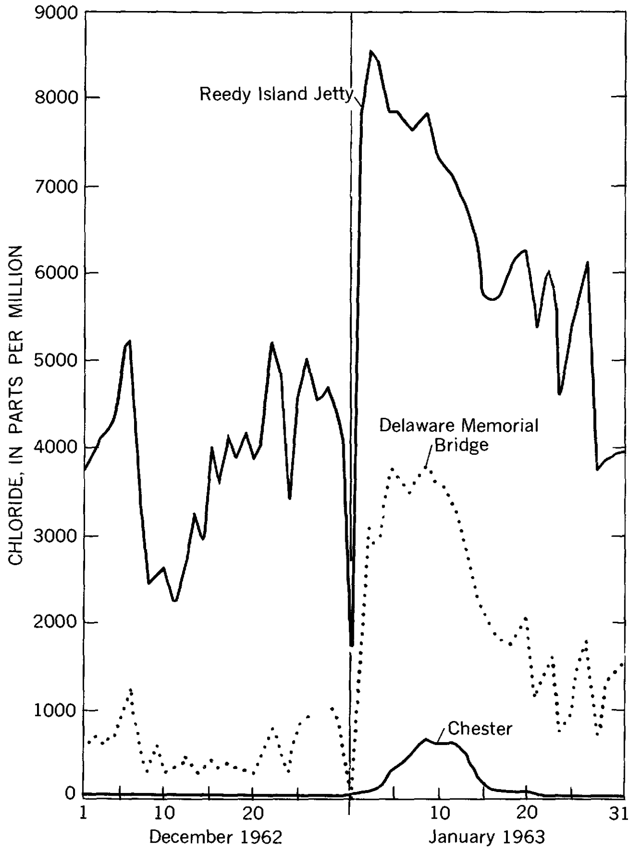

FIGURE 7.—Daily maximum chloride concentrations of Delaware River at Reedy Island Jetty, Del., Delaware Memorial Bridge, Del., and Chester, Pa., December 1962 and January 1963.

The record at this station includes the 6-month 1957 salinity invasion which was generally considered the most prolonged and severe since 1907 when the keeping of salinity records began. Fifteen miles upstream from Reedy Island Jetty at the Delaware Memorial Bridge, daily maximum chloride concentrations increased to a high of 3,800 ppm on January 5 and 9. Daily maximum concentrations remained above 3,000 ppm until January 13. At the Chester station, which is 13.5 miles above the bridge, daily maximum concentrations increased to 684 ppm on January 9, and remained greater than 50 ppm until January 22. Water in the Delaware estuary having a chloride concentration in excess of 50 ppm is generally considered to contain ocean salts.

The maximum penetration of ocean salts during this period was to a point near the mouth of the Schuylkill River in Philadelphia. Water analyzed at pier 11 North, which is about 8 miles above the mouth of the Schuylkill River, did not show any ocean salts. Even though the chloride concentrations recorded from the Delaware Memorial Bridge upstream to Philadelphia did not establish new maximums of record, concentrations were abnormally high for the time of year. Also, the significance of the event is apparent if the magnitude of the concentrations and the relatively short duration of the invasion are considered. During a 2- or 3-day period saline water advanced upstream approximately 15 miles from the Marcus Hook area (immediately below Chester) to Philadelphia.

The hardships and hazards caused by the low water levels on navigation and waterfront industries were mentioned briefly earlier. The sudden increase in salinity which followed the record low tide also caused concern to many industrial users since the water's usefulness is directly related to its salt content. High salt concentrations are objectionable mainly because of increased corrosion and scale formation. Tolerances for industrial use vary, but 200 ppm chloride in water has been suggested as the upper limit of tolerance for many purposes. Where concentrations exceed this level, many users are forced to look for a more costly but less objectionable supply of water.

The effects of the abnormally low tides on the dissolved-oxygen content of the estuary were less pronounced. Figure 8 contains graphs of daily minimum dissolved-oxygen concentrations at pier 11 North (Benjamin Franklin Bridge station) and at the Chester station during December 1962 and January 1963. These stations were not completely operative on December 31 and January 1 and 2 because the water surface had dropped below the instrument intakes. The available data, however, still indicated the changes which occurred. Generally, dissolved-oxygen concentrations in the estuarine water are progressively greater above Philadelphia. During this period of prolonged ebb currents, more dissolved oxygen was flushed downstream into the Philadelphia and Chester areas. Concentrations at Chester during the first week in January were considerably higher than before the low tides. A slight increase in dissolved oxygen was also apparent at the pier 11 station. As the tides returned to normal, dissolved-oxygen concentrations reverted to their previous levels. Lower than normal low tides on January 24 and 28 produced similar but less significant changes in dissolved oxygen.

Slight changes in water temperature occurred as the river fell to a record low. The temperature of the water in the lower reaches of the estuary was 2° or 3°F cooler than that recorded at the stations before the record low tide owing to the cold snap of December 30 and 31.

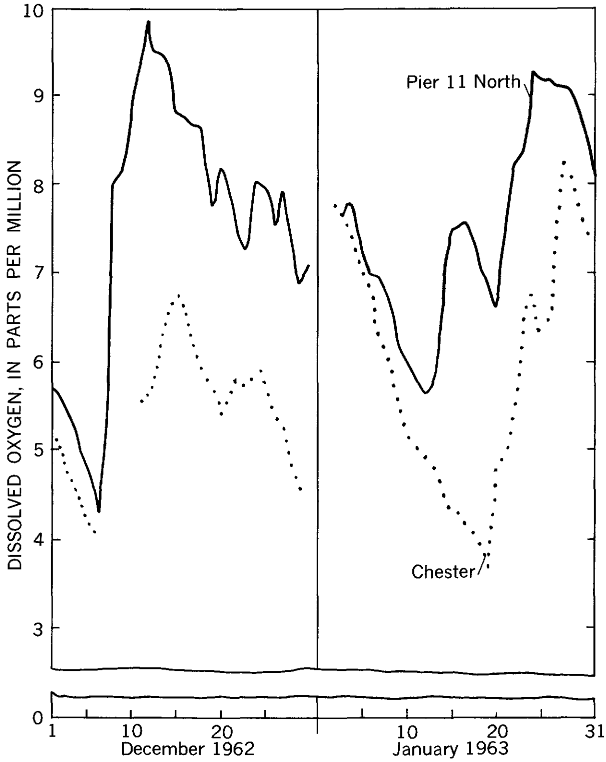

FIGURE 8.—Daily minimum dissolved-oxygen concentrations of the Delaware River at pier 11 North, Philadelphia and Chester, Pa., December 1962 and January 1963.

SUMMARY AND CONCLUSIONS

The low tide of December 31, 1962, was a momentous natural phenomenon. The ususual magnitude of this event and its effects on the estuarine water and its users were noteworthy. At Philadelphia, Pa., this low tide was 8.5 feet below mean sea level, which was 1.7 feet lower than any previous minimum low tide since 1899. Most of the elevations for the December 31 low tide from just below Trenton, N.J., to Reedy Point, Del., varied from 8.5 to 9.6 feet below mean sea level. The greatest drop was in a reach above the Burlington-Bristol Bridge, where the water level of the low tide on the Pennsylvania shore was 11 feet below mean sea level, about 2 feet lower than that on the opposite New Jersey bank.

No records of the low tide were available at locations along most of the Delaware Bay; however, the low tide elevation of −8.6 feet at Reedy Point, Del., and −4.5 feet at Breakwater Harbor, Del., gives an approximate profile of low tide in the Delaware Bay. The low tide elevation that occurred at Breakwater Harbor was not record low, as slightly lower tides have been recorded during 5 years of an intermittent record since 1919. Also, the elevation of the low tide at Atlantic City, N.J., was −4.6 feet, which was 0.8 foot higher than the record low in March 1932. Thus, new records were set only in the Delaware River estuary, not in the lower Delaware Bay or in the Atlantic Ocean near the mouth of the bay.

Wind speed, duration, and direction were evidently the dominant causes of this abnormally low tide in the estuary. Variable and irregular profiles of low tide were caused by the fluctuating intensity, duration, and angle of the wind over the estuary. The cause of the extremely low tides, however, appears to be a strong wind from the northwest which lasted for a period of 30 hours or more. The direction of reach from just below Wilmington, Del., to the sea is in this general direction. Such a wind thus tends to sweep a huge volume of water out of the reach and to the sea, and the intensity and duration of the wind was found to be related to the abnormality of the low tide.

In addition to the valuable comparison that was afforded by the long-time record at Philadelphia, Pa., a study of the occurrence of abnormally low low tides during the period 1932–62 showed that the extreme low tides, 5.6 feet below mean sea level or lower, have occurred during the winter months.

A significant decrease in salinity occurred when the wind caused a large volume of fresher water from upstream to flow out of the estuary. With the return to normal tide levels, a severe invasion of saline water followed as sea water rushed in to replace the depleted fresh-water volume. The dissolved-oxygen content was also affected but to a considerably smaller extent.

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