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TIDES AND CURRENTS IN DELAWARE BAY AND RIVER

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PREFACE

This volume constitutes the third of a series on tides and currents in important waterways of the United States. The first volume of this series was Tides and Currents in New York Harbor, Special Publication No. 111; the second was Tides and Currents in San Francisco Bay, Special Publication No. 115. The purpose of these publications is to make available to the mariner, the engineer, the scientist, and the public generally the tidal and current data now in the files of the Coast and Geodetic Survey.

This publication differs from the other two of the series in that it deals largely with the river type of tide rather than with the open ocean type, and in the discussion which follows an attempt is made to distinguish between the characteristics of the river tide and those of the open ocean tide.

The material presented in this volume is based on observations made at various times in Delaware Bay and River. The current data are largely from a comprehensive survey made during the summer of 1924. In addition to the tidal observations made by this survey, observations made by the United States Engineer office have been included.

As a general introduction to tides and currents the first two sections of Special Publication No. 111 dealing with general characteristics of tides and tidal currents are reprinted in the appendix.

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APPENDIX

TIDES IN DELAWARE BAY AND RIVER

INTRODUCTION

Delaware Bay and River and their tributaries form one of the important waterways on the Atlantic coast. Located on it are the commercially important ports of Philadelphia, Wilmington, Chester, Marcus Hook, Camden, and Trenton, the combined foreign and domestic trade of which amount to several billion dollars annually.

From its source in the vicinity of the Catskill Mountains, the river flows approximately 300 miles in a southerly direction, and empties into the bay below Liston Point. The tidal influence extends to the vicinity of Trenton, which is at the head of navigation, approximately 115 nautical miles from the entrance to the bay.

Into Delaware Bay and River empty numerous tributary rivers and creeks draining a total area of approximately 13,000 square statute miles. Among the largest of these rivers are the Rancocas, Schuylkill, Christiana, Salem, Maurice, and Cohansey. A lock canal between Delaware City and Chesapeake City serves as connecting link between the Delaware and Chesapeake waterways. There is under construction at the present time a sea-level canal between these two bays.

Tidal observations, first recorded in this waterway about 1840, have been made at intervals in various localities up to the present time. Since these earlier observations were made at a time when no considerable importance was attached to tidal phenomena and were taken primarily for establishing a plane of reference for the various hydrographic surveys then in progress, both the methods of observing and the instruments used were undeveloped, and the results obtained were subject to various sources of error. The various kinds of time used were factors of great uncertainty in many cases in these early days, and it was not until about 1885, with the adoption of standard time, that this element of uncertainty was eliminated. Another source of error lay in the use of the early tide staffs, especially in the relation of the zero of the staff to fixed bench marks on shore.

In 1854, with the advent of a tide gauge which registered automatically the heights of the tide on a marigram, the results showed a considerable improvement, the personal equation having been entirely eliminated. The need for knowledge of tides, not only for reduction of soundings, but for scientific study of the tidal phenomena and their relations, was more and more keenly felt and a greater importance was attached to these observations. From this time on rapid strides were made in tides. Automatic gauges were installed at many places on the Atlantic and Pacific coasts, and were maintained with but slight interruptions for years. From these observations various datum planes have been determined and constants derived for use in predicting the times and heights of tide for the tide tables.

The results of these observations have also permitted a better study of the tidal phenomena and have added considerably to our knowledge of tides in general.

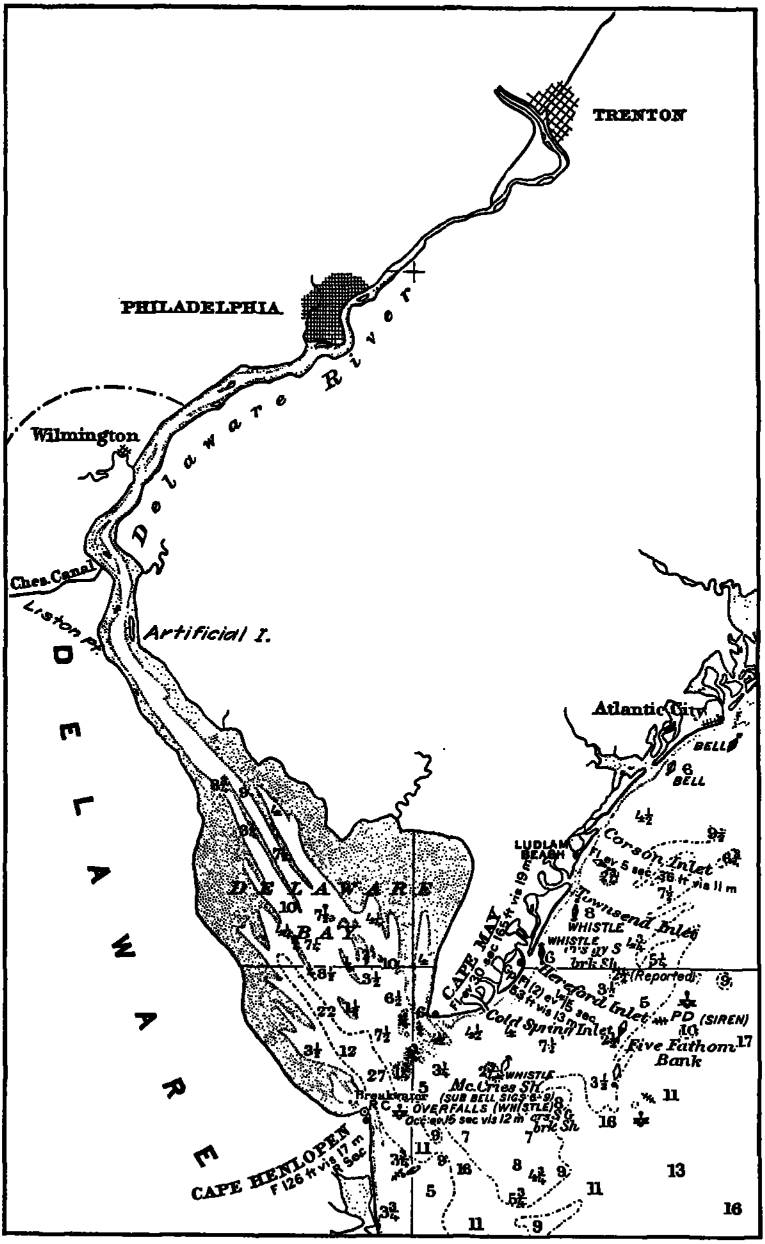

FIG. 1.—Delaware Bay and River

Part I.—TIDES IN DELAWARE BAY AND RIVER

By L. M. Zeskind, *Lieutenant (j. g.), United States Coast and Geodetic Survey*

THE DELAWARE WATERWAY

1. COMPONENT PARTS

This volume treats of the tides and currents of the navigable portion of the Delaware waterway, namely, between the Capes and Trenton. It is divided into two parts, the first dealing with tides, the second with currents. For the purposes of this publication it is found convenient to divide the waterway into five sections. The first section includes all of the bay and the river to Artificial Island (3 miles north of Liston Point); the second, Artificial Island to Philadelphia; the third, Schuylkill River from its mouth to the Fairmount dam; the fourth, the port of Philadelphia; and the fifth, Philadelphia to the head of navigation at Trenton.

2. DELAWARE BAY

The upper limit of Delaware Bay is rather uncertain. The United States Coast Pilot describes the boundary between the bay and river as being marked by two stone monuments, one on the west bank at Liston Point and the other on the east bank at Hope Creek. Since there is no fixed line of demarcation between the bay and the river, this must therefore be taken as an arbitrary division. For the purpose of this publication the bay is taken to extend to the southern part of Artificial Island.

The open ocean tide enters Delaware Bay between Cape May, on the New Jersey side, and Cape Henlopen, on the Delaware side, and sweeps over numerous sand shoals as it progresses in a northwesterly direction up the bay.

Where it meets the ocean, between Cape May and Cape Henlopen, the bay has a width of about 10 nautical miles. It gradually widens until at Miah Maull Light it reaches a maximum width of about 23 nautical miles, then narrows to a width of 5 miles at its upper extremity. The bay covers an area of approximately 650 square statute miles with an average depth at mean low water of 17 feet. Extensive flats with but few sand beaches line both shores of the bay.

The largest of the many tributary rivers which discharge into the bay are the Maurice and Cohansey. They drain a large interior area.

3. DELAWARE RIVER—ARTIFICIAL ISLAND TO PHILADELPHIA

Delaware River, from Artificial Island to Philadelphia, has a length of 43 nautical miles and varies from a width of 2½ nautical miles at its lower end to half a nautical mile at Philadelphia. It runs in a general northeasterly direction, the river surface being broken at intervals by islands, dikes, and jetties. A dredged channel, with a minimum width of 800 feet and a depth varying between 30 and 35 feet at mean low water, is maintained by the United States Engineers.

The most important of the rivers entering this section of the Delaware is the Christiana, near the mouth of which is located the port of Wilmington. The Christiana rises in the western part of the State, and flows in a generally northeasterly direction for approximately 17 miles, reaching the Delaware at a point 2 miles southeast of the city of Wilmington. The river drains an area of approximately 520 square statute miles. The tidal influence extends throughout almost the entire length.

At Delaware City the Chesapeake and Delaware Canal, previously referred to, has its western terminus. The canal is 13 miles long and 20 feet wide in the locks, of which there are three. When improvements are completed the canal will have a depth of 12 feet and a width of 150 feet and will accommodate the larger bay boats.

4. SCHUYLKILL RIVER

Schuylkill River, the largest tributary of the Delaware system, has its source in Broad Mountain in the northeastern part of Schuylkill County, Pa., and flows in a general southeasterly direction for approximately 130 miles, emptying into the Delaware River just below Philadelphia, at the League Island Navy Yard. It drains an area of approximately 2,000 square statute miles in the southeastern part of the State of Pennsylvania. The tidal influence extends up the river for a distance of 7½ nautical miles to Fairmount, where it is stopped by a dam. Dredged channels make it possible to carry a depth of 15 feet up the river to the dam.

5. DELAWARE RIVER—VICINITY OF PHILADELPHIA

The port of Philadelphia, which depends upon Delaware Bay and River for carrying a large part of its commerce, is one of the most important on the Atlantic seaboard. Deep-draft vessels coming up the bay reach the docks without any difficulty, and millions of tons of cargo, both foreign and domestic, with a value running into billions, pass through this port annually. Since 1890, when the islands obstructing the channels were removed and the river dredged, the tide has had a clean sweep past the port. The tidal flow, however, is interrupted when it reaches Petty Island, about 1 mile above the city. The depth of channel at Philadelphia at the time of the survey in July, 1924, was 31 feet, the width opposite Market Street, 2,000 feet. Across the river from Philadelphia is Camden, a large manufacturing city.

6. DELAWARE RIVER—PHILADELPHIA TO TRENTON

The Delaware River as it passes Philadelphia becomes of lesser commercial importance. Above Philadelphia the only shipping is by shallow-draft boats, the channel decreasing from a depth of 31 feet at Philadelphia to 9¾ feet at Duck Island, 3 miles south of Trenton. The average width of river is 1,000 feet. As the tide advances northeastward from Philadelphia to Trenton, a distance of 29 nautical miles, it follows a circuitous path, encountering island obstructions and shoals at intervals over its entire length.

At Riverside, N. J., the Rancocas River empties its drainage waters into the Delaware. The Delaware and Raritan Lock Canal, used by barges and small boats, links the Delaware waterway at Bordentown, N. J., with the New York waterway at New Brunswick, N. J., on the Raritan River.

THE TIDE AT PHILADELPHIA

The principal series of tidal observations in the Delaware waterway is that obtained from an automatic gauge, which was maintained almost continuously between 1901–1920, at the foot of Chestnut Street, Philadelphia. For the tables and discussions that follow, the period from 1901 to 1920 has been taken. Since the more important tidal variations go through a complete cycle in approximately 19 years, it is customary to accept the values of tidal constants based upon a 19-year series as the mean values. The values derived for the full series at Philadelphia will therefore be mean values.

The tides were graphically recorded on a Coast and Geodetic Survey automatic gauge, the heights being referred to the zero of the fixed staff near by by a comparison of the height of the curve above the arbitrary datum traced on the tide roll with the reading on staff. The zero of the staff was connected by levels with several bench marks near the tide station. By frequent check level lines run between the tide staff and the bench marks it was found that the elevation of the zero of staff had not varied to any appreciable extent during the entire time of observations. In the tables and discussions of high water, low water, river level, tide level, the heights are therefore represented in feet above the zero of the fixed staff.

Wherever possible tides at the different stations along the river were referred to Philadelphia as a standard station.

It is to be borne in mind that a distinct difference exists between the open ocean and the river tides. In discussing Philadelphia we are dealing with a river station, and facts brought out in this connection can not be taken to apply necessarily to open ocean tides, such as are encountered in the lower part of Delaware Bay.

7. LUNITIDAL INTERVALS

The true lunitidal interval, or the time by which the high or low water follows the transit of the moon, is the difference between the mean local time of the tide and the mean local time of the moon's transit. Since standard time is most commonly used, and the moon's transit is given in astronomic tables for the meridian of Greenwich, it is found more practical to compute a lunitidal interval for the standard time of tide and the transit of Greenwich, and then to reduce it to the true lunitidal interval by applying a single correction, which obviously must be constant for any particular locality.

In Table 1 are given the high and low waters at Philadelphia for the first 29 days of July, 1915. A summer month was selected because the tides are less apt to be affected by wind and weather during this season. In columns 7 and 8 of the table are given the intervals for successive high and low waters. Intervals derived from the lower transits of the moon are in parentheses. The mean or true intervals at the foot of the table are obtained by subtracting 0.18 hour (the correction referred to above) from the average values for the month. In examining the individual values of the table, it will be seen that both the high and low water intervals undergo a regular periodic monthly variation, depending on the phases of the moon, as explained in the Appendix.

TABLE 1.—*High and low waters, Philadelphia, July, 1915*

Date	Moon's transit, meridian of Greenwich	Time of—		Duration of—		Lunitidal interval		Height of—		Range	
		High water	Low water	Rise	Fall	High water	Low water	High water	Low water	Rise	Fall
	Hours	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Feet*	*Feet*	*Feet*	*Feet*
1	3.6	4.8				1.2		10.1			
	(16.0)	17.4	12.7	4.7	7.9	(1.4)	9.1	9.3	3.8	5.5	6.3
2	4.4	5.8	0.6	5.2	7.2	1.4	(8.6)	9.7	3.8	5.9	5.5
	(16.8)	18.1	13.2	4.9	7.4	(1.3)	8.8	9.7	4.0	5.7	5.7
3	5.1	6.6	1.6	5.0	7.5	1.5	(8.8)	9.4	4.1	5.3	5.6
	(17.5)	19.0	14.0	5.0	7.4	(1.5)	8.9	9.5	3.8	5.7	5.6
4	5.8	7.2	2.5	5.0	7.5	1.4	(9.0)	8.8	4.1	4.7	5.4
	(18.2)	20.0	14.8	5.2	7.6	(1.8)	9.0	9.3	3.6	5.7	5.2
5	6.5	8.0	3.2	4.8	7.2	1.5	(9.0)	9.1	4.4	4.7	4.9
	(18.9)	21.0	15.7	5.3	7.7	(2.1)	9.2	8.9	3.9	5.0	5.2
6	7.2	9.0	4.3	4.7	7.3	1.8	(9.4)	8.2	3.8	4.4	5.1
	(19.6)	21.8	16.3	5.5	7.3	(2.2)	9.1	9.0	3.3	5.7	4.9
7	8.0	10.0	5.3	4.7	7.5	2.0	(9.7)	8.2	3.8	4.4	5.2
	(20.4)	22.5	16.7	5.8	6.7	(2.1)	8.7	9.8	4.0	5.8	4.2
8	8.8	11.0	6.0	5.0	7.5	2.2	(9.6)	8.8	4.6	4.2	5.2
	(21.2)	22.9	17.7	5.2	6.7	(1.7)	8.9	9.4	4.9	4.5	3.9
9	9.6		7.3		8.4		(10.1)		3.2		6.2
	(22.1)	12.0	18.7	4.7	6.7	2.4	9.1	8.1	3.4	4.9	4.7
10	10.5	0.0	7.9	5.3	7.9	(1.9)	(9.8)	9.4	3.5	6.0	5.9
	(22.9)	12.7	19.6	4.8	6.9	2.2	9.1	8.6	4.1	5.1	4.5
11	11.4	0.7	8.7	5.1	8.0	(1.8)	(9.8)	10.1	4.4	6.0	5.7
	(23.8)	13.3	20.0	4.6	6.7	1.9	8.6	9.1	4.7	4.7	4.4
12		1.3	9.7	5.3	8.4	(1.5)	(9.9)	10.7	4.4	6.0	6.3
	12.2	14.0	20.8	4.3	6.8	1.8	8.6	8.9	3.9	5.5	5.0
13	(0.6)	1.8	10.0	5.0	8.2	(1.2)	(9.4)	10.2	4.3	6.3	5.9
	13.0	14.5	21.6	4.5	7.1	1.5	8.6	9.1	3.9	4.8	5.2
14	(1.4)	2.7	10.7	5.1	8.0	(1.3)	(9.3)	10.2	4.2	6.3	6.0
	13.8	15.0	22.3	4.3	7.3	1.2	8.5	9.1	3.9	4.9	5.2
15	(2.2)	3.5	11.4	5.2	7.9	(1.3)	(9.2)	10.0	4.0	6.1	6.0
	14.6	15.8	23.0	4.4	7.2	1.2	8.4	9.2	3.9	5.2	5.3
16	(2.9)	4.1	11.8	5.1	7.7	(1.2)	(8.9)	9.9	4.2	6.0	5.7
	15.3	16.6	23.9	4.8	7.3	1.3	8.6	9.4	4.2	5.2	5.2
17	(3.7)	4.7		4.8		(1.0)		9.8		5.6	
	16.0	17.4	12.5	4.9	7.8	1.4	(8.8)	9.5	4.2	5.3	5.6
18	(4.4)	5.4	0.7	4.7	7.3	(1.0)	8.7	9.3	4.0	5.3	5.5
	16.8	18.2	13.1	5.1	7.7	1.4	(8.7)	9.3	3.7	5.6	5.6
19	(5.2)	6.4	1.5	4.9	7.3	(1.2)	8.7	9.3	4.1	5.2	5.2
	17.6	19.1	14.0	5.1	7.6	1.5	(8.8)	9.6	3.8	5.8	5.5
20	(6.0)	7.3	2.7	4.6	7.6	(1.3)	9.1	8.8	3.9	4.9	5.7
	18.5	20.3	15.0	5.3	7.7	1.8	(9.0)	9.6	3.3	6.3	5.5
21	(6.9)	8.3	3.5	4.8	7.2	(1.4)	9.0	9.2	4.1	5.1	5.5
	19.4	21.2	15.6	5.6	7.3	1.8	(8.7)	10.2	3.8	6.4	5.4
22	(7.9)	9.4	5.0	4.4	7.8	(1.5)	9.6	9.0	4.3	4.7	5.9
	20.4	22.3	16.7	5.6	7.3	1.9	(8.8)	10.3	3.7	5.6	5.3
23	(9.0)	10.6	6.3	4.3	8.0	(1.6)	9.9	8.9	4.1	4.8	6.2
	21.5	23.4	17.8	5.6	7.2	1.9	(8.8)	10.4	3.7	6.7	5.2
24	(10.1)	11.7	7.5	4.2	8.1	(1.6)	10.0	9.0	4.0	5.0	6.4
	22.6		19.0		7.3		(8.9)		3.7		5.3
25	(11.1)	0.4	8.4	5.4	8.0	1.8	9.8	10.5	3.9	6.8	6.6
	23.6	12.7	20.0	4.3	7.3	(1.6)	(8.9)	9.1	3.6	5.2	5.5
26		1.3	9.3	5.3	8.0	1.7	9.7	10.3	3.8	6.7	6.5
	(12.1)	13.7	21.0	4.7	7.3	(1.6)	(8.9)	9.1	3.6	5.3	5.5
27	0.6	2.1	10.2	5.1	8.1	1.5	9.6	10.3	3.7	6.7	6.6
	(13.0)	14.5	21.9	4.3	7.4	(1.5)	(8.9)	9.2	3.3	5.5	5.9
28	1.5	3.0	10.8	5.1	7.8	1.5	9.3	10.1	3.7	6.8	6.4
	(13.9)	15.3	22.5	4.5	7.2	(1.4)	(8.6)	9.3	3.9	5.6	5.4
29	2.3	3.6	11.5	5.1	7.9	1.3	9.2	10.0	3.8	6.1	6.2
	(14.6	16.1	23.5	4.6	7.4	(1.5)	(8.9)	9.4	3.8	5.6	5.6
Sums				270.8	420.5	88.5	509.0	528.7	219.6	302.8	309.1
Means				4.92	7.51	1.41	8.91	9.44	3.92	5.50	5.52

It is further noted that on July 2, when the moon is on the Equator, the two high water intervals for the day have almost the same value, likewise the two low water intervals do not vary appreciably. On July 9, when the moon is at its greatest north declination the two high water and the two low water intervals for the day vary among themselves by the greatest amount. On July 17, when the moon is on the Equator in going from north to south declination, there is little variation in the intervals for the day. It is evident, therefore, that when the moon is at its greatest north and south declination, both the high and low water intervals vary among themselves by the greatest amount, and when the moon is on the Equator the variation is the least.

From the table it is seen that the lunitidal interval for any tide does not vary over an hour from the mean for the month. It is obvious, however, that during the months when storms are frequent greater variation in the lunitidal intervals would be noted.

Table 2 gives the monthly values of the lunitidal intervals for the years 1901 and 1920. Each monthly mean is for a group of the first 29 days of the month. All values refer to the moon's transit across the meridian of Philadelphia.

TABLE 2.—*Lunitidal intervals, Philadelphia: Monthly means for 1901 and 1920*

Month	High-water intervals		Low-water intervals	
	1901	1920	1901	1920
	Hours	*Hours*	*Hours*	*Hours*
January	1.61	1.80	8.99	9.15
February	1.84	1.59	9.08	8.95
March	1.56	1.36	9.06	9.17
April	1.35	1.29	9.03	8.97
May	1.29	1.42	8.97	8.91
June	1.32	1.38	8.96	8.83
July	1.37	1.42	8.90	8.95
August	1.27	1.43	8.96	8.98
September	1.36	1.44	8.97	8.86
October	1.43	1.56	8.97	9.01
November	1.53	1.63	9.04	9.08
December	1.42	1.51	9.09	9.13
Sums	17.35	17.83	108.02	107.99
Means	1.45	1.49	9.00	9.00

The value in the table for any month of observations does not vary more than 0.2 of an hour from the mean for the year, and the difference between the mean values for the two years is very slight.

In Table 3 we have the annual means of HWI and LWI for a period of 20 years divided into two 10-year groups. The value for any year seldom varies more than a tenth of an hour from the mean for the group. Considering the two groups we find that the intervals in the first group are slightly greater than the second. This would indicate a possible change in the intervals during the 20 years of observations. It is evident from the data of the preceding tables that lunitidal intervals are fairly constant, and even from a short series of observations a close approximation to the mean value may be had. For Philadelphia the accepted values for the high and low water lunitidal intervals are taken as the means of the two groups in Table 3, or 1.49 hours for the HWI and 8.97 hours for the LWI.

TABLE 3.—*Lunitidal intervals, Philadelphia, annual means*

Year	HWI	LWI	Year	HWI	LWI
	Hours	*Hours*		*Hours*	*Hours*
1901	1.45	9.00	1911	1.35	8.88
1902	1.38	9.06	1912	1.41	8.88
1903	1.47	9.10	1913	1.40	8.93
1904	1.58	9.02	1914	1.45	8.87
1905	1.62	9.08	1915	1.42	8.92
1906	1.53	9.03	1916	1.50	8.94
1907	1.50	9.00	1917	1.56	8.98
1908	1.47	8.98	1918	1.57	9.00
1909	1.50	8.93	1919	1.50	8.98
1910	1.52	8.93	1920	1.49	9.00
Sums	15.02	90.13	Sums	14.65	89.38
Means	1.50	9.01	Means	1.47	8.94

In Table 4 is shown the annual variation of lunitidal intervals for a period of 20 years divided into 2 groups of 10 years each. Each value of the table, therefore, represents the mean for ten 29-day groups of observations.

TABLE 4.—*Lunitidal intervals, Philadelphia, annual variation*

Month	HWI		LWI	
	Series 1901–1910	Series 1911–1920	Series 1901–1910	Series 1911–1920
	Hours	*Hours*	*Hours*	*Hours*
January	1.63	1.58	9.12	9.02
February	1.76	1.61	9.19	9.01
March	1.44	1.42	9.11	9.00
April	1.42	1.34	9.02	8.97
May	1.41	1.35	8.93	8.88
June	1.37	1.37	8.90	8.85
July	1.38	1.39	8.89	8.88
August	1.41	1.37	8.90	8.86
September	1.45	1.43	8.92	8.84
October	1.50	1.50	8.97	8.89
November	1.59	1.58	9.03	8.99
December	1.67	1.64	9.13	9.06
Mean	1.50	1.47	9.01	8.94

An examination of the table brings out the fact that both high water and low water lunitidal intervals go through a periodic seasonal change. This is shown best by an inspection of the graphs of the annual variation. From these it is readily seen that the intervals are greatest in the winter months and lowest in the summer months.

In Figure 2 are represented the annual variation of both high and low water intervals based on the entire 20 years of observations. The HWI curve, after reaching its maximum in February, drops sharply to a low level in April, and remains at this level during spring and summer. In the fall it begins to rise again. The LWI curve is somewhat different. Although it similarly reaches its peak in February, the decline from then on is not so abrupt, and does not reach a minimum until midsummer. In the early fall it begins to rise. Another conspicuous difference is observed in the difference in range of annual variation between the two intervals, it being noted that the variation of the high water is considerably greater than that of the low water.

That the variation in lunitidal intervals is related to and dependent on the river level can not be doubted, for we find that in January and February, when the river level is lowest, the lunitidal intervals

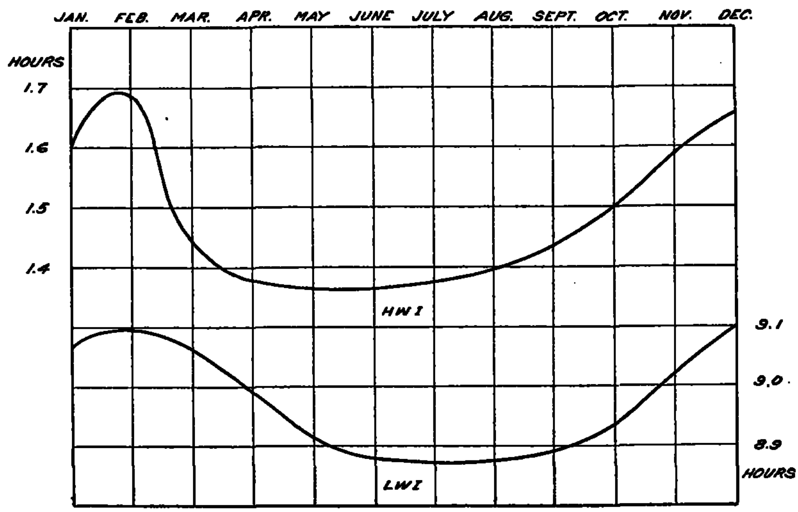

FIG. 2.—Annual variation in lunitidal intervals, Philadelphia

are greatest and when in the summer months the river level is highest, the lunitidal intervals are lowest. This fact may be explained as follows: When the river level is low, greater friction is offered the tidal wave and its progress is impeded; when the river level is highest, the friction offered is the least and the tidal wave is propagated with a greater speed.

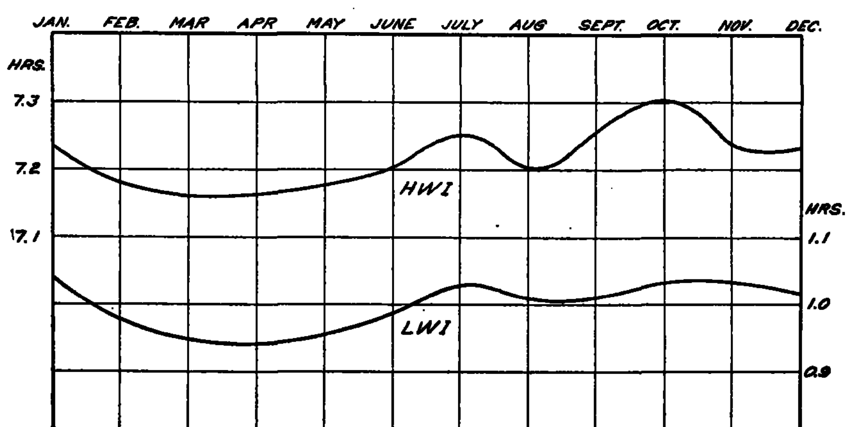

FIG. 3.—Annual variation in lunitidal intervals, Atlantic City

Figure 3 shows the annual variation of high and low water lunitidal intervals for Atlantic City, based on nearly 10 years of continuous observations from 1911 to 1920.

It is to be noted that Atlantic City is located on the open ocean and it would therefore be reasonable to expect a variation in intervals different from that of Philadelphia.

An examination of the graphs of the figure shows that while the intervals pass through an annual variation there is a pronounced difference in the graphs at the two places. At Philadelphia the difference between the highest and lowest values of HWI is 0.32 of an hour, as compared with 0.14 of an hour for Atlantic City, and 0.22 of an hour for LWI as compared with 0.17 of an hour for Atlantic City. It is further noted that unlike Philadelphia, where the maximum value for both high and low water intervals occurs in February, the maximum at Atlantic City occurs during the autumn months and the intervals are on a downward trend during the winter months. Likewise the values of the intervals instead of reaching a maximum during the summer months, as at Philadelphia, reach a minimum during the early spring.

In the reduction of HWI and LWI for tables of tidal data that follow, use is made of the annual variation above described. Since in many cases it is impossible to get a simultaneous comparison of the subordinate stations with a standard station for a reduction to mean value of tidal constants, it is found practical to derive from the graph of annual variation a correction factor depending upon the time of year in which observations were made. By correcting the intervals by this factor, we obtain a value which as a rule will approximate the mean values for the station in question.

8. DURATION OF RISE AND FALL

The duration of rise, or the time during which the tide is rising, is obtained by subtracting from the time of high water the time of the preceding low water, and the duration of fall, or the time during which the tide is falling, is obtained by subtracting from the time of low water the time of the preceding high water. For a month or more of observations the duration of rise may be derived by subtracting from the high water interval the low water interval, and the duration of fall, vice versa.

The mean duration of rise of tide is derived by substracting the mean low water lunitidal interval from the mean high water lunitidal interval, and the duration of fall, vice versa. Obviously the mean duration of rise plus the mean duration of fall must equal the time of a tidal cycle, or 12.42 hours. Referring to Table 1, we find that the duration of rise plus the duration of fall for an individual cycle is more or less than the time of a tidal cycle. This is due in large part to wind and weather. In winter months, when the storm effects are felt most, the individual duration of rise or fall may vary as much as an hour or two from its mean value, the wind advancing or retarding the tidal movement of the water.

Referring again to Table 1, columns 5, 6, 7, and 8, it is evident that the variation is greater between the individual values of the duration of rise and fall than the lunitidal intervals. However, for a month of observations the duration of rise, as derived from the mean of the high and low water intervals, will agree almost exactly with that determined from the times of high and low waters.

In Table 5 are given the duration of rise and fall for each month of the years 1901 and 1920, as determined from the monthly values of lunitidal intervals in Table 2. As in the case of the lunitidal intervals there is but little difference between the means for the two years.

TABLE 5.—*Duration of rise and fall, Philadelphia; monthly means for 1901 and 1920*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Means
1901	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*
Rise	5.04	5.18	4.92	4.74	4.74	4.78	4.89	4.73	4.81	4.88.	4.91	4.75	4.86
Fall	7.38	7.24	7.50	7.68	7.68	7.64	7.53	7.69	7.61	7.54	7.51	7.67	7.56
1920													
Rise	5.07	5.06	4.61	4.74	4.93	4.97	4.89	4.87	5.00	4.97	4.97	4.80	4.91
Fall	7.35	7.36	7.81	7.68	7.49	7.45	7.53	7.55	7.42	7.45	7.45	7.62	7.51

From the means of the annual values for HWI and LWI in Table 3, 4.93 hours for the mean duration of rise and 7.49 hours for the mean duration of fall are derived for Philadelphia, the sum of the two values necessarily equaling 12.42 hours or the time of a tidal cycle. It is apparent, therefore, that for Philadelphia the duration of fall is greater than the duration of rise by approximately 2½ hours. This is characteristic of river tides where the permanent current, due to fresh water run-off, opposes the flood tide. In the fall of the tide, the fresh water seeking its way to the ocean adds its strength to the tidal ebb and prolongs the time during which the tide is falling.

For a tidal station which is not subject to freshet or river conditions the duration of rise and duration of fall will, in general, be nearly equal. It will be shown later, when the tables of tidal data are discussed, that there is a progressive change in the duration of rise and fall in the Delaware waterway from the entrance to the bay to the extremity of tidewater at Trenton, the duration of rise decreasing and duration of fall increasing in going upstream.

Referring again to table 3, if we derive the durations of rise and fall for the two 10-year periods 1901–1910 and 1911–1920, we have for the first group 4.91 and 7.51, and for the second group 4.95 and 7.47. Although the differences between the two groups are small they indicate a probable change in the durations of rise and fall at Philadelphia.

TABLE 6.—*Duration of rise and fall, Philadelphia, annual variation*

Month	Duration of rise	Duration of fall	Month	Duration of rise	Duration of fall
	Hours	*Hours*		*Hours*	*Hours*
January	4.96	7.46	July	4.92	7.50
February	5.01	7.41	August	4.93	7.49
March	4.79	7.63	September	4.98	7.44
April	4 81	7.61	October	4.99	7.43
May	4.89	7.53	November	5.00	7.42
June	4.91	7.51	December	4.98	7.44

Table 6 gives the annual variation in duration of rise and fall at Philadelphia for the period 1901 to 1920. Between the highest and lowest monthly values of each there is a difference of 0.22 hour or 13 minutes. In Figure 4 the variation in the duration of fall is represented graphically.

An inspection of the graph indicates that the duration of fall, like the lunitidal intervals, has an annual periodicity. From a minimum in February it rises sharply to a maximum during March and from then on gradually declines. Obviously duration of rise will be represented by a complementary curve, with rise least in March and greatest in February.

Reference to graphs of annual variation in river level and high water for Philadelphia, on pages 15 and 18, indicates a similarity between these and the annual variation of duration of fall.

9. MEAN RIVER LEVEL

One of the most important results of automatic tide gage operation for long periods of time is the establishment of the plane of mean sea level for many places along the Atlantic and Pacific seaboard. Its

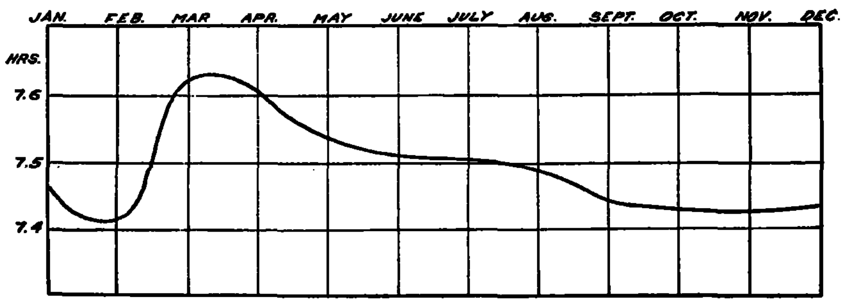

FIG. 4.—Annual variation of duration of fall, Philadelphia

value as a datum plane of the first importance can not be disputed, and it concerns not only the scientist but the engineer as well. (See Appendix, p. 113.)

Mean sea level is that plane about which the tide oscillates. It is the average height of the sea, and is determined by averaging the hourly heights of tide for a period of time depending on the degree of accuracy desired.

A distinction must here be made between sea level and river level, since at Philadelphia we are dealing with a station that is located on a river, and therefore the term "sea level" does not apply. River level may or may not be subject to tidal influence. In this publication, however, we are dealing with stations on a tidal waterway and the river level, therefore, is affected by the tide. As a general definition, we may say that the mean river level for any particular place is the average height of the river for an extended period of time, and for places subject to tidal influence is determined in the same way as sea level.

Since sea level or river level is affected by wind, weather, and astronomic causes, it is evident that the longer the period of time over which the observations extend, the better the mean value obtained. This fact is brought out in the following tables.

TABLE 7.—*Daily river level on staff, Philadelphia, July, 1915*

Date	Feet	Date	Feet	Date	Feet
1	7.06	11	7.22	21	6.95
2	7.09	12	7.09	22	6.93
3	6.94	13	7.03	23	6.69
4	6.59	14	7.05	24	6.92
5	6.68	15	7.00	25	6.84
6	6.12	16	7.17	26	6.85
7	6.47	17	7.16	27	6.81
8	7.08	18	6.78	28	6.93
9	6.04	19	6.90	29	7.08
10	6.55	20	6.60	30	7.01
Sum	66.62	Sum	70.00	Sum	69.01
Mean	6.66	Mean	7.00	Mean	6.90

In Table 7 is given the variation in river level at Philadelphia for each day of July, 1915, a typical summer month. It is seen from the table that during the month daily river level may vary by as much as 1.2 feet. It is also evident that even for a summer month, when the effect on the tide of variations in meteorological conditions is the least, there can be a difference of as much as 0.34 foot in the means of three 10-day groups.

TABLE 8.—*Monthly river level on staff, Philadelphia, for 1901, 1907, 1913, and 1920*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
	Feet	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*
1901	5.91	4.90	6.14	7.06	7.01	6.91	6.64	6.94	6.98	6.42	6.21	6.56	6.47
1907	6.33	5.80	6.48	6.40	6.59	6.85	6.58	6.48	6.52	6.46	6.84	6.82	6.51
1913	6.50	5.86	6.23	6.71	6.62	6.58	6.41	6.62	6.54	6.85	6.50	6.20	6.47
1920	6.05	6.02	6.64	7.20	6.85	6.87	6.74	6.89	6.76	6.78	6.69	6.90	6.70

Table 8 contains the heights of river level referred to staff, month by month, for the four years 1901, 1907, 1913, and 1920. The difference between the value for February, 1901, and April, 1920, is 2.30 feet. February, being a winter month, is subject to variable meteorological conditions, and the particular value in question is 0.9 foot below the next nearest value. For any year, however, there is a variation of a foot or more in level. At an open ocean station wide variation in the monthly values is infrequent.

TABLE 9.—*River level on staff, Philadelphia; annual means, 1901 to 1920*

Year	Feet	Year	Feet
1901	6.47	1911	6.51
1902	6.78	1912	6.41
1903	6.69	1913	6.47
1904	6.41	1914	6.45
1905	6.38	1915	6.61
1906	6.53	1916	6.50
1907	6.51	1917	6.52
1908	6.40	1918	6.60
1909	6.38	1919	6.78
1910	6.51	1920	6.70
Sum	65.06	Sum	65.55
Mean	6.51	Mean	6.55

Table 9 represents the annual means of river level at Philadelphia from 1901 to 1920, divided into two groups of 10 years each. It is seen from this table that even for annual means there can be a difference of 0.4 foot between the greatest and least values. For the first of the two groups into which the 20 years of observations have been divided, a mean value of 6.51 feet is derived, and for the second 6.55 feet. The best determined value of mean river level for Philadelphia may be taken as 6.53 feet, the mean for the 20-year period.

In the foregoing tables and discussions there was manifested considerable variation in river level from day to day, month to month, and year to year. River level is easily affected by wind and weather and the height at any time will differ under varying meteorological conditions. It is to be expected, therefore, that a value for river level over a short period of time may differ considerably from a mean value determined from a long series of observations.

TABLE 10.—*River levels on staff, Philadelphia; annual variation*

Month	Series 1901–1910	Series 1911–1920	Means 1901–1920
	Feet	*Feet*	*Feet*
January	6.20	6.24	6.22
February	5.93	6.12	6.02
March	6.61	6.43	6.52
April	6.71	6.81	6.76
May	6.65	6.74	6.69
June	6.75	6.76	6.75
July	6.60	6.70	6.65
August	6.70	6.76	6.73
September	6.72	6.69	6.70
October	6.66	6.70	6.68
November	6.28	6.45	6.36
December	6.26	6.28	6.27
Mean	6.51	6.55	6.53

Since there are seasonal changes in meteorological conditions it might be expected that there would likewise be seasonal changes in river level. That the river level at Philadelphia does actually pass through an annual variation may be seen from an examination of the data of Table 10. In this table are given the mean monthly values for years 1901–1910, and 1911–1920, as well as the mean for the entire series. In each case it is evident that the plane of mean river level is low in February and generally high in the summer months, and between the maximum and minimum there appears to be a difference of 0.7 foot or more. Figure 5 represents graphically the variation for the period 1901–1920.

In the figure a definite seasonal regularity or periodicity is displayed in the variation of river level. As shown in the previous annual variation curves there was a similar regularity in the lunitidal intervals and duration of rise. Just as in the latter curve we found the minimum to occur in February, here too the river level is a minimum during this month. The maximum, however, remains almost constant during the spring and summer months. In October the river level begins to drop sharply until it reaches its minimum in February. Between the maximum value of 6.76 feet in April and minimum of 6.03 feet in February there is a difference of 0.73 of a foot.

10. THE PLANES OF HIGH WATER

Because of the varying positions of the sun and moon with respect to the earth we may have various planes of high water; higher high water, lower high water, tropic higher high water, tropic lower high water, spring high water, neap high water, perigean high water, and apogean high water.

When the moon is new or full—that is, when the tidal effects of moon and sun conspire—the high water is higher than usual, and in averaging up these values over a considerable period of time the plane of spring high water is derived. Similarly when the moon is in the first or third quarters—that is, when the tidal force exerted by the moon is opposed to that of the sun—the neap tide is produced and an average of a considerable number of high waters taken at such times gives the plane of neap high water.

The moon makes a revolution around the earth in approximately 27½ days. As the orbit of its movement is an ellipse there are times when the moon is nearest, or in perigee, to the earth and times when

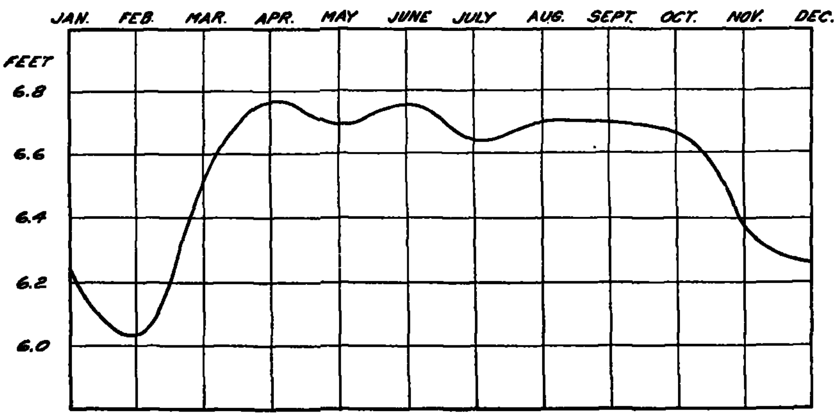

FIG. 5.—Annual variation in river level, Philadelphia

it is farthest away, or in apogee. The high water produced when the moon is in perigee is called the perigean high water, and the average of a number of such high waters gives the plane of perigean high water. Likewise the plane of apogean high water is the average of a number of high waters occurring when the moon is in apogee.

Periodic changes in the moon's declination also introduce several high-water planes; that is, higher high water, lower high water, tropic higher high water, and tropic lower high water. For any day there are two high waters, one of which is usually higher than the other. The higher of these high waters is called the higher high water and the lower, the lower high water. These planes are determined by averaging separately over a considerable period of time the higher and lower daily high waters. When the moon is in its greatest north or south declination the diurnal inequality, or difference in height between two consecutive high waters, is the greatest. The average of the higher and lower of these high waters determine, respectively, the tropic higher high water and tropic lower high water planes.

The discussions that follow will be limited to the five planes: Mean high water, spring high water, neap high water, tropic higher high water and tropic lower high water, the other planes not being deemed of sufficient importance to warrant detailed discussion here.

In the ninth column of Table 1 are shown the values of high water throughout a representative summer month. From these values it is apparent that not only is there considerable difference between the successive high waters, but there is also a large monthly variation, the difference between the highest and lowest values amounting to 2.6 feet. As the tabular values are for a summer month when the tide is least affected by meteorological conditions, we must attribute most of this variation to lunar influence.

Again in Table 1, column 9, it is seen that on July 2, when the moon was on the Equator, the high water diurnal inequality, or difference between the two highs for the day, is nil, while on July 9, when the moon is at its greatest north declination, the high water diurnal inequality is a maximum.

TABLE 11.—*Monthly mean high water on staff for 1901, 1907, 1913, and 1920*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Means
	Feet	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*
1901	8.26	6.98	8.49	9.49	9.60	9.55	9.35	9.62	9.58	8.95	8.60	9.02	8.95
1907	8.65	7.87	8.81	8.82	9.15	9.45	9.29	9.10	9.07	8.90	9.26	9.19	8.96
1913	8.92	8.28	8.62	9.26	9.23	9.23	9.08	9.19	9.02	9.19	8.86	8.48	8.95
1920	8.29	8.50	9.16	9.68	9.35	9.45	9.38	9.43	9.27	9.26	9.08	9.30	9.18

Table 11 gives the monthly means of high water for the years 1901, 1907, 1913, and 1920. A difference of 2.70 feet results between the highest and lowest monthly values during the four years. Of the four years, the least annual variation is noted in 1913, where a difference of approximately 1 foot results between the highest and lowest values.

TABLE 12.—*High water on staff, Philadelphia; annual means, 1901 to 1920*

Year	Feet	Year	Feet
1901	8.96	1911	8.95
1902	9.30	1912	8.92
1903	9.21	1913	8.95
1904	8.87	1914	8.90
1905	8.82	1915	9.06
1906	9.01	1916	8.91
1907	8.96	1917	8.91
1908	8.89	1918	8.96
1909	8.84	1919	9.20
1910	8.90	1920	9.18
Sum	89.76	Sum	89.94
Mean	8.98	Mean	8.99

Table 12 gives the yearly values from 1901 to 1920 divided into two 10-year groups. Between the highest and lowest of these yearly means there is a difference of 0.39 foot, although the mean values for the two 10-year groups agree closely. It is apparent, therefore, that only an approximate value for high water can be derived from a year or less of observations.

TABLE 13.—*High water above river level, Philadelphia; annual means, 1901 to 1920*

Year	Feet	Year	Feet
1901	2.49	1911	2.44
1902	2.52	1912	2.51
1903	2.52	1913	2.48
1904	2.46	1914	2.45
1905	2.44	1915	2.45
1906	2.48	1916	2.41
1907	2.45	1917	2.39
1908	2.49	1918	2.36
1909	2.46	1919	2.42
1910	2.39	1920	2.48
Sum	24.69	Sum	24.39
Mean	2.47	Mean	2.44

In Table 13 the yearly heights of high water above river level are shown. In comparing Tables 12 and 13 a conspicuous difference is noted between the high water as referred to staff and the high water referred to river level. In the former the greatest difference between the highest and lowest was 0.39 foot while in the latter case the difference is 0.16 foot. It appears, therefore, that the planes of high water and river level must pass through a somewhat similar annual variation. This will be discussed later in comparing the two graphs.

Since the inclination of the moon's orbit to the plane of the earth's equator passes through a complete cycle in approximately 19 years, during which it varies from 18½° to 28½°, the tidal force also passes through a cycle of variation during this period of time. In order to reduce to a mean value it is necessary to apply a correction [1] to the individual yearly values in Table 13. Table 14 shows the corrected annual means of high water for each of the 20 years of observations.

TABLE 14.—*High water above river level, Philadelphia; annual means corrected for longitude of moon's node*

Year	Feet	Year	Feet
1901	2.44	1911	2.50
1902	2.46	1912	2.58
1903	2.45	1913	2.56
1904	2.39	1914	2.52
1905	2.37	1915	2.51
1906	2.43	1916	2.45
1907	2.41	1917	2.42
1908	2.48	1918	2.35
1909	2.48	1919	2.38
1910	2.43	1920	2.43
Mean	2.43	Mean	2.47

A comparison of Tables 13 and 14 shows that although the means for the respective 10-year groups vary slightly, the mean value of high water for the 20-year groups represented in the two tables agree. This is to be expected because the correction for the inclination of the moon's orbit, or longitude of the moon's node, referred to above, passes through a cycle in approximately this time. For the accepted value of mean high water above river level we may take 2.46 feet. The mean of the yearly values of the second group in Table 14 is 0.04

[1] See R. A. Harris' Manual of Tides, Part III, U. S. Coast and Geodetic Survey, Report for 1894, p. 247.

foot higher than those of the first group. While this figure is small, it may indicate a corresponding rise in the plane of high water during the period 1911 to 1920.

In Table 11 the monthly values of high water indicated a seasonal change in the plane of high water. Table 15, which gives the annual variation based on 20 years of observations, shows a regularity in the variation of the plane, and it is noted that from a minimum of 8.27 feet on staff in February it rises to a maxium of 9.38 feet in June.

TABLE 15.—*High water on staff, Philadelphia; annual variation*

Month	High water	Month	High water	Month	High water	Month	High water
	Feet		*Feet*		*Feet*		*Feet*
January	8.50	April	9.22	July	9.28	October	9.10
February	8.27	May	9.25	August	9.31	November	8.72
March	8.90	June	9.38	September	9.21	December	8.59

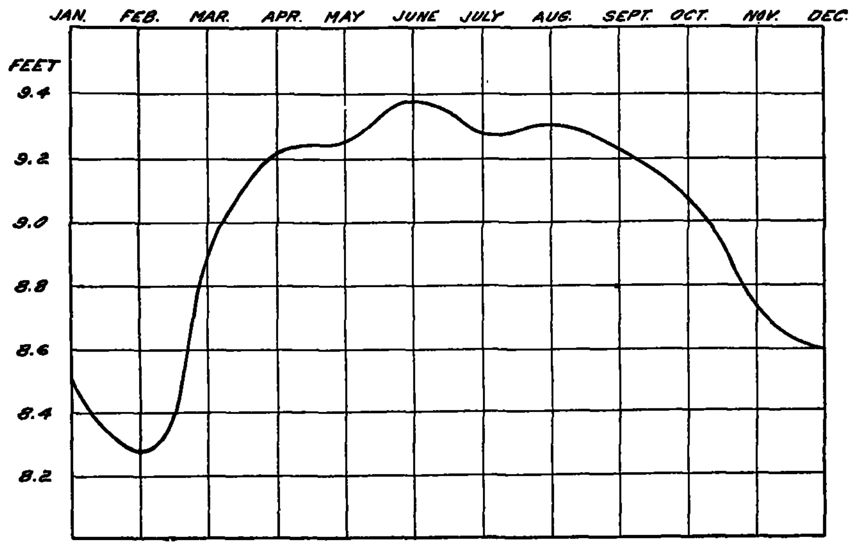

FIG. 6.—Annual variation in high water, Philadelphia

That there is a similarity in the annual variation of river level and high water is seen from a comparison of Figures 5 and 6.

In Figure 6 the annual variation of high water, based on 20 years of observations at Philadelphia, is shown graphically. Although there is a significant similarlity in the annual variations of river level and high water, two prominent differences are distinguishable. It will be noted that while the annual range of variation of river level is 0.73 foot, that of high water is 1.11 feet, or almost 0.4 foot greater. The above phenomena appears to be characteristic of river tides where the tidal movement is restricted to narrow channels. Still another difference noted in that while the river level remains more or less constant during the spring and summer months, and does not begin to drop until October, the high water, after reaching a maximum in June, begins to decrease almost immediately.

Spring high water is that high water which occurs at the time of of spring tide. It is well to call attention here to the fact that the various tides due to varying lunar positions do not occur at exactly the same time that the moon undergoes the changes, but follows them by a fixed interval. This interval of time by which the tides follow the moon's various changes is called the age of the tide.

The interval of time by which the spring tide follows new or full moon is called the phase age of the tide. To get the plane of spring high water, it is customary to add the phase age to the time of full or new moon and take the two consecutive high waters which fall nearest this time as the spring high waters. Obviously there will be but four such high waters for any month, and for an accurate determination of this plane the observations should therefore extend over a long period of time. From 2 years of observations, 1901 to 1902, the spring high water is found to be 2.68 feet above the mean river level, while for the same period of time high water above mean river level equals 2.46 feet. Apparently, then, spring high water above mean river level is approximately 9 per cent greater than mean high water above the same plane. The plane of spring high water as well as other planes may also be determined from the harmonic constants.[2]

The plane of neap high water is derived in a similar manner to that of spring high water when the moon is at first or third quarter. For the same two years as above, the plane of neap high water above mean river level is 2.15 feet, and the rise of this plane above mean river level is therefore approximately 13 per cent less than that of mean high water.

From tabulations of tropic tides for the two years 1901 and 1902, it is found that tropic higher high water is 2.76 feet above mean river level and tropic lower high water is 1.80 feet above mean river level. Tropic higher high water is, therefore, 0.29 foot greater than mean high water, and the rise above mean river level is approximately 12 per cent greater than that of mean high water. Tropic lower high water is 0.67 foot lower than mean high water, or the rise of tropic lower high water above mean river level is approximately 27 per cent less than that of mean high water.

Besides the several high water planes above described which are brought about by astronomical causes there is an important plane due largely to meteorological causes, the plane of extreme or storm high water. Because of varying wind and weather conditions there are times when the plane of high water rises considerably higher than the average. This is particularly true in a river waterway where the storm effect on tidal planes is extremely pronounced and may cause a rise of high water several feet above average. In order to have a plane which shall take account of these extraordinary heights of tide the highest high water is taken for each month and averaged for the year.

[2] Manual of Tides, Part III, U. S. Coast and Geodetic Survey, Report for 1894, p. 144.

TABLE 16.—*Extreme high water above mean river level, Philadelphia; annual means and highest*

Year	Average	Highest		Year	Average	Highest	
	Feet	*Date*	*Feet*		*Feet*	*Date*	*Feet*
1901	4.10	Apr. 3	5.08	1911	3.87	Sept. 9 Oct. 18	4.48
1902	4.75	Oct. 1	5.48	1912	4.08	Feb. 22 Mar. 29 Apr. 19	4.58
1903	4.25	Oct. 11	6.68	1913	3.96	Oct. 1, 20	4.38
1904	3.72	Oct. 21	4.18	1914	4.14	Mar. 30	4.98
1905	3.93	Jan. 7	5.58	1915	4.47	Jan. 14	5.68
1906	3.96	Oct. 19	4.48	1916	4.01	June 17	4.88
1907	3.87	Dec. 15	4.48	1917	4.09	Apr. 6	5.48
1908	3.96	Feb. 1	4.88	1918	4.02	Apr. 11	4.98
1909	4.00	Feb. 24 Apr. 22	4.48	1919	4.14	Nov. 8	5.08
1910	4.04	Jan. 22	5.58	1920	4.15	Dec. 14	4.98
Sums	40.58		50.90	Sums	40.93		49.50
Means	4.06		5.09	Means	4.09		4.95

Table 16 shows the extreme high water by years divided into 2 groups, 1901 to 1910, and 1911 to 1920. Under the column headed "average" the value for each year is found by taking the mean of the 12 monthly highest high waters. There is also given in the table the highest tide observed in each year.

In columns 3 and 4, headed "highest," it is seen that at Philadelphia on October 11, 1903, the high water rose to a height of 6.68 feet above mean river level or more than 4 feet greater than the average rise. It is further noted that the rise of high water above river level was almost 1½ feet more than the mean range of tide at Philadelphia or approximately 172 per cent greater than the mean rise of the high water above river level.

At first thought we might expect considerable variation in results of any two periods of time of the average annual values of extreme high water since these high waters are produced by variations in meteorological conditions which are rather uncertain. As a matter of fact, however, there is found to be only a slight difference between the two 10-year periods in Table 15. For the first period we derive a value of 4.06 feet above mean river level and for the second 4.09 feet. From these values we find that the plane of extreme high water rises approximately 66 per cent higher above mean river level than does mean high water. Even for the averages of the highest values—one for each year of the groups—it is seen that the mean for the first group, 5.09 feet, compares closely with that of the second group, 4.95 feet. We may conclude from the above that the plane of extreme high water and highest high water, when determined from a number of years, constitute well determined planes. Between the highest and lowest individual values of extreme high water we find a difference of approximately 2½ feet, while between the highest and lowest average yearly values for the 20 years there is a difference of a little more than 1 foot.

11. THE PLANES OF LOW WATER

For each of the high water planes discussed in the preceding section there is a corresponding low water plane. Table 17, which follows, gives the results of observations at Philadelphia for 1901 to 1920 divided into two 10-year groups.

TABLE 17.—*Low water on staff, Philadelphia; annual means, 1901 to 1920*

Year	Feet	Year	Feet
1901	3.73	1911	3.66
1902	3.96	1912	3.59
1903	3.92	1913	3.66
1904	3.66	1914	3.73
1905	3.59	1915	3.83
1906	3.73	1916	3.79
1907	3.75	1917	3.83
1908	3.61	1918	3.93
1909	3.58	1919	4.04
1910	3.68	1920	3.92
Sum	37.21	Sum	37.98
Mean	3.72	Mean	3.80

From a comparison of the above table with that of Table 12 (annual mean of high water on staff) it is seen that the annual means vary in a somewhat similar manner. Between the highest and lowest yearly values of Table 16 there is a difference of 0.46 foot, and between the two 10-year groups a difference of 0.08 foot.

TABLE 18.—*Low water below river level, Philadelphia; annual means, 1901 to 1920*

Year	Feet	Year	Feet
1901	2.74	1911	2.85
1902	2.82	1912	2.82
1903	2.77	1913	2.81
1904	2.75	1914	2.72
1905	2.79	1915	2.78
1906	2.80	1916	2.71
1907	2.76	1917	2.69
1908	2.79	1918	2.67
1909	2.80	1919	2.74
1910	2.83	1920	2.78
Sum	27.85	Sum	27.57
Mean	2.79	Mean	2.76

In Table 18 are shown the annual means of low water below river level. As in Table 13 the mean of the first group is slightly greater than that of the second. For the 20 years a mean value of 2.77 feet is derived. Between the highest and lowest values there is a difference of 0.18 foot.

TABLE 19.—*Low water below river level, Philadelphia; annual means corrected for longitude of moon's node*

Year	Feet	Year	Feet
1901	2.69	1911	2.92
1902	2.75	1912	2.90
1903	2.69	1913	2.90
1904	2.67	1914	2.80
1905	2.72	1915	2.84
1906	2.74	1916	2.75
1907	2.72	1917	2.70
1908	2.79	1918	2.66
1909	2.83	1919	2.70
1910	2.88	1920	2.72
Mean	2.75	Mean	2.79

If, as in the case of the high waters, we correct the low waters to their mean values 2.75 feet is derived for the first and 2.79 for the second group, or an increase of 0.04 foot during the last 10 years of observations. The mean of the 2 groups, or 2.77 feet, may be taken as the mean value of low water below river level at Philadelphia. Just as we found indications of a rise in the plane of high water from Table 13 we have indications of a fall in the plane of low water, and the change in both cases is practically the same. It will be shown in the section on range of tide at Philadelphia that the annual variation of range for the two 10-year groups also indicates an increase in the range of tide of approximately 0.1 foot.

In the previous section, 2.46 feet was derived for the value of high water plane above river level. Comparing this with the accepted value of 2.77 feet for the plane of low water below river level, it is evident that the planes are not symmetrical with respect to river level, the fall of low water being more than 0.3 foot greater than the rise of high water. For a station not affected by river conditions, as at Delaware Breakwater, we find that this difference between the two planes is only 0.08 foot. The difference existing between the outside station at Delaware Breakwater and the river station at Philadelphia may be ascribed largely to the effect produced by fresh water run-off. A study of the tide curve at Philadelphia will show that the gradient for the fall of tide is less than that for the rise of tide. An explanation of the cause of this difference was given in the discussion of duration of rise and fall.

TABLE 20.—*Low water on staff, Philadelphia; annual variation*

Month	Low water	Month	Low water	Month	Low water	Month	Low water
	Feet		*Feet*		*Feet*		*Feet*
January	3.65	April	4.00	July	3.64	October	3.90
February	3.54	May	3.78	August	3.77	November	3.64
March	3.88	June	3.78	September	3.83	December	3.60

The annual variation in the plane of low water based on the 20 years of observations from 1901 to 1920 is shown in Table 20. Between the highest and lowest monthly values there results a difference of 0.46 foot. Comparing this difference with that derived between the maximum and minimum of Table 15, or 1.04 feet, it is observed that the annual variation for the plane of low water is less than half that of the plane of high water. This is best seen by comparison of Figures 6 and 7.

Unlike the annual variation of the tidal planes previously discussed, which have been similar in most respects, we find in examining Figure 7 a sharp contrast in the annual variation of the plane of low water, for instead of passing through one cycle with a single maximum and minimum it passes through two cycles. If we compare Figures 6 and 7 we find that both high water and low water are a minimum in February, and that they both similarly reach a maximum in April. In the graph of low water, however, we find that instead of remaining at this maximum during the spring and summer months, as happens in the case of the high water, it decreases from a maximum in April to a second minimum in July, and then increases to a second maximum in October after which, like the high water, it rapidly descends until February. A probable explanation for this phenomenon may be had by a study of the relation between river discharge and the planes of high and low water. It will be shown later that river discharge has a pronounced influence on both planes, but with a greater effect on that of low water. We may, therefore, ascribe the characteristic variation of this plane as due in large part to the river discharge.

Table 21 below contains, besides mean low water, the results for other datum planes from a tabulation of the two-year series 1901 and 1902, and corrected for inclination of the moon's orbit.

TABLE 21.—*Low water planes, Philadelphia; below mean river level*

	Feet
Mean low water	2. 77
Spring low water	2. 83
Neap low water	2. 66
Tropic lower low water	2. 96
Tropic higher low water	2. 67

As in the case of the high water planes where it was seen that the *tropic* higher high water constituted the highest plane given, here we

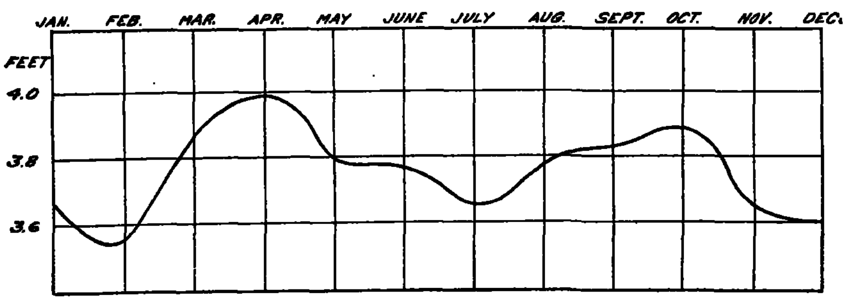

FIG. 7.—Annual variation in low water, Philadelphia

find that the tropic lower low water is the lowest plane. A conspicuous difference to be noted, however, is the smaller differences between the heights of the various low water planes as compared with those of high water. For example, between the highest and lowest of the low water planes we have a difference of 0.30 foot, as compared with 0.96 foot for the difference between the highest and lowest of the high water planes. This might have been anticipated from the graphs of the annual variation of high and low waters where it was observed that the greater difference existed between the maximum and minimum monthly values of the high water.

From the table it is seen that below the plane of river level spring low water falls 2 per cent lower than mean low water. In the preceding section we found that spring high water rose 9 per cent higher than mean high water. The plane of neap low water is 4 per cent higher than mean low water, compared with 13 per cent for neap high water below mean high water. Tropic lower low water is 8 per cent lower than mean low water, compared with 12 per cent for tropic higher high water above mean high water; and tropic higher low water is 4 per cent higher than mean low water compared with 27 per cent for tropic lower high water below mean high water.

Just as we defined the plane of extreme high water as the average over a considerable period of time of the greatest high waters, one for each month of the year, we may similarly define the plane of extreme low water by substituting the words "lowest low waters" for "highest high waters." Table 22 gives the yearly averages of the extreme low waters below mean river level, together with the date and value of the extreme low water of each year.

TABLE 22.—*Extreme low water below mean river level, Philadelphia; annual means and lowest*

Year	Average	Lowest		Year	Average	Lowest	
	Feet	*Date*	*Feet*		*Feet*	*Date*	*Feet*
1901	4.30	Feb. 5	6.32	1911	4.34	Dec. 29	5.72
1902	4.16	Jan. 4 / Mar. 20	5.12	1912	4.47	Jan. 6	6.62
				1913	4.61	Dec. 9	6.62
1903	3.92	Jan. 13	5.42	1914	4.35	Jan. 13	6.42
1904	4.22	Apr. 21	5.12	1915	4.10	Dec. 15	5.22
1905	4.11	Dec. 1	5.52	1916	4.21	Feb. 28	5.32
1906	4.17	Dec. 8	5.72	1917	3.99	Dec. 11	5.52
1907	3.97	Jan. 21, 23	4.82	1918	3.99	Mar. 11	5.92
1908	4.27	Feb. 2	5.42	1919	4.04	Mar. 29	6.82
1909	4.35	Feb. 1	5.42	1920	4.09	Feb. 27	5.82
1910	4.32	Feb. 7	6.32				
Sums	41.79		55.20	Sums	42.19		60.00
Means	4.18		5.52	Means	4.22		6.00

As in preceding tables the 20-year period of observations is divided into two 10-year groups. For the first group, 1901–1910, we get a mean value of 4.18 feet and for the second a value of 4.22 feet for the plane of average extreme low water below mean river level. Here again there is an indication that there has been a lowering in the plane of low water, and the amount of decrease agrees almost exactly with that for the plane of mean low water. Between highest and lowest values of the yearly averages there is a difference of approximately 0.7 foot, the highest value occurring in 1913 when the plane of extreme low water fell to 4.61 feet below river level. The plane of average extreme low water may be taken as the mean of the 20 years of observations, or 4.20 feet, from which we find that the plane falls 50 per cent further below mean river level than does the plane of mean low water.

The lowest low water during the period 1901 to 1920 occurred on March 29, 1919, when the low water fell to 6.82 feet. This represents a distance below mean river level 144 per cent greater than that of mean low water. Between the highest and lowest individual values of the extreme low waters we find a difference of exactly 2 feet; and between the highest and lowest values of yearly averages there is a difference of 0.69 foot. It is evident from Tables 16 and 22 that extreme tides occur mostly during the winter months.

12. THE PLANE OF MEAN TIDE LEVEL

Mean tide level may be defined as the plane lying midway between the planes of mean high water and mean low water, and is determined by taking the average of the low waters and high waters over a considerable period of time. If high water and low water were symmetrical with respect to mean river level, tide level and river level would be identical. For an outside station these two planes are almost identical, but for a river station there appears to be considerable difference between the two planes. This fact may be attributed to the difference in character of the tide curve for a river station. At Philadelphia a comparison of the yearly values of river level and tide level will show a very nearly constant relation. From 20 years of observations it is found that the plane of mean tide level is 0.16 foot below the plane of mean river level. The above value may be derived directly from mean high and low water planes by taking half of the difference between the two.

It is obvious that the graph of annual variation of mean tide level will follow closely that of mean river level and that both curves will exhibit the mean of annual variation of the high and low water planes.

13. THE RANGE OF THE TIDE

Range of tide is the difference in height between high and low waters, and the mean range of tide may be defined as the difference in height between the plane of mean high water and the plane of mean low water. Various ranges, may therefore, be obtained from the preceding high and low water tables.

It is seen from Table 1 that the range of tide exhibits similar variations during a month as do the other tidal constants. Table 23 gives the yearly range of tide at Philadelphia from 1901 to 1920, divided into two 10-year groups.

TABLE 23.—*Range of tide, Philadelphia; annual means, 1901 to 1920*

Year	Feet	Year	Feet
1901	5.23	1911	5.30
1902	5.34	1912	5.33
1903	5.29	1913	5.28
1904	5.22	1914	5.18
1905	5.23	1915	5.23
1906	5.28	1916	5.12
1907	5.22	1917	5.07
1908	5.28	1918	5.03
1909	5.25	1919	5.16
1910	5.22	1920	5.26
Sum	52.56	Sum	51.96
Mean	5.26	Mean	5.20

The values in Table 23 are obtained by subtracting the yearly values of low water, referred to staff, from the corresponding values of high water; or they may be obtained by adding the yearly heights of high water above river level to the heights of low water below river level. The yearly means corrected for longitude of the moon's node are given in Table 24.

TABLE 24.—*Mean range of tide, Philadelphia; annual means corrected for longitude of moon's node*

Year	Feet	Year	Feet
1901	5.13	1911	5.43
1902	5.20	1912	5.48
1903	5.13	1913	5.46
1904	5.06	1914	5.32
1905	5.09	1915	5.34
1906	5.16	1916	5.20
1907	5.15	1917	5.10
1908	5.26	1918	5.01
1909	5.28	1919	5.08
1910	5.30	1920	5.14
Sum	51.76	Sum	52.56
Mean	5.18	Mean	5.26

In Table 24 the corrected mean range of tide for the period 1901–1910, is 5.18 feet, and for the period 1911–1920, it is 5.26 feet. It appears, therefore, that the range as determined from the latter period is 0.08 foot greater than the earlier period. The mean of the two groups, or 5.22 feet, may be accepted as the mean range of tide at Philadelphia. As in the case of the tidal planes there appears to be a regular seasonal change or periodicity in the range of the tide. Figure 8 represents the variation graphically for the periods 1901–1910 and 1911–1920.

It is apparent from a glance at the figure that for both the period 1901–1910 and 1911–1920, the curves of annual variation are similar and that for the latter period the heights are consistently greater. The graphs resemble in many respects that of the annual variation in high water. If we were to plot the annual variation of this same plane for a station not influenced by river tides we would find little or no seasonal change. We may therefore attribute the annual

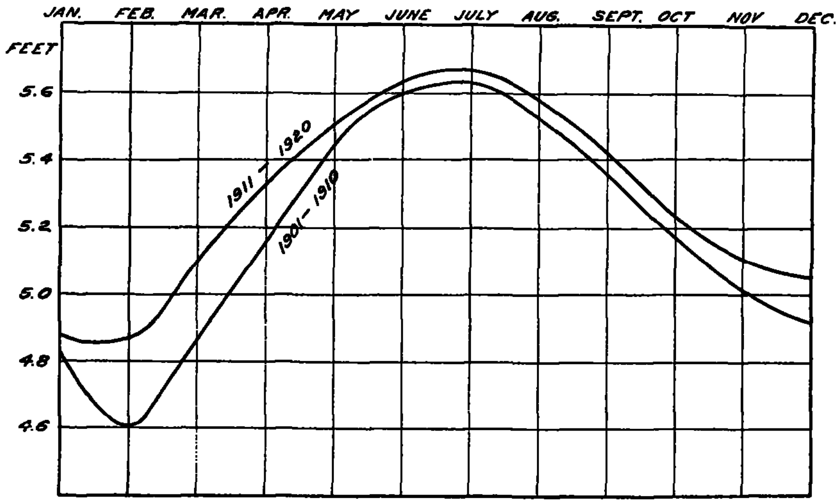

FIG. 8.—Annual variation in range of tide, Philadelphia

variation of range as produced largely by river conditions. In another section of this publication it will be shown that the farther up the river, the greater will be the annual variation of range of tide. Since range of tide is by definition the difference between high and low waters the mean of the two curves represented in Figure 8 will therefore be the difference between Figures 6 and 7.

It is apparent that Figure 8 resembles Figure 6 more closely. The lowest range occurs during the month of February and the highest during the month of July. Between the maximum and minimum heights of the annual variation of range there is a difference of almost a foot. That the annual variation of range is closely allied to the river discharge will be shown later.

In the tables of tidal data further on in this volume, use is made of this annual variation in the reduction of observed ranges to their mean values for stations where no simultaneous comparison with a standard station is possible. By applying to the observed range a factor depending upon the time of observation we are able to get a close approximation to the mean range for the particular station in question.

From the definition of range of tide it follows that for the various high and low water planes due to the variations in the positions of the sun and moon with respect to the earth, there will be corresponding ranges; and likewise for the planes produced by varying meteorological conditions there will also be corresponding ranges. These ranges are mean range, spring range, neap range, perigean range, apogean range, great diurnal range, small diurnal range, great tropic range, small tropic range, extreme range, and greatest range. The designations of spring, neap, perigean, and apogean ranges are evident from the definitions of the high and low water planes of the same name and need no further description.

Great diurnal range is the difference between the planes of higher high water and lower low water. Small diurnal range is the difference between the planes of lower high water and higher low water. Great tropic range is the difference between the planes of tropic higher high water and tropic lower low water. Small tropic range is the difference between the planes of tropic lower high water and tropic higher low water. Extreme range is the difference between the planes of extreme high water and extreme low water, and greatest range is the difference between highest observed high water and lowest observed low water.

Table 25 gives the values for the more important of these ranges at Philadelphia. These values are derived from the high and low water planes of the preceding sections.

TABLE 25.—*Tidal ranges, Philadelphia, Pa.*

	Feet		Feet
Mean range	5. 22	Small tropic range	4. 46
Spring range	5. 51	Extreme range	8. 27
Neap range	4. 81	Greatest range	13. 50
Great tropic range	5. 71		

In the above table the best known values for Philadelphia are shown. The mean range is the mean of the 20 years of observations from 1901 to 1920. Spring, neap, great tropic, and small tropic ranges are based on the two years of observations from 1901 to 1902, and the extreme range and greatest range are based on the 20 years of observations from 1901 to 1920.

14. HARMONIC CONSTANTS

Harmonic constants are used primarily in the prediction of tides for the various ports of the world and are based on an analysis of the hourly heights of the tide. In the Coast and Geodetic Survey the derived constants are used to give settings on the tide-predicting machine, by which the tide is predicted for many places. Harmonic constants can be used also in the determination of the tidal planes and in deriving the ages of the tide.[3]

At Philadelphia harmonic analyses of the hourly ordinates of tide have been made for the years 1901 and 1902. The length of series in each case is 369 days. Table 26 gives the mean value

[3] For a discussion of harmonic analysis see Harmonic Analysis and Prediction of Tides, by Paul Schureman, U. S. Coast and Geodetic Survey, Special Publication No. 98.

for the various constants based on the two years. In the table the amplitudes of the components are given in column headed *H* and the epochs in column headed *κ*.

TABLE 26.—*Harmonic constants, Philadelphia*

[Values in parentheses have been inferred from other constants]

Component	1901		Component	1901		Component	1901	
	H	*κ*		*H*	*κ*		*H*	*κ*
	Feet	*Degrees*		*Feet*	*Degrees*		*Feet*	*Degrees*
J_1	(0.020)	(225)	N_2	0.388	28	S_4	0.006	344
K_1	0.316	218	2N	(0.052)	(7)	S_6	0.007	22
K_2	0.091	78	O_1	0.252	203	T_2	(0.019)	(88)
L_2	0.210	61	OO	(0.011)	(233)	λ_2	(0.017)	(67)
M_1	0.025	329	P_1	0.098	209	μ_2	0.120	171
M_2	2.367	49	Q_1	(0.049)	(195)	ν_2	0.147	22
M_3	0.018	195	2Q	(0.007)	(188)	ρ_1	(0.010)	(196)
M_4	0.368	7	R_2	(0.003)	(88)			
M_6	0.112	206	S_1	----	----			
M_8	0.069	156	S_2	0.315	88			

As noted above the ages of the tide may be derived from harmonic constants. The formulas for the various ages are given below:

Phase age, in hours ---------- $0.984\ (S_2° - M_2°)$
Parallax age, in hours ---------- $1.837\ (M_2° - N_2°)$
Diurnal age, in hours ---------- $0.911\ (K_1° - O_1°)$

As previously defined the phase age of the tide is the interval by which spring tides follow new or full moon, or the interval by which the neap tide follows the moon's first or third quarter. From the above formula we derive for the phase age of the tide at Philadelphia 38.4 hours.

The parallax age of the tide is the interval by which perigean and apogean tides follow, respectively, the times when the moon is in perigee and apogee. From the formula above we derive for the parallax age at Philadelphia 38.6 hours.

The diurnal age of the tide is the interval by which the tropic tide follows the moon's semi-monthly maximum north and south declination. We derive for Philadelphia from the formula above a value of 13.7 hours as the diurnal age of the tide.

15. EFFECTS OF WIND AND WEATHER

In the foregoing sections we found that the planes of extreme high water and extreme low water and the extreme range of tide were much greater than the average. The plane of extreme high water rose 1½ feet above mean high water; the extreme low water plane likewise fell 1½ feet below mean low water, and the extreme range was 3 feet greater than the mean range. It was also shown that the spring and tropic tides are somewhat greater than the average. From harmonic constants the perigean tide is also found to be somewhat greater than the average. Assuming that to the average high water and to the average low water is applied the increase which would be brought about by a coincidence of a spring tide, a perigean tide, and a tropic tide, it would be found that the high water and low water planes thus produced would be approximately 1 foot less than the extreme high and low water planes, and the range would be approximately 2 feet less than the extreme range. It is evident, therefore, that the extreme tides must be due to other than astronomic causes.

If we investigate the meteorological conditions at the times of the extreme tides represented in Tables 16 and 22 we find in the majority of cases high winds or sudden changes in barometer or both. We may, therefore, conclude that the planes of extreme high and low waters are produced largely by wind and weather. It is to be noted further that in almost every case the highest and lowest tides were confined largely to the winter months when storms are most prevalent, and that the highest high waters generally occurred with an easterly wind and a falling barometer, and the lowest low waters occurred when the wind was blowing from the northwest and the barometer had been low and was rising. At times, however, we find that the extreme tides occur with a normal barometric pressure, strong winds alone producing the effect on the tide. If we refer to Figure 1, showing the Delaware Waterway, it is evident that a northwest wind tends to blow the water out of the river and therefore produce a tide lower than usual, and an east wind tends to drive the ocean waters up the bay and river and thus produce a high water that is higher than usual. Likewise an increasing barometric pressure tends to lower the low water and a decreasing barometric pressure tends to raise the high water.

It is observed during storms that corresponding to a lowering of the plane of low water there is generally a lowering of the plane of high water and corresponding to a rise in the plane of high water there is generally a rise in the plane of low water. The effect of the storm therefore is to raise or lower the river level, and this brings about higher or lower high and low water planes.

Not only are the tidal planes affected by wind and weather but the range and time of tide are also changed, as the following considerations show.

The lowest low water at Philadelphia during the period 1901 to 1920 occurred on March 29, 1919, at about 8 a. m., and resulted from strong northwest winds which began to blow with considerable force the day previous and reached a maximum velocity of 36 miles per hour at noon on the 29th. On the 26th the barometer began dropping and reached the lowest level of 29.45 on the evening of the 27th, or approximately 36 hours prior to the extreme low water recorded. The barometer then began to rise and on the 29th it was well on the upward trend. From a height of 7.4 feet on the 27th the river level began a sharp decline reaching a minimum of 2.35 feet on March 29, representing a drop of over 5 feet in 36 hours. Coincident with the fall of river level we find that the low water and high water planes also fell, the former dropping approximately 5 feet and the latter 4½ feet. It is evident, therefore, that the effect of the storm was to lower the plane of river level and consequently the planes of low and high water.

Considering now the range of tide, we find that the low water in question, which corresponded to a staff reading of −0.3 foot, fell 4.4 feet from the preceding high water and rose 5.1 feet to the succeeding high water. From the predicted tides the above ranges should have been 5.2 feet and 5.8 feet, respectively. We see, therefore, that the range of tide was decreased approximately three-fourths foot because of the storm. An examination of the range of tide for the day preceding the storm shows a range of 2.8 feet from the high and low water on the night of the 28th, which compared with a calculated range of 5.1 feet, or a difference of 2.3 feet. For the entire period of the storm the average decrease of range was approximately 1½ feet. We see, therefore, that the storm also has a pronounced effect on the range of tide. This was to be expected, since it was previously shown that the river level passed through a curve of annual variation similar to that of the range of tide, and, therefore, any effect of river level would be reflected in the range of tide.

Still another effect of the storm is seen from a comparison of the actual and calculated times of tide. On March 29 the calculated time for the low water was 6:30 a. m., and the observed time was 7:42 a. m. The actual time of tide, therefore, was approximately 1¼ hours later than the predicted time. For the calculated times of low and high waters on the evening of the 28th we have 6:09 and 11:17 p. m., respectively, and for the corresponding observed times we have 8:18 and 11:42 p. m. Between the predicted and observed times of low water there is a difference of more than two hours, and between the predicted and observed times of high water a difference of nearly half an hour, the observed tide in each case occurring later. For the entire period of the storm the low water occurred approximately 1½ hours later and the high water approximately one-half hour later than the predicted tides. It is seen, therefore, that not only is there a lowering of the low water plane but a change in time of tide, the greatest effect being on the time of low water.

From the above facts it is obvious that since the time of low water is delayed approximately one hour more than the time of high water, the duration of rise must be decreased and the duration of fall increased by a similar amount. For the 28th a duration of rise of about 3 hours and a duration of fall of 10 hours is derived. Under normal conditions the duration of rise should have been approximately five hours, and the duration of fall approximately seven hours.

The highest high water during the period 1901 to 1920 occurred at 4.55 p. m., on October 11, 1903, when a height of 6.7 feet above mean river level was recorded. A study of the meteorological conditions shows that on the 9th the barometer dropped to 29.63 and remained near this level during the storm. Although the wind blew for several days from the northeast at Philadelphia with a maximum velocity of 37 miles per hour, the wind at the entrance to the bay was from the east, driving the ocean waters into the bay and river.

As in the case of the northwest storm the entire tidal régime was disturbed. Considering the river level we find that it rose from a height of 6.9 feet on staff on October 9 to 11.0 feet on the 11th, or approximately 4 feet. Coincident with the rise of river level we find for the same period that the high water plane and low water plane also rose, the former rising approximately 4 feet and the latter approximately 5 feet. Here again it is observed that the effect of the storm was to greatly change the river level and consequently the high and low water planes. It is to be noted that here, too, the storm had a greater effect on the low water plane than on that of high water. For the particular high water in question we find that the undisturbed height of this tide should have been 3.7 feet above river level. Comparing this with the actual height of 6.7 feet we find that the tide rose 3.0 feet above the predicted height.

For the range of tide it is found that the high water, corresponding to a staff reading of 13.2, rose 3.7 feet from the preceding low water and fell 4.5 feet to the following low water. From the predicted tides these ranges should have been 5.8 and 6.0 feet. For the entire period of the storm it is found that the average decrease of actual range over the calculated was more than 1½ feet. If we examine the times of tide, it will be found that for the highest tide observed during the storm the high and low waters were but little affected.

In the previous discussion it was shown that in both the northwest storm and the easterly storm the entire tidal régime was disturbed. From a study of the highest and lowest tides represented in Tables 16 and 22, it appears that as a general rule the plane of river level and consequently the plane of high water and the plane of low water is

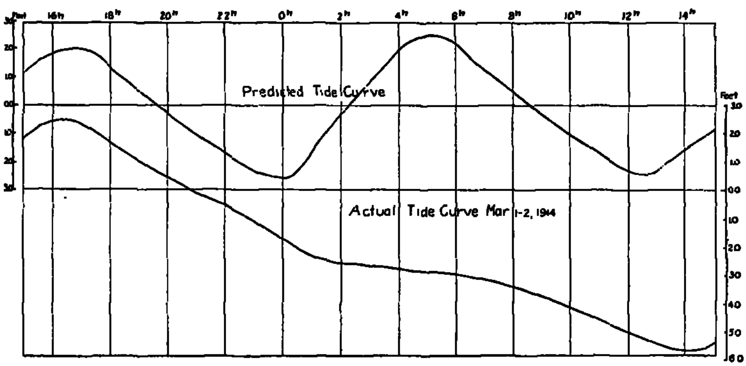

FIG. 9.—Predicted and observed tide curves, Philadelphia, March 1-2, 1914

either increased or decreased according to whether the wind is blowing up or down the waterway, and that the range of tide is decreased and the time of the tide occurs later when the storm winds are from the north sector.

In the above cases representing highest high water and lowest low water the times and heights of tide were altered by the storms, but the general shape of the tide curve was not changed appreciably, there being two high waters and two low waters on each day.

An interesting case in which the entire tidal régime has been altered and the shape of the tide curve consequently greatly modified, is shown in Figure 9. During the blizzard at Philadelphia in March, 1914, the wind began blowing from the northwest on March 1, at the rate of 25 miles per hour and at 6 a. m., on March 2 it reached a velocity of 40 miles which was maintained for a considerable period.

In Figure 9 is shown the tide curve registered on automatic tide gauge at Philadelphia during the height of storm, together with the predicted or calculated curve. The horizontal lines represent mean river level. An inspection of the figure shows a conspicuous difference between the two curves, there being registered by the automatic gauge but one high and one low water during the 24 hours when normally there should have been two high waters and two low waters. The effect of the storm was to drive the water out of the river and bay and thus tend to nullify the tide. It is seen that the tide began to fall at 4 p. m. on March 1 and continued to fall until 2 p. m. on March 2, a duration of fall of 22 hours. During most of the time the height of tide was below mean river level. The average river level on staff for March 2 was 2.64 feet, compared with 6.53 feet for mean river level. In other words, it dropped almost 4 feet below normal and for the particular day in question it was 1 foot below the plane of mean low water. The tide above discussed is extremely unusual, the general effect being as previously described.

16. SUMMARY OF TIDAL DATA

In Table 27 is given a summary of tidal data for Philadelphia as derived and discussed in the foregoing section. It is to be noted that while the more important constants are based on 20 years of observations, the spring, neap, and tropic ranges and planes are derived from but 2 years of observations and can therefore be taken only as approximate values.

TABLE 27.—*Tidal data, Philadelphia*

TIME RELATIONS	Hours
High-water interval	1. 49
Low-water interval	8. 97
Duration of rise	4. 93
Duration of fall	7. 49
Phase age	38. 4
Parallax age	38. 6
Diurnal age	13. 7
RANGES	Feet
Mean range	5. 22
Spring range	5. 51
Neap range	4. 81
Great tropic range	5. 71
Small tropic range	4. 46
Extreme range	8. 27
	Ratios
Greatest range	13. 50
Spring range÷mean range	1. 05
Neap range÷mean range	0. 92
Great tropic range÷mean range	1. 09
Extreme range÷mean range	1. 58
Greatest range÷mean range	2. 59
HEIGHT RELATIONS	Feet
Mean high water above mean river level	2. 46
Spring high water above mean river level	2. 68
Neap high water above mean river level	2. 15
Tropic higher high water above mean river level	2. 76
Tropic lower high water above mean river level	1. 80
Extreme high water above mean river level	4. 08
Highest high water above mean river level	6. 68
Mean low water below mean river level	2. 77
Spring low water below mean river level	2. 83
Neap low water below mean river level	2. 66
Tropic lower low water below mean river level	2. 96
Tropic higher low water below mean river level	2. 67
Extreme low water below mean river level	4. 20
Lowest low water below mean river level	6. 82
Mean tide level below mean river level	0. 16

THE TIDE IN DELAWARE BAY

The earliest observations of the tide in Delaware Bay on record in this office were made in 1836 at Cape May landing. From this time on, scattered tidal observations were made on staff or tape gauges at various places along the bay. In 1919 an automatic gauge was established on the Government Pier at Lewes and was operated

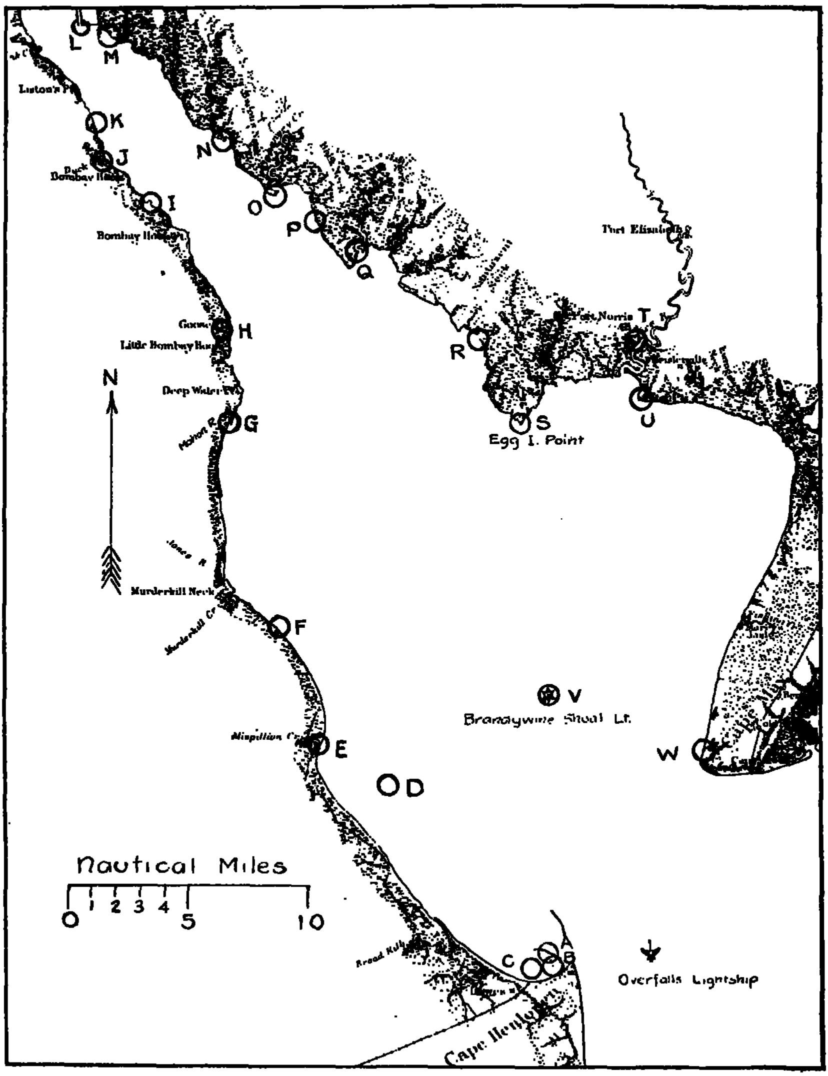

FIG. 10.—Tide stations, Delaware Bay

with slight interruptions until 1923. This series of four years represents the best obtained in Delaware Bay. There are also two other series for Government Pier given in Table 28, four months, 1883–84, and three months, 1910–1914. In comparing the values for the different series slight differences are observed. While there is a close agreement between the 1910–1914 and 1919–1923 series, a slight discrepancy is observed between these and the 1883 series. This difference may in part be accounted for by the breakwater construction work taking place at Cape Henlopen between the earlier and later observations. The agreement between the three series is good, but for the best determined values we may take those resulting from the four-year series.

TABLE 28.—*Tidal data, Delaware Bay*

Station	Locality	Lunitidal intervals		Duration of rise	Mean range	Observations	
		HWI	LWI			Date	Length
	WESTERN SHORE	*Hours*	*Hours*	*Hours*	*Feet*		
A	Delaware Breakwater	7.88	1.63	6.25	4.16	1863–1868	1 month.
B	Government Pier, Lewes	8.20	1.90	6.30	4.01	1883–84	4 months.
	do	8.28	1.82	6.46	4.10	1910–1914	3 months.
	do	8.28	1.89	6.39	4.11	1919–1923	4 years.
C	Railroad Wharf, Lewes	7.81	1.66	6.15	3.99	1882	4 days.
D	Shoal south of Mispillion River	9.77	2.51	7.26	4.60	1883	2 days.
E	Mispillion Lighthouse	8.72	3.85	4.87	3.84	1883	17 days.
F	Mispillion Neck	8.86	2.69	6.17	4.98	1883–84	24 days.
G	Mahon River Lighthouse	9.94	3.50	6.44	5.64	1841–1843	5 months.
	do	9.39	3.50	5.89	5.31	1883	2 months.
H	Leipsic Creek Entrance	9.49	3.73	5.76	5.44	1882	8 days.
I	Woodland Beach	10.17	4.67	5.50	[1] 5.69	1924	3 months.
J	Duck Creek Entrance	10.40	4.90	5.50	5.08	1841	1 month.
	do	10.35	4.70	5.65	5.50	1882	½ month.
	do	10.34	4.87	5.47	5.89	1910	4 days.
K	Collins Beach	10.59	4.71	5.88	5.67	1881	½ month.
	EASTERN SHORE						
L	Artificial Island	10.41	5.07	5.34	[1] 5.90	1924	3 months.
M	Stony Point	10.47	4.98	5.49	6.03	1900	13 days.
N	Bayside	9.99	4.27	5.72	5.67	1882	16 days.
	do	9.80	4.33	5.47	5.88	1924	25 days.
O	Cohansey River Light	9.72	4.34	5.38	6.13	1841	1½ months.
P	Seabreeze	9.69	3.92	5.77	5.90	1880–1882	1½ months.
Q	Back Creek Entrance	9.08	3.28	5.80	5.65	1882	5 days.
R	Fortescue Beach	9.06	3.17	5.89	6.00	1880–1882	1 month.
S	Egg Island Light	9.15	3.24	5.91	5.79	1841–42	2 months.
	do	8.81	2.83	5.98	5.77	1867–1885	18 days.
T	Port Norris	9.08	3.30	5.78	5.68	1885	11 days.
U	Maurice River Light	8.80	2.84	5.96	5.60	1884–85	2 months.
V	Brandywine Light	8.22	2.25	5.97	4.85	1914	5 days.
W	Cape May Steamboat Landing	7.83	1.97	5.86	4.65	1836	1 month.
	do	7.91	1.74	6.17	4.74	1867	10 days.
	do	8.29	1.91	6.38	4.78	1883	3 days.
	do	8.16	1.90	6.26	4.71	1885	1 month.

[1] Range based on two and one-half years of high and low waters.

In Table 28 is given high water interval, low water interval, duration of rise, and mean range for the various tidal stations. The table is divided into two parts, the first containing stations on the western shore and the second containing stations on the eastern shore. Figure 10 shows the location of the stations. Where it was possible to do so the best mean values were obtained by a comparison with simultaneous observations at a standard station such as Delaware Breakwater, Fort Hamilton, Sandy Hook, etc. In many cases, however, this was not possible, and to get the closest approximation to mean values use was made of the phenomena of the annual variations of lunitidal intervals and range of tide. From Figures 2 and 8 it was evident that both the range and lunitidal intervals varied from month to month throughout the year. By observing the amount which each monthly value is above or below the mean, we may obtain factors by which a short series of observations can be corrected to give a generally closer approximation to mean value. Through the use of this method were reduced all those series of observations which could not be compared simultaneously with standard stations.

Curves showing annual variation were drawn for all tidal stations along the waterway where sufficient data was at hand. In order to determine the annual variation at any particular station, an interpolation was made of values from these curves. The various curves will be shown elsewhere in this volume.

From a study of the data represented in Table 28 it will be seen that both the time and range of tide increases from the Capes.

Between Government Pier, Lewes, Del., and Artificial Island the two extremities of this section of the waterway, a distance of approximately 42 nautical miles, the range increases from 4.11 feet at the former place to 5.90 feet at the latter, and the high water interval increases from 8.28 to 10.41 hours. Hence it is seen that not only is there a difference of range between the two extremities but also a difference in time of tide. If only the time of tide changed, and the range remained much the same throughout, we would expect a progressive type of wave. If, on the other hand, the time differed but little, and only the range changed, we would expect a stationary type of wave. However, from the tidal data it is evident that both time and range change from one extremity of the waterway to the other, and we must, therefore, look for a combination progressive-stationary type of wave.

For a body of water to support a stationary tidal wave its period of oscillation should be nearly the same as that of the tide, or approximately 12 hours. If we determine the period of the bay from the formula

$$T=\frac{4L}{\sqrt{gh}}$$

in which L = length of body of water or approximately 255,000 feet, g = acceleration of gravity or 32.2 feet per second, and h = average depth of water or 23.2 feet, we get 11.1 hours. This aproximates to the period of oscillation of the tide, and the body of water will, therefore, support a stationary wave.

The reason for the stationary features has been brought out, and if in the formula for a progressive wave $v=\sqrt{gh}$ in which v = velocity of tide, g = acceleration of gravity and h = average depth of waterway we apply the values given above, a velocity of 27.3 feet per second is obtained for the rate of progress of the tidal wave. As the distance between the two extremities of the waterway is approximately 255,000 feet, the time that it should take for the tidal wave to be propagated from Delaware Breakwater to Artificial Island—the two extremities of the waterway—should be approximately 9,300 seconds. As determined from Table 28 the actual time of propagation of the tidal wave is 8,200 seconds.

From the above we see that the actual tide agrees closely in time of propagation with the progressive type of wave and the heights agree with the stationary type. We may conclude, therefore, that the type of tide in the waterway is a combination of the stationary and progressive wave types.

Due to the rotation of the earth there is a tendency to deflect all moving bodies to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. We would therefore expect in the Delaware Bay that on the flood tide the water would be deflected to right, or east shore, and high water would therefore be higher on this bank, and on the ebb tide the water would again be deflected to the right, or this time to the western shore, and therefore the low water would be higher here. It is evident from the above considerations that the tide should rise higher and fall lower on the eastern, or New Jersey shore, and hence the range should be greater on this shore.

Comparing the actual tidal ranges on the two shores relative to the axis of the waterway, we find that the range on the New Jersey shore is considerably greater. The theoretical amount, in feet, by which the ranges on the two banks of a tidal stream differ is represented by the formula [4] $3\frac{vd \sin \phi}{g}$ in which v = velocity of the water in knots; d = width of waterway in nautical miles, ϕ = the latitude, and g = acceleration of gravity in feet per second. For a waterway of considerable width and varying depth, such as the Delaware Bay, this formula can only be taken as approximate.

Between Cape May and Cape Henlopen there is a distance of approximately 10 nautical miles, and the average current at the time of high and low water is about 1 knot. The latitude at the middle of the section across the Capes is 38° 52′ and the sine of this angle is 0.63. Applying these values in the formula above we have for the calculated difference in range between Cape Henlopen and Cape May 0.65 foot. From Table 28 the actual difference in range of tide, as represented by stations B and W, is 0.60 foot. Considering now a section across Bayside, where the bay has narrowed considerably, we find that the difference in range between the two shores, as determined from the formula above agrees fairly well with that of the actual range, as determined from stations at Woodland Beach and Bayside. In this case $v = 1.3$ knots, $d = 4$ miles and $\phi = 39° 23′$. Applying these values in the formula we get a calculated difference in range between the two sides of 0.31 foot. From Table 28 the actual difference as represented by stations N and I is found to be 0.20 foot.

Since the width of bay and strength of current vary for different sections, the difference in range between the two shores will differ throughout the bay. This feature may best be seen from Figure 11.

In the figure are shown two curves, one representing the range of tide on the Delaware side of the bay, and the other, that on the New Jersey side. These curves are based on the data presented in Table 28, the initial point of both curves being taken at Five-Fathom Bank, about 13 miles outside the Capes. It is apparent that the difference in range between the two sides increases as we go up the bay, reaching a maximum of approximately 1 foot at a section about 15 miles from the Capes, whence it begins to decrease until at a section through Stony Point the difference between the two banks is but 0.2 foot, approximately. Beyond this point the river contracts sharply and there is no appreciable difference in range. By comparison of Figures 10 and

[4] See U. S. Coast and Geodetic Survey, Special Publication No. 111, Tides and Currents in New York Harbor, p. 68.

11 it is evident that as the width of the bay increases the difference in range increases, and as the width of the bay decreases the difference in range between the two sides decreases.

Referring again to Table 28 we have for Station B, Government Pier, Lewes, Del., 8.28 hours for the high water interval, 1.89 hours for the low water interval, with a resulting duration of rise of 6.39 hours. For Artifical Island we have 10.41 for the HWI and 5.07 for the LWI, with a resulting duration of rise of 5.34 hours. It will be seen that while the HWI increased 2.13 hours, the LWI increased 3.18 hours, or over one hour more than the HWI, resulting in the decreased duration of rise noted. The mean time of tide between

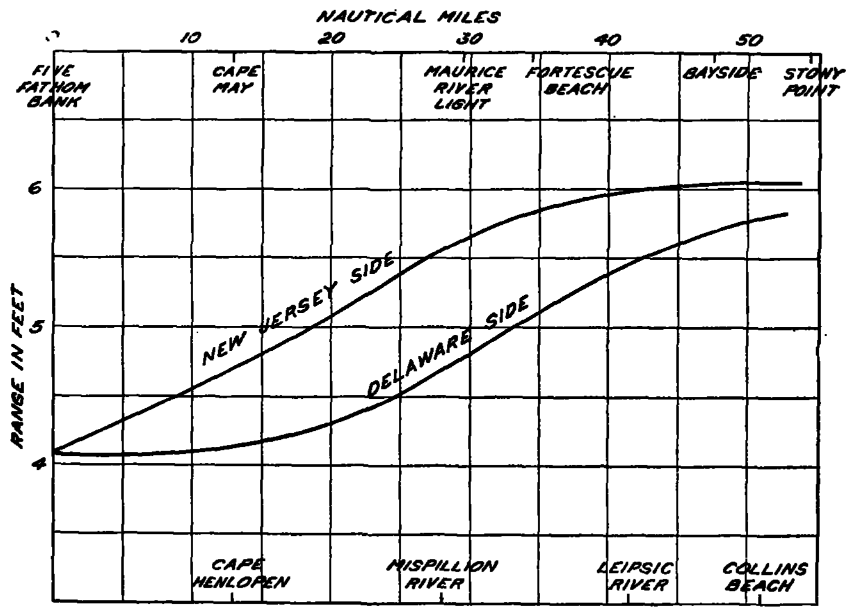

FIG. 11.—Range of tide on two sides of Delaware Bay

Delaware Breakwater and Artificial Island may be taken as 2.7 hours, the correction for difference in longitude being small. An explanation of the difference between the rate of change of the HWI and LWI may be had in the following. As the tidal wave is propagated up the bay, it meets an obstacle in the river water seeking its way to the ocean. The current produced by the freshets therefore tends to retard the time of low water, decreasing the duration of rise.

In a previous section it was pointed out that for Philadelphia there was an annual variation of the entire tidal régime. The same phenomena are observed in the Delaware Bay, although not to such a marked degree as in the river.

TABLE 29.—*Tide level in feet, Delaware River; annual variation*

Month	Delaware Breakwater[1]	Woodland Beach[2]	Artificial Island[2]
	Feet	*Feet*	*Feet*
January	3.91	2.72	2.40
February	4.11	2.95	2.80
March	4.04	2.93	3.20
April	4.20	3.07	3.50
May	4.40	3.17	3.57
June	4.32	3.15	3.55
July	4.34	3.20	3.60
August	4.42	3.26	3.58
September	4.46	3.35	3.70
October	4.34	3.25	3.46
November	4.38	3.15	3.42
December	4.22	2.95	3.12
Mean	4.26	3.10	3.33

[1] Referred to 0 of staff.
[2] Referred to 0 of precise levels run by United States Engineers, 1911–1913.

Table 29 gives the annual variation in tide level at three stations where the tidal observations were of sufficient length to determine these data. The values given for Delaware Breakwater were determined from series 1919–1923, for Woodland Beach 1922–1924, and for Artificial Island from 1921–1924. At Delaware Breakwater the heights are referred to the zero of staff at that place, while at the other two stations the heights are referred to the zero of a line of precise levels extending from Woodland Beach to Trenton. In each case it will be observed that the lowest level occurs in January and the highest in September, and varies during the year 0.55 foot at Delaware Breakwater, 0.63 foot at Woodland Beach, and 1.30 feet at Artificial Island. A comparison of the mean values for Woodland Beach and Artificial Island brings out the fact that the mean tide level for the year is 3.10 feet for the former station, and 3.33 feet for the latter, or a difference of 0.24 foot. Since the two stations are referred to the same zero the planes are directly comparable and the results therefore indicate a higher level at the upper station.

TABLE 30.—*Annual variation of river level, Station B, Government Pier, Lewes, Del.*

Month	River level	Month	River level	Month	River level
	Feet		*Feet*		*Feet*
January	3.94	June	4.17	November	4.25
February	3.97	July	4.20	December	4.08
March	3.85	August	4.28		
April	4.06	September	4.33	Mean	4.13
May	4.20	October	4.21		

In Table 30 is shown the annual variation of river level at Lewes, Del. From an inspection of the data it appears that the river level is a minimum in March and a maximum in September, and the greatest difference in level during the year is about 0.5 foot. The mean value of river level is derived as 4.13 feet on staff. For this same period of time a value of 4.10 is derived for the mean value of tide level, or 0.03 foot less than river level. This corresponds exactly to the difference between these planes at Atlantic City, which is located on the open coast. It was noted in a previous section that at Philadelphia the plane of mean river level is 0.16 foot greater than mean tide level and, as previously explained, is to be attributed to river conditions.

For the series 1919–1923 at Government Pier, Lewes, Del., the highest high water occurred on January 29, 1922, with a registered height of 9.3 feet and the lowest low water occurred on March 28, 1919, when a height of −0.8 foot was registered. The greatest range of tide as determined from this series is, therefore, 10.1 feet. For this station the mean range of tide, as determined from the same series, is 4.11 feet and the ratio of the greatest range to the mean range is 2.46. The average extreme high water is 8.44 feet and the average extreme low water is 0.16 foot. The extreme range is, therefore, 8.28 feet. The ratio of the extreme range to mean range is 2.01.

For Station B, Government Pier, Lewes, a harmonic analysis of a 369 day series from January 7, 1919, to January 10, 1920, has been made. The results of the analysis are given in Table 31 below.

TABLE 31.—*Harmonic constants, Station B, Delaware Bay*

Component	Station B (Government Pier, Lewes, Del.)		Component	Station B (Government Pier, Lewes, Del.)	
	H	κ		H	κ
	Feet	*Degrees*		*Feet*	*Degrees*
J_1	(0.019)	(132)	P_1	0.104	124
K_1	0.340	125	Q_1	0.035	104
K_2	0.099	272	$2Q$	(0.007)	(98)
L_2	0.076	278	R_2	(0.003)	(264)
M_1	0.010	109			
			S_1	0.034	82
M_2	1.942	240	S_2	0.375	264
M_3	0.012	213	S_4	0.008	309
M_4	0.035	229	S_6	0.002	63
M_6	0.019	261	T_2	0.071	296
M_8	0.003	348			
			λ_2	0.044	298
N_2	0.433	218	μ_2	0.054	203
$2N$	0.057	170	ν_2	0.096	223
O_1	0.260	112	ρ_1	(0.010)	(106)
OO	(0.011)	(139)			

THE TIDE IN LOWER DELAWARE RIVER

Lower Delaware River runs in a general northeasterly direction from Artificial Island to Philadelphia. This section is approximately 40 miles in length, and varies from a width of 3 miles at its lower end to less than one-half mile at Philadelphia. Numerous islands, shoals, and dikes hinder the free movement of the tide in the waterway.

TABLE 32.—*Tidal data, lower Delaware River*

Station	Locality	Lunitidal intervals		Duration of rise	Mean range	Observations	
		HWI	LWI			Date	Length
		Hours	*Hours*	*Hours*	*Feet*		
A	Reedy Island Light, Del	10.69	5.05	5.64	5.77	1875–1881	23 days.
B	Reedy Island Quarantine, Del	10.65	5.27	5.38	5.91	1896–1900	4 years.
	do	10.94	5.57	5.37	[1] 5.56	1924	3 months.
C	Port Penn, Del	11.24	5.02	6.22	5.80	1840	3 days.
	do	10.67	5.35	5.32	5.87	1881–1893	20 days.
D	Delaware City, Del	11.10	5.86	5.24	5.80	1875–1881	1 month.
	do	11.04	5.72	5.32	6.00	1900	8 days.
	do	11.27	5.94	5.33	5.49	1923–25	16 months.
E	Pea Patch Island, Del	11.22	6.09	5.13	6.16	1840	6 days.
	do			5.25	5.90	1880	1 year.
	do	11.11	5.61	5.50	5.75	1881	13 days.
F	New Castle, Del	11.57	6.18	5.39	5.50	1840	5 months.
	do	11.56	6.39	5.17	6.00	1873–1886	½ month.
	do	11.64	6.52	5.12	[2] 5.42	1924	3 months.
G	Pennsville, N. J	11.35	6.22	5.13	5.91	1900	18 days.
H	Christiana Creek Entrance, Del	11.81	6.59	5.22	5.90	1881	12 days.
I	Edgemoor, Del	11.98	6.80	5.18	6.03	1878	2 months
	do			5.08	5.64	1880	7 months.
	do	11.82	6.52	5.30	5.95	1900	13 days.
	do	11.99	6.97	5.02	[3] 5.38	1924	3 months.
J	Marcus Hook, Pa	12.25	7.29	4.96	6.06	1878–79	1 year.
	do	12.03	7.36	4.67	6.08	1881	10 days.
	do	0.09	7.42	5.09	5.51	1915–16	1 year.
	do	0.08	7.44	5.06	[4] 5.41	1924	3 months.
K	Chester, Pa	0.37	7.80	4.99	6.08	1866–1870	1 month
L	Baldwins, Pa	0.52	7.86	5.08	[3] 5.28	1924	13 months
M	Essington, Pa	0.57	8.04	4.95	5.83	1881	23 days.
N	Billingsport, N. J	0.79	8.14	5.07	6.02	1881	23 days.
O	Hog Island, Pa	0.59	8.17	4.84	5.22	1918–19	17 months.
P	Fort Mifflin, Pa			4.92	5.93	1879–80	14 months
	do	0.83	8.33	4.93	5.88	1882–83	6 months.
	do	0.96	8.37	5.01	[3] 5.17	1924	3 months.
Q	Red Bank, N. J	0.80	8.13	5.09	5.82	1861	6 days.
R	League Island, Pa	0.80	8.23	4.99	6.17	1865–1878	5 months.
	do	0.64	8.22	4.84	5.82	1881–1889	10 days.
	do	0.95	8.40	4.97	5.26	1919	1 year
S	Gloucester, N. J	1.06	8.45	5.03	6.00	1870	24 days

[1] Range based on 3 years of high and low waters.
[2] Range based on 8½ years of high and low waters.
[3] Range based on 2⅔ years of high and low waters.
[4] Range based on 9⅔ years of high and low waters.

Table 32 gives the results of observations dating back to 1840. The longest series is at Reedy Island, where four years of continuous observations were made on an automatic gauge between the years 1896–1900. In connection with the various harbor improvement projects being carried on by the United States Engineers, automatic tide gauges have been maintained (among other places) for the past few years at Reedy Island, New Castle, Edgemoor, Marcus Hook, Baldwins, and Fort Mifflin. In Table 32, for the above-mentioned stations the range is determined from all high and low waters, while the HWI, LWI, and duration of rise are based on the observational data obtained from the gauges during July, August, and September, 1924. All data is reduced to a mean value by simultaneous comparison with the standard station at Philadelphia. Since the station at Philadelphia was not established until 1900, it was found advisable to make use of curves of annual variation previously mentioned, to reduce short series of observations made prior to this time to best mean value.

In examining the data in Table 32 several striking features are observed, one of which is the wide difference in the range of tide between the earlier and later series. For example, for Station B, Reedy Island, Del., the table gives 5.91 feet for the 4-year series 1896–1900 and 5.56 feet for the series 1921–1924, the latter being based on over three years of high and low waters. These values indicate a decrease in range of tide of 0.35 foot between 1900 and 1924.

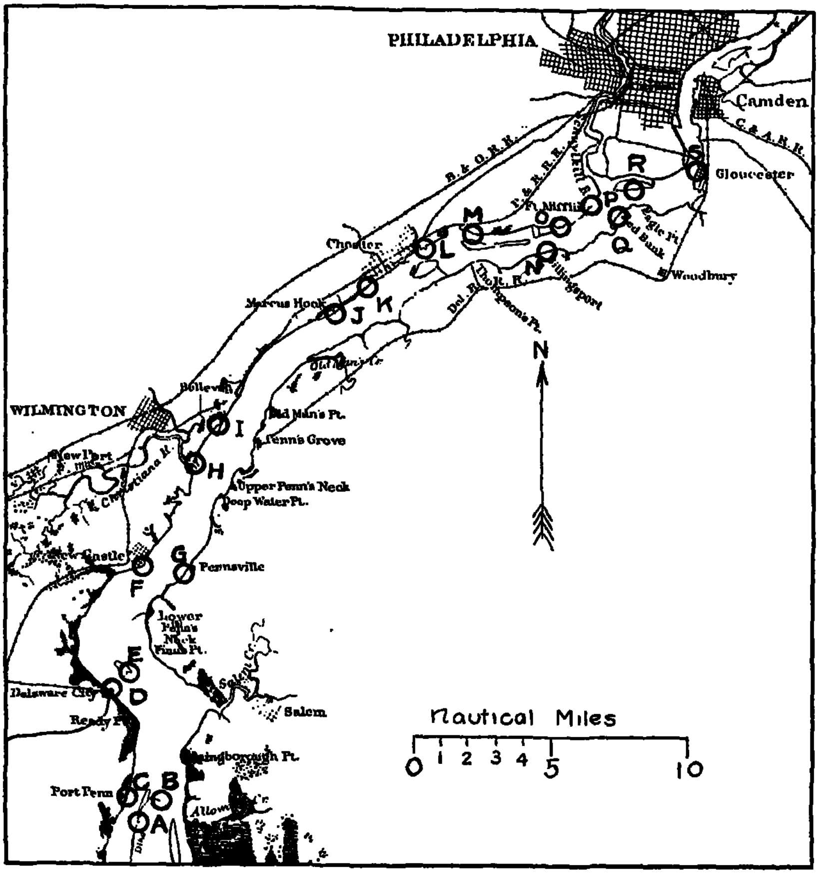

FIG. 12.—Tide stations, lower Delaware River

Examining now Station J, Marcus Hook, we observe the value of the range to be 6.06 feet for the 1-year series of 1878–79, 5.51 feet for the 1-year series of 1915–16, and 5.41 feet for the 9⅔ years of high and low waters prior to 1924. Similarly from values in the table, a progressive decrease in range of tide in recent years is observed for stations at New Castle, Edgemoor, Fort Mifflin, and League Island. Corresponding with this change in range there is also observed to be a change in the tidal datum planes. This is brought out in Table 33.

TABLE 33.—*Changes in tidal datum planes*

Station	Referred to	Series	MTL	MHW	MLW
			Feet	*Feet*	*Feet*
Philadelphia	Staff of 1901	1891–92	6.07	8.91	3.23
		1901–1920	6.36	8.96	3.76
Marcus Hook	Staff of 1878	1878–79	3.12	6.10	0.14
		1915–16	3.42	6.17	0.67
New Castle	B. M. No. 4	1840–1886	13.06	16.04	10.08
		1916–1924	13.70	16.42	10.99

In the table, tidal planes at three stations are compared for the period prior to the year 1892 and for the period following the year 1900. For stations at Philadelphia and Marcus Hook the planes are well determined. It is to be noted that for the series 1901–1920 at Philadelphia the plane of mean tide level increased 0.29 foot, the plane of mean high water 0.05 foot, and that of mean low water 0.53 foot over that of series 1891 to 1892. At Marcus Hook for the one-year series 1915–16 the planes have increased in value over the one-year series of 1878–79, as follows: MTL, 0.30 foot, MHW 0.07 foot, and MLW 0.53 foot. From the above it is evident than changes in tidal planes for the two stations have taken place in recent years, and that the rise in the plane of mean tide level has been accomplished by a rise in the plane of mean low water, the plane of mean high water being little affected. At New Castle, where the observations prior to 1892 are made up of several short series, this conclusion is further substantiated. It will be observed that from the values of the table the MTL has been raised 0.64 foot, MHW 0.38 foot, and MLW 0.91 foot.

Not only have the heights of tide been affected, but here also appears to have been some change in the time of tide. At Reedy Island the HWI increased from 10.65 to 10.94 hours and the LWI from 5.27 to 5.57 hours. At New Castle, Edgemoor, Marcus Hook, Fort Mifflin, and League Island there are likewise indications that the time of tide now occurs later. It appears, then, that the entire tidal régime of the lower Delaware River has been changed somewhat and that a decrease in range of tide has been accompanied by the raising of the low water level, the high water level remaining almost constant. The change in range of tide may be more clearly seen from the following figure.

In Figure 13 is shown the range of tide for the entire Delaware waterway, divided into two periods—from the beginning of tidal observations in 1836 to 1890, and from 1900 until the present time. For Delaware Bay to a point 5 miles north of Woodland Beach there was no noticeable difference in range between the two periods and the curve therefore shows but a single line. However, for Delaware River the ranges as determined from the observations prior to 1890 are as much as 0.7 foot greater than the ranges as determined from observations between 1900 and 1924, inclusive. To have disturbed the tidal régime to such an extent it would be expected that considerable change was made in the physical character of the waterway. If we examine the reports of the Chief of Engineers, United States Army, it is found that during the period 1890–1900 extensive improvements were made throughout the Delaware River.

In its original condition the river presented obstructions at many places along its course. At Mifflin Bar there was but 17 feet at mean low water, at Cherry Island flats and Schooner Ledge 18 feet, at Baker or Stony Point Shoal, Bulkhead Shoal, and Duck Creek Flats about 20 feet. Because of these shoals the controlling depth of the Delaware River to Philadelphia was limited to 17 feet at mean low

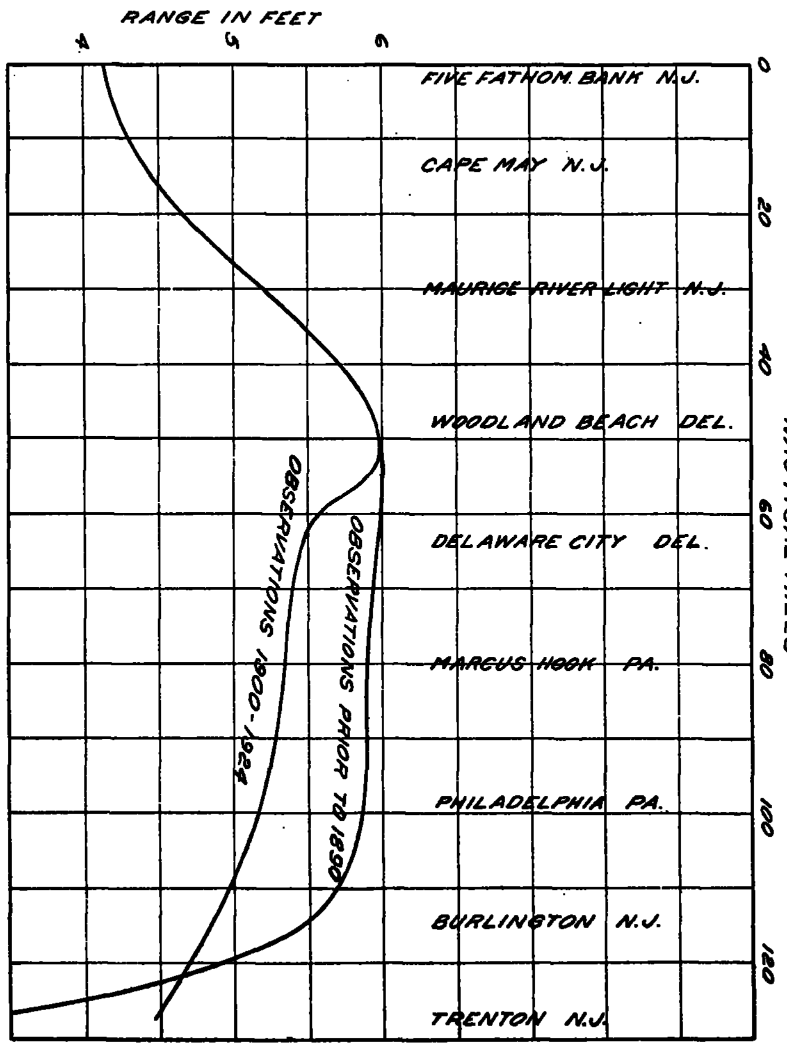

FIG. 13.—Range of tide, Delaware Bay and River

water. A project was started between 1885 and 1890 for the general improvement of Delaware Bay and River to permit deep-draft vessels to reach the many important ports located on the waterway. In order to accomplish this improvement a channel 30 feet deep and 600 feet wide was dredged from deep water in the bay to Philadelphia, and numerous dikes and bulkheads were constructed to control the tidal flow and direct the course of the currents.

It would be expected that because of the extensive physical changes in the waterway the tidal régime would be greatly disturbed, and we may, therefore, attribute the changes in tidal constants as due largely to the improvements mentioned.

Referring again to Figure 12 it will be observed that in the 60 nautical miles, approximately, between Five-Fathom Bank and Artificial Island the range of tide increases almost 2 feet. From Artifical Island where the range is a maximum for the entire waterway it begins to decline, decreasing 0.7 foot in the 40 nautical miles, approximately, between this point and Philadelphia. It will be observed that in the approximate 5 miles, from Artificial Island to Reedy Island the decline is very sharp, and a decrease of almost 0.4 foot in the range is noted. From Reedy Island to Philadelphia the decrease in range is uniform, falling 0.4 foot in the 45 miles (approximate).

From the amount of dredging that has been done in the Delaware River one would look for an increased range of tide, since it would be expected that less friction would be offered to the tidal movement. It has been observed, however, from Figure 12 that instead of the range increasing it actually decreases. If the improvements were confined solely to a deepening of the channel the range of tide undoubtedly would have increased. It was previously pointed out, however, that not only was there a deepening but also considerable widening of the waterway by the dredging away of numerous shoal areas. Apparently the greater effect on the tidal movement was that produced by the latter factor.

From Tables 28 and 35 the difference in time of tide between Artificial Island and Philadelphia derived from lunitidal intervals is 3.50 hours for the high water and 3.90 hours for the low water. For the actual difference in time of tide between the two points a correction of -0.03 hour must be applied, since the meridian of Philadelphia is approximately 24 minutes east of Artificial Island. Applying the correction to each of the values as determined above, a mean difference of time of 3.67 hours is obtained. For the lower Delaware River the average depth of waterway above mean river level is approximately 19 feet, and if this value is used in the formula for the rate of advance of a progressive tidal wave $v=\sqrt{gh}$, it is found that in this section of the river the wave should be propagated at the rate of approximately 14.5 nautical miles per hour. Since the distance between Artificial Island and Philadelphia is approximately 43 nautical miles, if the tidal movement is of the progressive wave type the distance should be traversed in $\frac{43}{14.5}$ or 2.97 hours. This value approximates the actual time given above, and it may, therefore, be concluded that the tide in the lower Delaware River is of the progressive wave type.

Under the discussion of the tide at Philadelphia it was shown that for this station the tidal quantities passed through an annual variaton. To a greater or less degree the same may be said of the entire Delaware waterway.

TABLE 34.—*Tide level in feet, lower Delaware River; annual variation*

Month	Reedy Island	New Castle, Del.	Edgemoor, Del.	Marcus Hook, Pa.	Baldwins, Pa.	Fort Mifflin, Pa.
	Feet	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*
January	3.08	3.13	3.13	3.17	3.03	3.27
February	3.30	3.23	3.17	3.29	3.23	3.43
March	3.37	3.44	3.53	3.38	3.60	3.53
April	3.40	3.65	3.70	3.70	3.83	3.70
May	3.58	3.84	3.80	3.67	3.93	3.83
June	3.50	3.75	3.77	3.71	3.73	3.63
July	3.56	3.74	3.80	3.70	3.73	3.67
August	3.66	3.81	3.80	3.76	3.70	3.67
September	3.65	3.78	3.80	3.69	3.73	3.55
October	3.48	3.66	3.70	3.59	3.60	3.65
November	3.42	3.53	3.50	3.46	3.45	3.40
December	3.18	3.30	3.40	3.19	3.35	3.35
Means	3.43	3.57	3.59	3.53	3.58	3.56

NOTE.—All heights referred to zero of precise levels run by United States Engineers, 1911–1913.

Table 34 gives the annual variation, in feet, of tide level for several stations in this section of the river, and for most stations is based on observations made between 1921–1924. For New Castle and Marcus Hook, however, the values are derived from observations between 1916–1924 and 1915–1924, respectively.

It will be seen that the tide level for all stations is lowest in January and generally highest in May. Between the highest and lowest monthly values the difference varies from 0.6 to 1 foot. It will also be observed that the mean tide level increases 0.14 foot in the 9 nautical miles from Reedy Island to New Castle, while in the 23 nautical miles from the latter station to Fort Mifflin there appears to be little difference in the plane.

Figure 14 represents graphically the annual variation in the plane of mean tide level for Delaware Breakwater, New Castle, Marcus Hook, and Philadelphia. These stations were selected because they represent the longest series of observations for Delaware Bay and lower Delaware River, the curves of the figure being based on 4, 9, 10, and 20 years, respectively, of high and low waters. It will be seen from an inspection of the figures that although there are minor irregularities a striking similarity exists between the graphs. In each case the tide level rises almost a foot from January to April or May, after which, with slight variation, it remains almost constant during the summer months. In September or October a sharp decline takes place reaching a minimum during the month of January. For Delaware Breakwater and New Castle, however, the graphs indicate a secondary minimum during June and July. In Special Publication No. 111 this same phenomenon was noted at Fort Hamilton in regard to sea level. Attention is directed to the fact that the amount of annual variation in the plane of tide level is very nearly as much at Delaware Breakwater as at Philadelphia.

In a comparison of tide level and river level made at Reedy Island (1896–1900), it appears that there is no appreciable difference between the two planes at this station.

In the previous section it was noted that the duration of rise of tide fell from 6.39 hours at Delaware Breakwater to 5.34 hours at Artificial Island, representing a decrease of almost 1 hour in 42 miles or approximately 0.025 hour per mile. For League Island, at the upper end of the lower Delaware River, Table 32 gives 4.97 hours for the duration of rise. It will be seen that in the approximately 40 miles between Artificial Island and League Island the duration of rise decreases 0.37 hour, or nearly 0.01 hour per mile.

Accompanying this decrease in duration of rise it will be noted that the high water interval increases from 10.41, at Artificial Island, to 13.37 at League Island, or 2.96 hours, and the low water interval increases from 5.07 hours to 8.40 hours, or 3.33 hours. The mean time of tide between Artificial Island and League Island may be taken as 3.1 hours, the correction for difference in longitude being negligible.

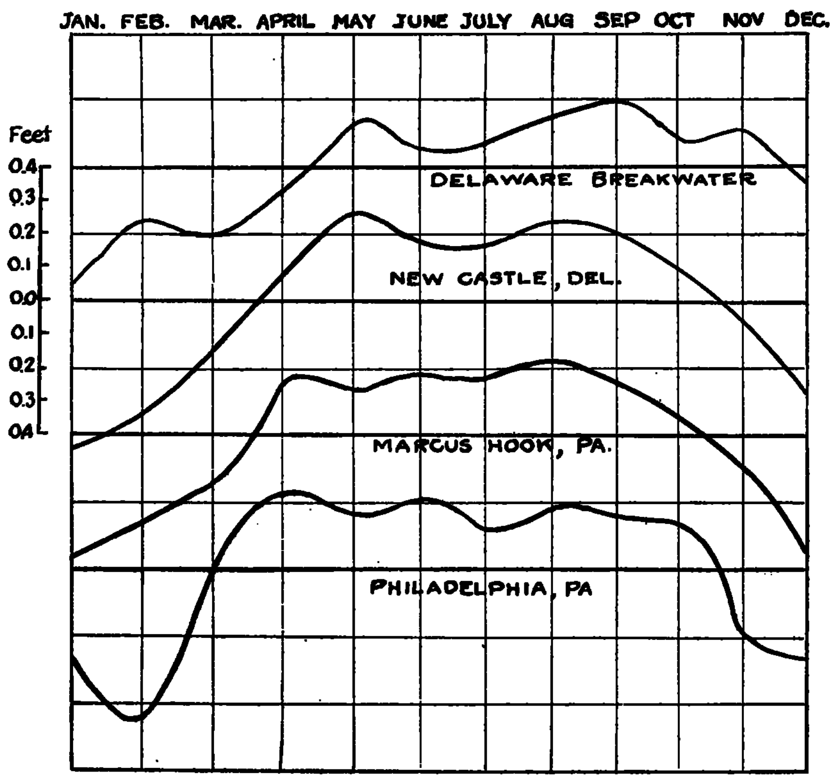

FIG. 14.—Annual variation in tide level, Delaware Bay and lower Delaware River

THE TIDE AT PHILADELPHIA AND VICINITY

In addition to the series obtained from the standard station at Chestnut Street, numerous shorter series of observations beginning in 1840 at Reed Street have been obtained in Philadelphia and vicinity. The locations of these stations are shown on Figure 15.

The longest series was 20 years at the standard station at Chestnut Street, Philadelphia, and as this station was discussed in detail in a previous section it need not be taken up here.

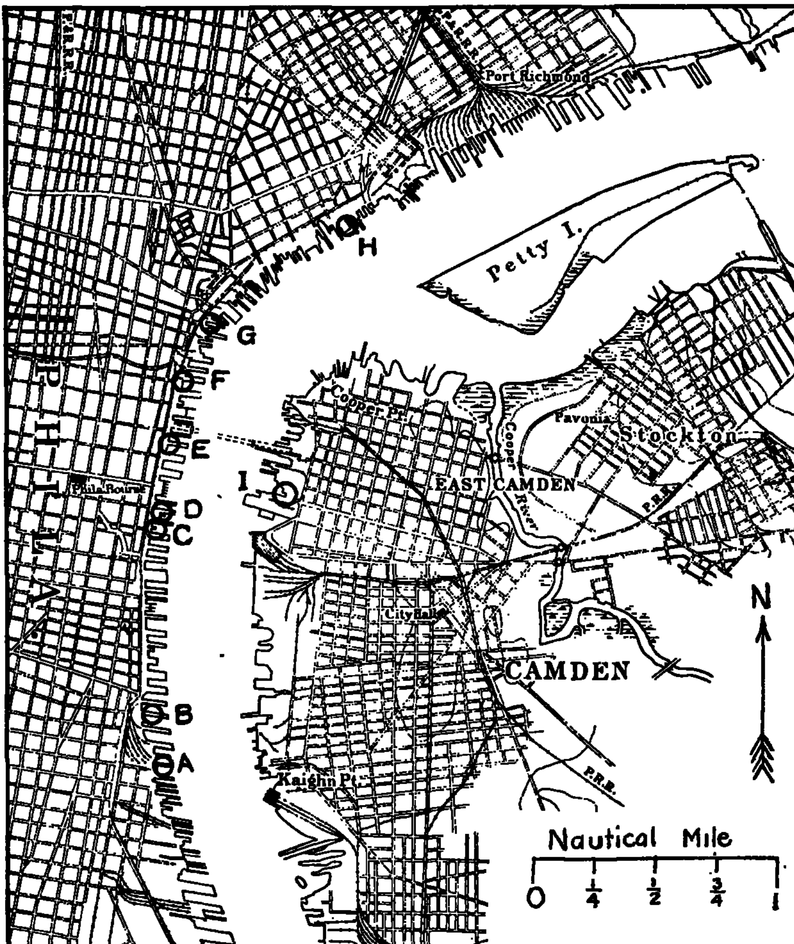

FIG. 15.—Tide stations, Philadelphia and vicinity

TABLE 35.—*Tidal data, Philadelphia and Camden*

Station	Locality	Lunitidal intervals		Duration of rise	Mean range	Observations	
		HWI	LWI			Date	Length
	PHILADELPHIA	*Hours*	*Hours*	*Hours*	*Feet*		
A	Reed Street	1.11	8.65	4.88	5.82	1843	6 months.
	do	1.09	8.74	4.77	5.90	1871	2½ months.
	do	1.16	8.50	5.08	5.96	1877–78	3 months.
B	Washington Avenue	1.40	8.91	4.91	5.67	1891–92	15 months.
C	Walnut Street	1.20	8.72	4.90	5.89	1840	5 months.
D	Chestnut Street	1.49	8.97	4.94	5.23	1900–1920	21 years.
E	Arch Street				5.45	1900	13 days.
	do	1.52	8.91	5.03	5.26	1922–1924	2½ years.
F	Callowhill Street	1.07	8.72	4.77	5.99	1843	9 days.
G	Poplar Street	1.18	8.88	4.72	5.95	1861	Do.
H	Otis Street, Kensington	1.50	9.18	4.74	5.66	1878–1886	3 months.
	CAMDEN						
I	Cooper Street	1.48	8.91	4.99	5.69	1886–1889	3 months.

Table 35 gives the tidal data for all observations in the vicinity of Philadelphia. Although there is considerable variation among the different series, it is evident from the data presented that little change took place in the tidal regimé from the time of the earliest observations until about 1890. From this latter time the tidal data indicate a distinct change. For example, if we compare Station A (Reed Street) and Station B (Washington Avenue), which are very close to each other and are, therefore, directly comparable as to tidal data, it will be seen that for the latter station, where the observations were made between 1891–92, the time of tide as represented by the HWI and LWI comes later than at the former station where all observations were made prior to 1890; similarly the range of tide is observed to be considerably less at the latter station. The conclusion is therefore reached that as in the rest of the Delaware River here, too, the tidal regimé has undergone a change since 1890, and that the change is to be attributed to the general improvement of the waterway which began about 1890. Probably the greatest effect on the tide at Philadelphia was produced by the dredging away (1892–1897) of Windmill Island, a shoal which existed in the harbor between Philadelphia and Camden and obstructed the free movement of the tide up the river.

Although the greatest change in the tidal regimé occurred during the period 1890–1900, it was indicated in the general discussion of the tide at Philadelphia that in the series 1900–1920 changes might be still taking place in the tide. From the preceeding discussions it was seen that the tidal quantities in a river are not constant, but are subject to change, depending upon the changes in the physical character of the waterway. The necessity for accepting results of the latest reliable series of observations is, therefore, evident.

THE TIDE IN SCHUYLKILL RIVER

Several short series of tidal observations have been made in that part of the river subject to tidal influence; that is, from the mouth to the Fairmount Dam, a distance of 8½ nautical miles. The locations of the stations at which these observations were taken is shown in Figure 16.

TABLE 36.—*Tidal data, Schuylkill River*

Station	Locality	Lunitidal intervals		Duration of rise	Mean range	Observations	
		HWI	LWI			Date	Length
		Hours	*Hours*	*Hours*	*Feet*	*Year*	
A	Girard Point	0.79	8.47	4.74	5.72	1875	8 days.
B	Penrose Ferry	0.53	8.47	4.48	5.83	1889	3 days.
	do	1.11	8.61	4.92	5.25	1916	1 month.
C	Gibsons Point Wharf	0.45	8.39	4.48	6.29	1871	20 days.
D	Buckley's Wharf	0.64	8.96	4.10	5.56	1885	12 days.
E	Gray's Ferry	0.66	8.82	4.26	5.60	1889	5 days.
F	Chestnut Street Bridge	1.24	9.02	4.64	5.40	1915	2 months.
G	Fairmont Bridge	0.37	8.55	4.24	6.20	1871	33 days.

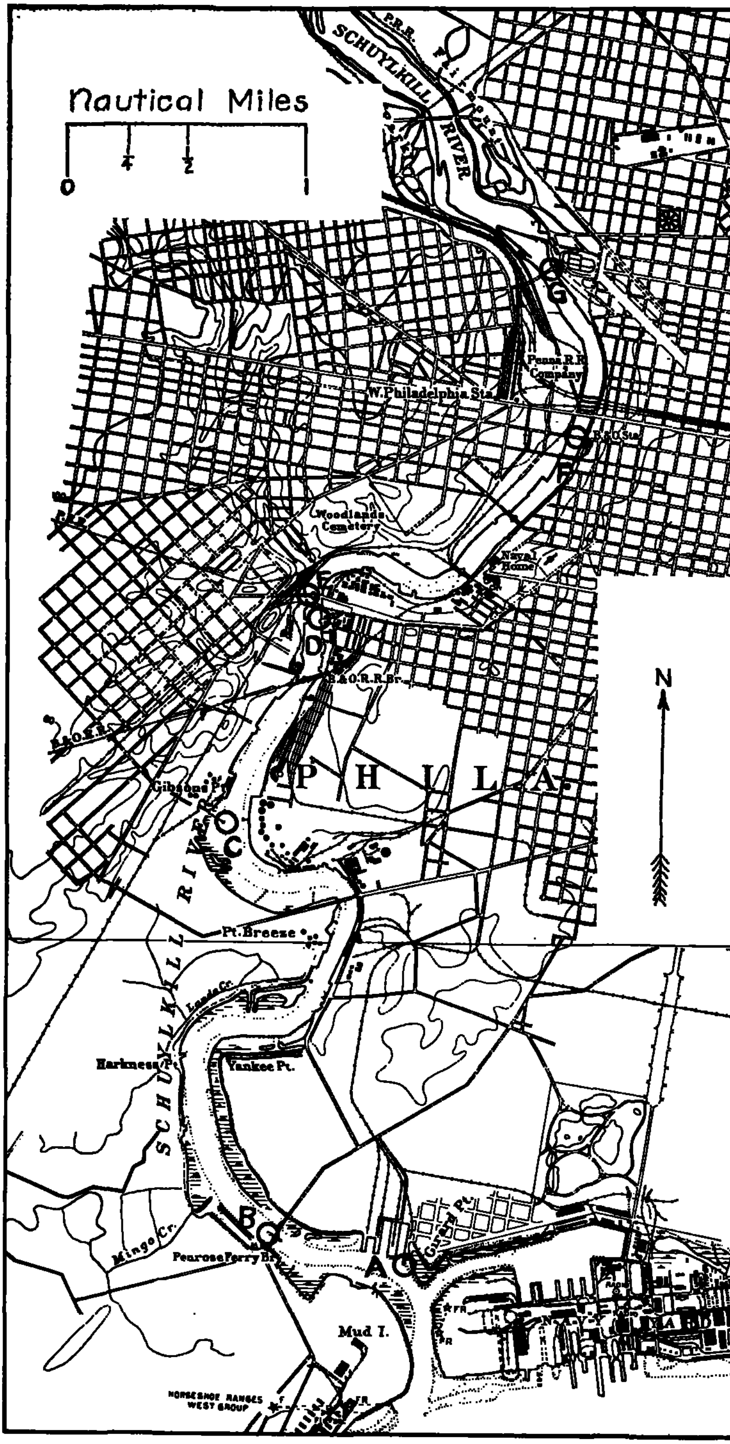

Fig. 16.—Tide stations in Schuylkill River

The results obtained from a tabulation of the data are given in Table 36. In this table the stations are arranged in order from the mouth upstream. Although the values have been reduced to a mean by correcting for annual variation, there still remains considerable irregularity in the data. Not only are the results obtained from observations inconsistent because of the short series but they are further complicated by freshet conditions and the obstruction which the dam offers to the tide. It is interesting to note that a considerable difference exists between the early observations and those of recent date. It is observed that for recent observations the time and range of tide have undergone considerable change, similar to the changes noted in tidal data for the Delaware River. From the table for tidal data it appears that the high and low water intervals have increased between 1871 and 1916, while the range in the river has decreased about 1 foot in the same time. Within the limits of error, results obtained at Gibsons Point Wharf for 1871 agree with those at Fairmount Bridge for the same year. Penrose Ferry and Grays Ferry agree, and for 1915–16 Penrose Ferry and Chestnut Street Bridge agree. From a study of the table little change in time of tide is indicated between the tidal extremities of the river.

Prior to 1870 the controlling depth in the Schuylkill River was 16 feet at mean low water, with but 10 feet on the bar at the mouth of the river. Beginning at this time several projects for the improvement of the river have been carried out at intervals, and at the present time the chart shows a channel depth varying from 28 feet at mean low water at the mouth to 21½ feet at Grays Ferry Bridge. Above this point shoals limit the controlling depth to 16 feet at mean low water.

From the observations at Chestnut Street Bridge the tide curve here appears to be far from regular. In Figure 17 is shown the graph made on November 5–6, 1915, by an automatic tide gauge maintained by the United States Engineers at the Chestnut Street Bridge. A striking feature is the sharp change which occurs in the slope of the curve near mean tide level on the rising tide, from 21 to 22 hours on the 5th and from 9 to 10 hours on the 6th. This feature appears to be characteristic of the tide at this station. It is also noted from observations at Penrose Ferry Bridge near the mouth of the river, but the change is not so sharp.

THE TIDE IN THE UPPER DELAWARE RIVER

Above Philadelphia the Delaware River contracts greatly until at Trenton it is barely 200 meters in width. The numerous shoals, islands, and dikes interfere to such an extent with the tidal movement that the tidal characteristics are profoundly effected. In addition, the meandering of the river and the large quantities of fresh water draining into it from the numerous tributaries serve further to complicate the tidal régime. It will be found in studying the various characteristics that the variations noted in the previous section are magnified to a considerable degree.

Series of observations have been made from 1878 to the present time at several places on the shores of the river, the locations of these stations being shown in Figure 18.

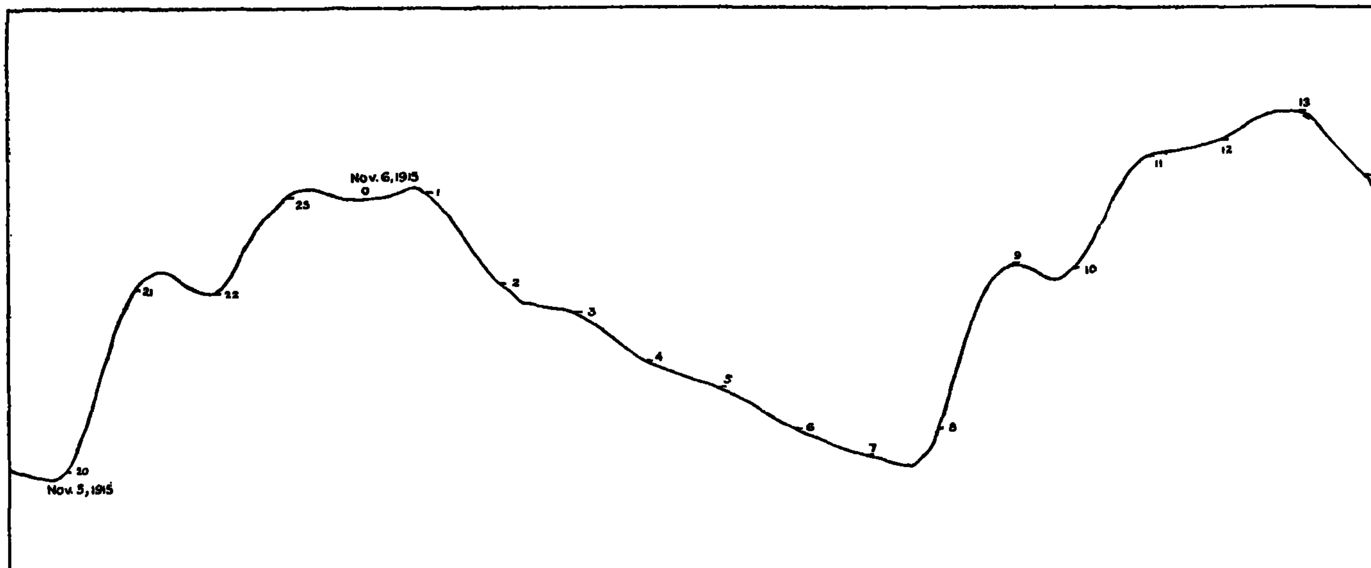

FIG. 17.—Tide curve in Schuylkill River (Chestnut Street Bridge) November 5–6, 1915

TABLE 37.—*Tidal data, upper Delaware River*

Station	Locality	Lunitidal intervals		Duration of rise	Mean range	Observations	
		HWI	LWI			Date	Length
		Hours	*Hours*	*Hours*	*Feet*		
A	Five Mile Point, Pa	1.96	9.55	4.83	5.81	1878	11 days.
B	Bridesburg, Pa	1.90	9.47	4.85	5.70	1885	17 months.
C	Burlington, N. J	2.93	10.50	4.85	5.71	1886	2 months.
	do	2.96	10.34	5.04	[1] 4.75	1924	3 months.
D	Whitehill, N. J	4.03	11.41	5.01	4.99	1886	2 months.
E	Trenton, N. J	4.38	0.13	4.25	3.55	1886	Do.
	do	4.06	11.75	4.73	[1] 4.55	1924	3 months.

[1] Range based on three years of high and low waters.

The data resulting from the observations are given in Table 37. The longest series are those at Burlington and Trenton, obtained by the automatic tide gauges operated by the United States Engineers with but slight interruptions between 1921–1924. For these stations the range has been derived from all high and low waters, while the lunitidal intervals are derived from the three months, July, August, and September, 1924. To reduce to mean values, a simultaneous comparison was made with Philadelphia.

In its original condition the channel of the Delaware River from Philadelphia to Trenton was narrow and in places obstructed by shoals with but 3 to 8 feet at mean low water. In recent years this portion of the river has been greatly improved by dredging and the building of bulkheads and dikes, and in May, 1925, a channel 200 feet or more in width with a controlling depth of 11 feet existed between Philadelphia and Trenton.

As in the lower section of the river, here too the data show a change in the tidal characteristics since extensive improvements were made in the waterway. Comparing the earlier and later series at Burlington, it appears that the time of tide now comes somewhat earlier, while the range has decreased about 1 foot. At Trenton the recent observations show an increase of 1 foot in the range at this station and a decrease of 0.32 hour in HWI and 0.80 hour in LWI. Corresponding to the change in time of tide there appears to be a change in the duration of rise and fall. In the table there is shown an increase in the duration of rise of almost 0.2 hour at Burlington and almost 0.5 hour at Trenton.

It was previously pointed out that the effect of harbor improvement in the lower Delaware River was to delay the time of tide and decrease the range of tide. A different phenomenon takes place in the upper Delaware River, the recent observations showing that the time of tide comes earlier, and, while at Burlington the range has decreased, at Trenton there appears to have been a large increase. The effect of the harbor improvement work seems to have been a deepening of the channel, so that less friction is offered to the tidal movement. It would, therefore, be expected that an increased range would be obtained at Trenton, since it is near the extremity of the tidal influence.

For Philadelphia the accepted values of HWI and LWI were given as 1.49 and 8.97 hours, respectively. For Burlington and Trenton the values obtained from the recent series are taken as the best determined values. At Burlington, therefore, the accepted values of HWI and LWI are 2.96 and 10.34 hours, respectively. The difference in HWI and LWI between the two stations is 1.47 and 1.37 hours, respectively, and since Burlington is 17 minutes of longitude east of Philadelphia a correction of -0.02 hour must be applied to difference in intervals to get the time of tide. The resulting mean difference in time of tide between Philadelphia and Burlington, a distance of 16 nautical miles, is 1.44 hours. Similarly the difference in time of tide between Burlington and Trenton, a distance of 13

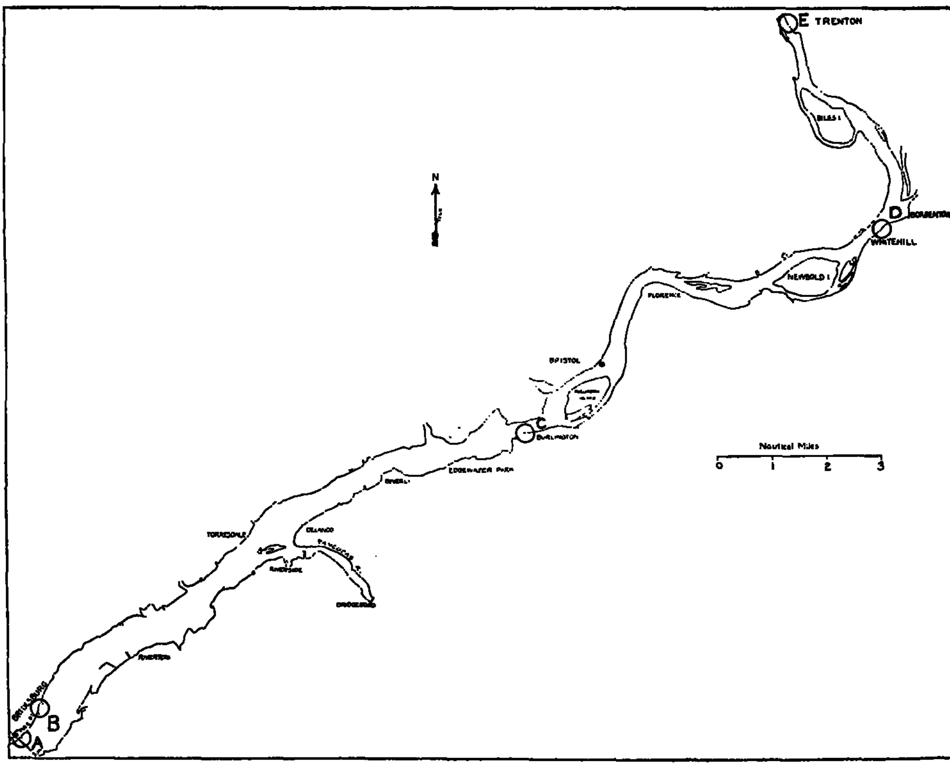

FIG. 18.—Tide stations, upper Delaware River

nautical miles, is derived as 1.26 hours. It is evident, therefore, that since Burlington is a little over halfway between Philadelphia and Trenton, the time gradient is practically the same in the two sections, and it may be assumed that the tide changes at a uniform rate in the upper Delaware River.

In the 29 nautical miles between Philadelphia (Chestnut Street) and Trenton the time of tide changes by 2.70 hours and the average depth of water in this section is 15 feet at mean river level. The velocity of propagation of a progressive wave is represented by the formula $v=\sqrt{gh}$, and if we substitute the value 15 for h, the velocity with which this type of wave should travel in the waterway is approximately 13 miles per hour, and the time to traverse the distance between the two extremities should be 2.2 hours. The actual time of tide appears, therefore, to be somewhat greater, but this difference may be explained by the friction offered the tidal wave by fresh water run-off, and the type of wave may therefore be said to be progressive.

TABLE 38.—*Tide level, upper Delaware River; annual variation*

Month	Burlington, N. J.	Trenton, N. J.	Month	Burlington, N. J.	Trenton, N. J.
	Feet	*Feet*		*Feet*	*Feet*
January	3.40	5.69	August	4.03	4.38
February	4.24	5.23	September	4.00	4.37
March	4.95	7.48	October	3.83	4.18
April	4.98	7.02	November	3.87	4.40
May	4.72	6.20	December	4.03	5.20
June	4.40	4.98			
July	4.22	4.70	Means	4.22	5.32

NOTE.—Heights are referred to 0 of precise levels run by United States Engineers, 1911–1913.

Table 38 gives the annual variation in tide level for Burlington and Trenton for the period February, 1921, to September, 1924. In Table 34, representing the annual variation of tide level in the lower Delaware River, the greatest annual variation from mean value for any station was 0.5 foot. Between the maximum monthly tide level and mean tide level there is a difference of 0.8 foot at Burlington compared with a difference of 2 feet approximately at Trenton. At the latter station the difference between highest and lowest monthly mean tide level is approximately 3 feet. It is to be expected that, due to narrow channel and shoalness of the stream, the fresh-water effect on the tidal characteristics would be greater in the upper part of the river.

In Figure 19 the annual variation of tide level at Philadelphia, Burlington, and Trenton is shown in graphic form. From inspection, it is seen that for the latter two places the level generally reaches a maximum in March or April, after which it drops sharply and is generally lowest during the late summer and early fall. This phenomenon is in sharp contrast with the annual variation for the lower river, as indicated at Philadelphia, where it was observed that the river level was generally high during the spring and summer months and low during fall and winter months.

As many tide stations between Woodland Beach, in Delaware Bay, and Trenton, at the upper end of the river, have been connected by a line of precise levels by the United States Engineers the mean tide levels of these stations are referred to the same zero. It is, therefore, possible to compare the values of mean tide level for various places in the waterway. In Table 29, 3.10 feet was derived as the mean tide level at Woodland Beach, and in Table 34, 3.56 feet was derived for the mean tide level at Fort Mifflin. It is evident, therefore, that at the upper station the level is approximately 0.5 foot higher than the lower station. Since the two stations are 43 miles apart the tide level increases at the rate of approximately 0.01 foot per mile. Table 38 gives 5.32 feet as the mean tide level at Trenton, N. J. Between Fort Mifflin and Trenton there is an increase of approximately 1.8 feet, and since a distance of 36 miles separates the two stations, the tide level in this section of the river appears to increase at the rate of approximately 0.05 foot per mile or about five times the rate of increase in the lower section.

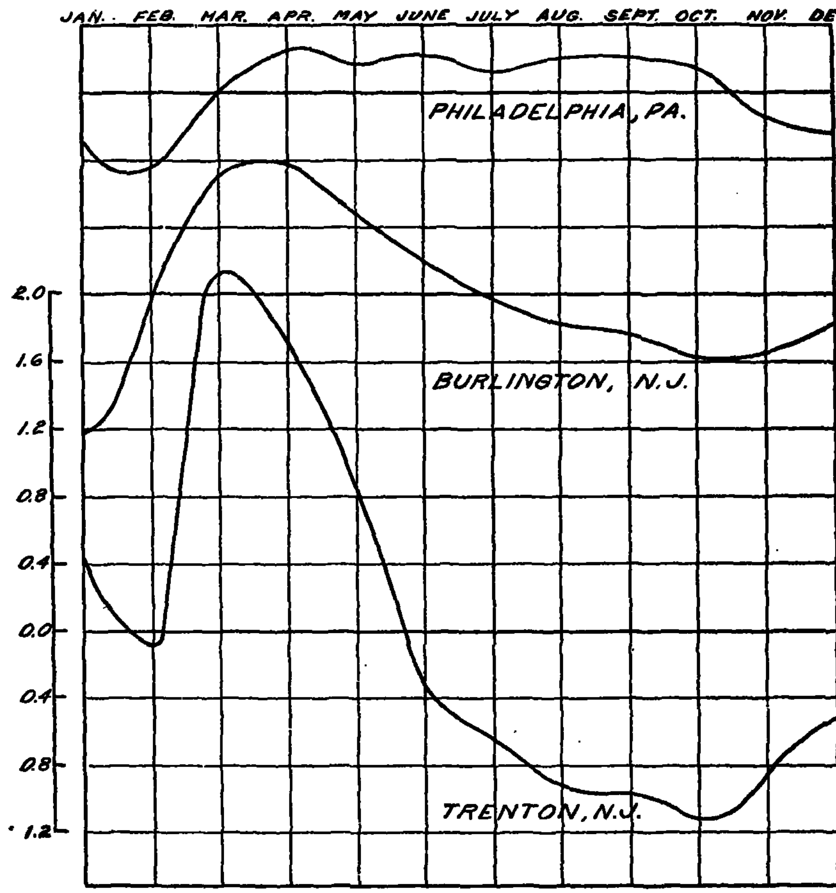

FIG. 19.—Annual variation in tide level, upper Delaware River

From a line of precise levels run by this Bureau between Sandy Hook (an open ocean station) and Philadelphia, it was found that mean sea level (or river level) is 0.8 foot higher at the latter place. Hence there appears to be an approximate slope of 0.01 foot per mile in river level between Philadelphia and the open ocean. This corresponds with the slope of tide level derived above between Fort Mifflin, 7 miles south of Philadelphia, and Woodland Beach, 34 miles north of the Capes.

TABLE 39.—*River discharge, Trenton, N. J.; annual variation*

Month	Discharge in second-feet	Month	Discharge in second-feet
January	11,110	July	5,400
February	8,100	August	3,005
March	24,900	September	2,990
April	22,950	October	3,025
May	14,975	November	5,260
June	7,850	December	11,045

The influence of the river conditions on the tide is illustrated by a comparison of the tide level with the river discharge at Trenton. In Table 39 is shown for Trenton, N. J., the annual variation of the river discharge in cubic feet per second, based on the period January 1921, to August, 1924, inclusive. These data are taken from the Geological Survey surface water supply papers. An examination of the data shows that like the tidal characteristics there is a periodicity

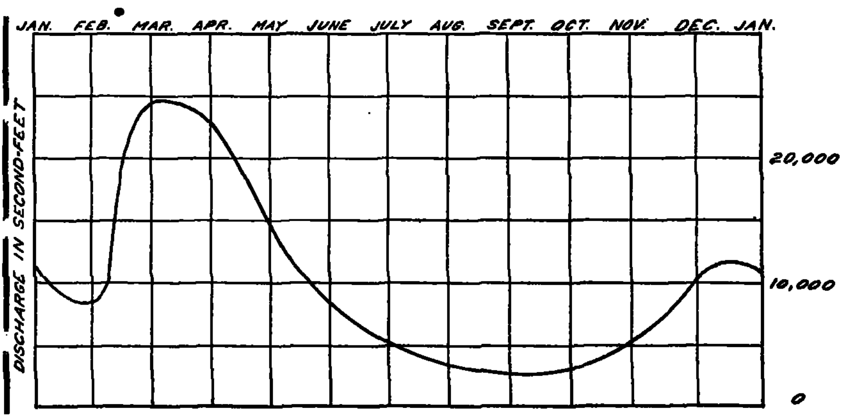

FIG. 20.—Annual variation in river discharge, Trenton

in the annual variation. This may be more clearly seen in the graph of the annual variation as shown in Figure 20.

It will be observed that the annual variation of river discharge is strikingly similar to that of the tide level, as represented in Figure 19. From a minimum in February the river discharge rises sharply to a maximum of 24,900 second-feet in March, after which it declines during the spring months, reaching the lowest discharge of the year during September with a value of approximately 3,000 second-feet. A second and smaller maximum is reached in January. It appears then that, like the tide level, the river discharge is generally lowest in the summer months and highest in spring months. Since Trenton is at a considerable distance from the open sea, and at a place in the river where the channel is narrow and shoal, the tidal effect is weak and, therefore, easily influenced by the river discharge. It is to be expected, therefore, that the annual variation of tide level will resemble that of river discharge.

At Burlington, 13 miles south of Trenton, the river discharge is again reflected in the tide level but to a lesser degree. From Philadelphia to the sea the variation in tide level is little affected by the

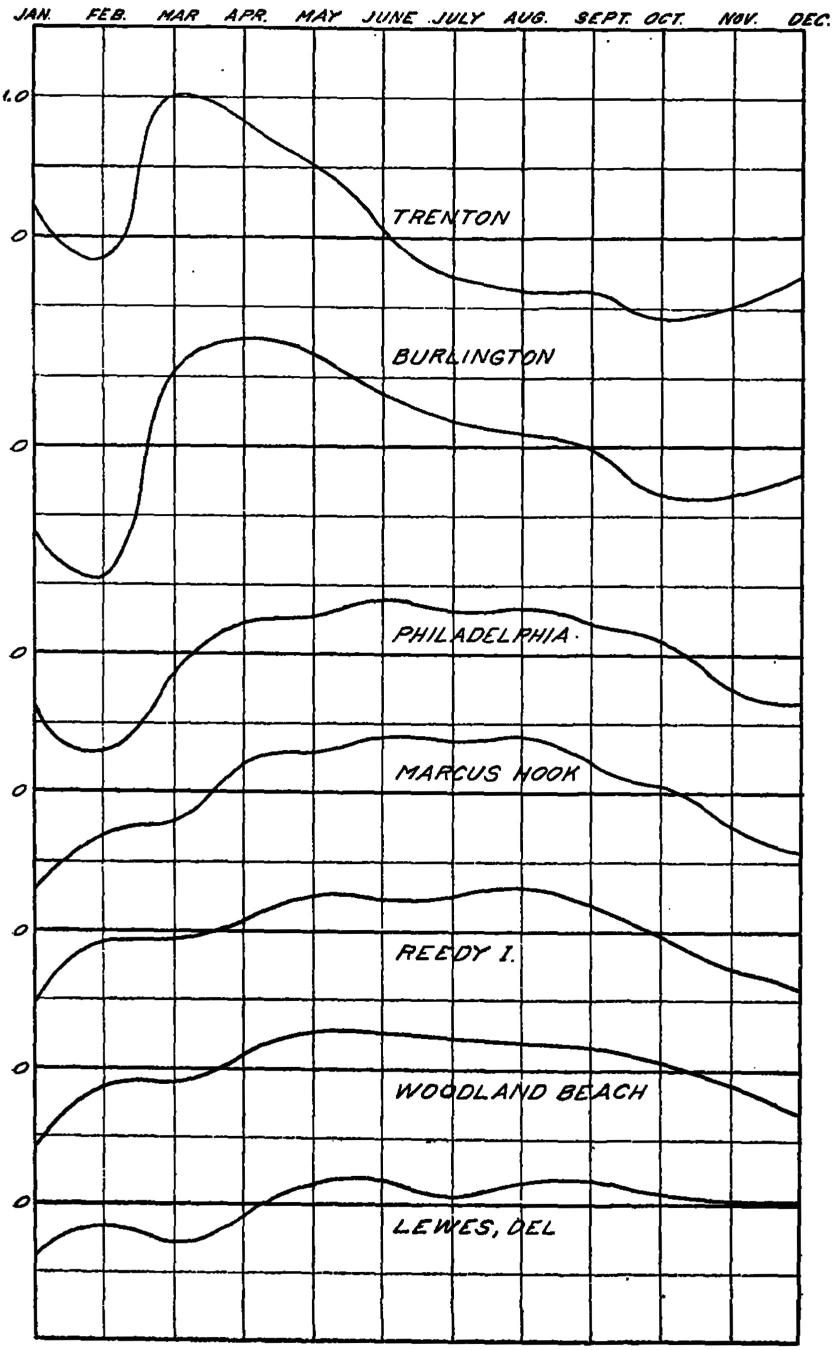

Fig. 21.—Annual variation in high water, Delaware Bay and River

river discharge, and the curves exhibit the characteristics of the open ocean type of tide.

A corresponding effect of the river discharge is seen in the planes of high and low water and range of tide in the upper Delaware River, and the annual variation of the two planes here differ markedly from that in the lower river and bay. These differences may be noted in the graphs that follow which result from the most recent series of observations; between 1921 and 1924 at Trenton and Reedy Island; 1922–1924 at Burlington and Woodland Beach; 1901–1920 at Philadelphia, and 1915–1924 at Marcus Hook.

17. ANNUAL VARIATION OF PLANE OF HIGH WATER

In Figure 21 are represented graphically the annual variations of high water at stations from Lewes to Trenton. It is evident from an inspection of the graphs that the range of annual variation increases progressively from the open ocean to the tide water extremity at Trenton. Between the highest and lowest monthly values, the high-water plane varies by approximately 0.6 foot at Lewes, Del., compared with 1.6 feet at Trenton, N. J. Besides this variation in the height of the plane the general form of curve differs between the stations near the sea and those farthest away. For example, in the lower river and bay the high water after reaching a maximum height in the spring remains almost constant during the summer months, and begins to drop in the fall. A distinct contrast to this takes place in the upper river. Here the plane of high water rises sharply to its maximum in March or April and almost immediately begins to drop, becoming comparatively low in summer. It is to be noted that for the entire river and bay the plane of high water is generally lowest in the winter months.

18. ANNUAL VARIATION OF PLANE OF LOW WATER

A glance at Figure 22 shows that the annual variation of the plane of low water is not of a uniform character. It is seen that for stations at and below Philadelphia the range of annual variation is appreciably less than that for the high water plane, while for stations above Philadelphia the opposite is true. For example, at Reedy Island the difference between the highest and lowest monthly value of the low water plane is approximately 0.5 foot compared with approximately 0.8 foot for high water. At Trenton, however, we have a difference of 4.3 feet in low water compared with 1.6 feet in high water. It is evident that in the upper river where the river discharge exerts a predominating effect on the tide the low water plane is more disturbed than that of the high water. This appears to be due to the fact that as the freshets occur the greater river discharge brings about a rise in the river and tide level but at the same time the current produced decreases the range of tide. While the effect of the higher tide level has been to raise both the planes of high and low water, the decreased range tends to lower the high and raise the low water plane. Obviously the resultant effect will bring about a greater increase in the plane of low water over that of high water. Referring to Figure 22 again, attention is directed to the fact that at both Philadelphia and Marcus Hook, which are based on long series, the low water plane

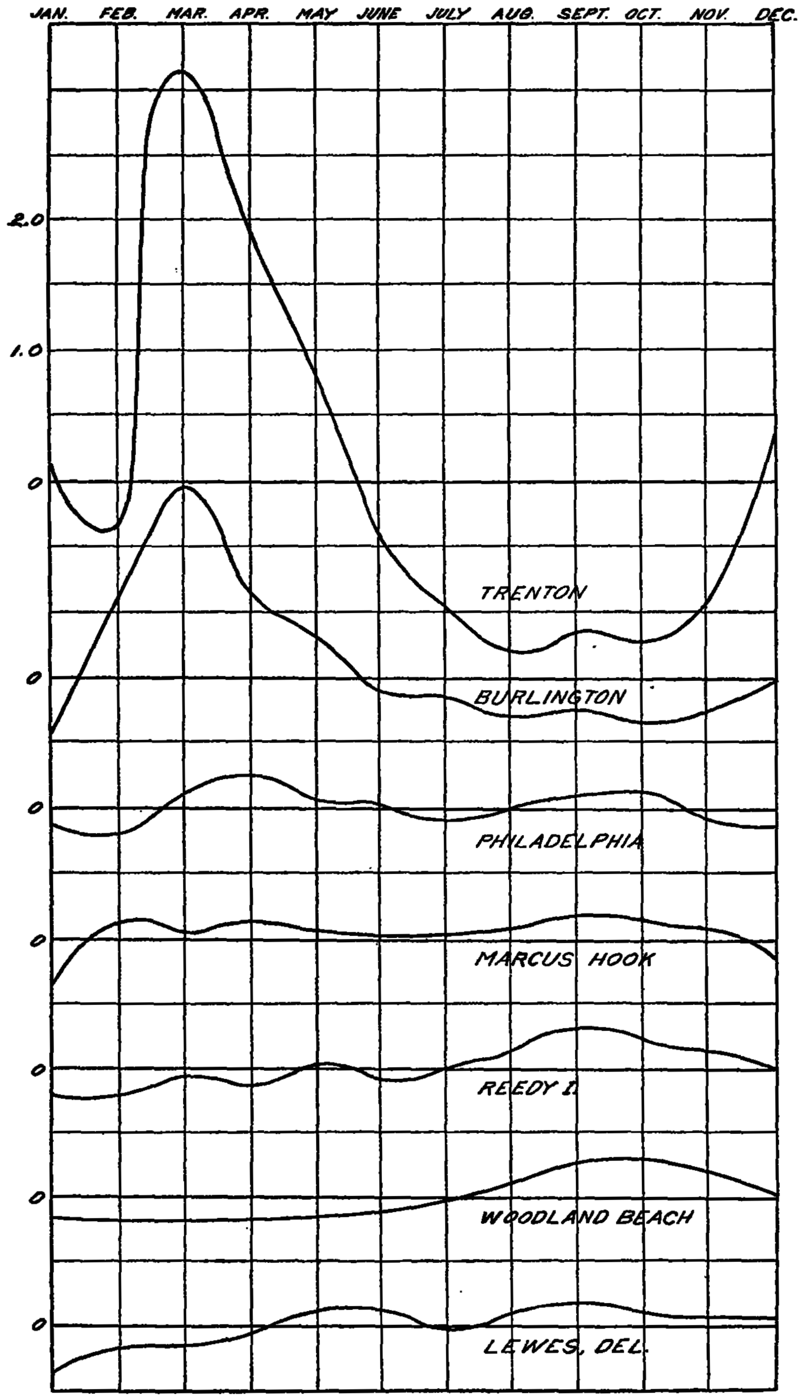

FIG. 22.—Annual variation in low water, Delaware Bay and River

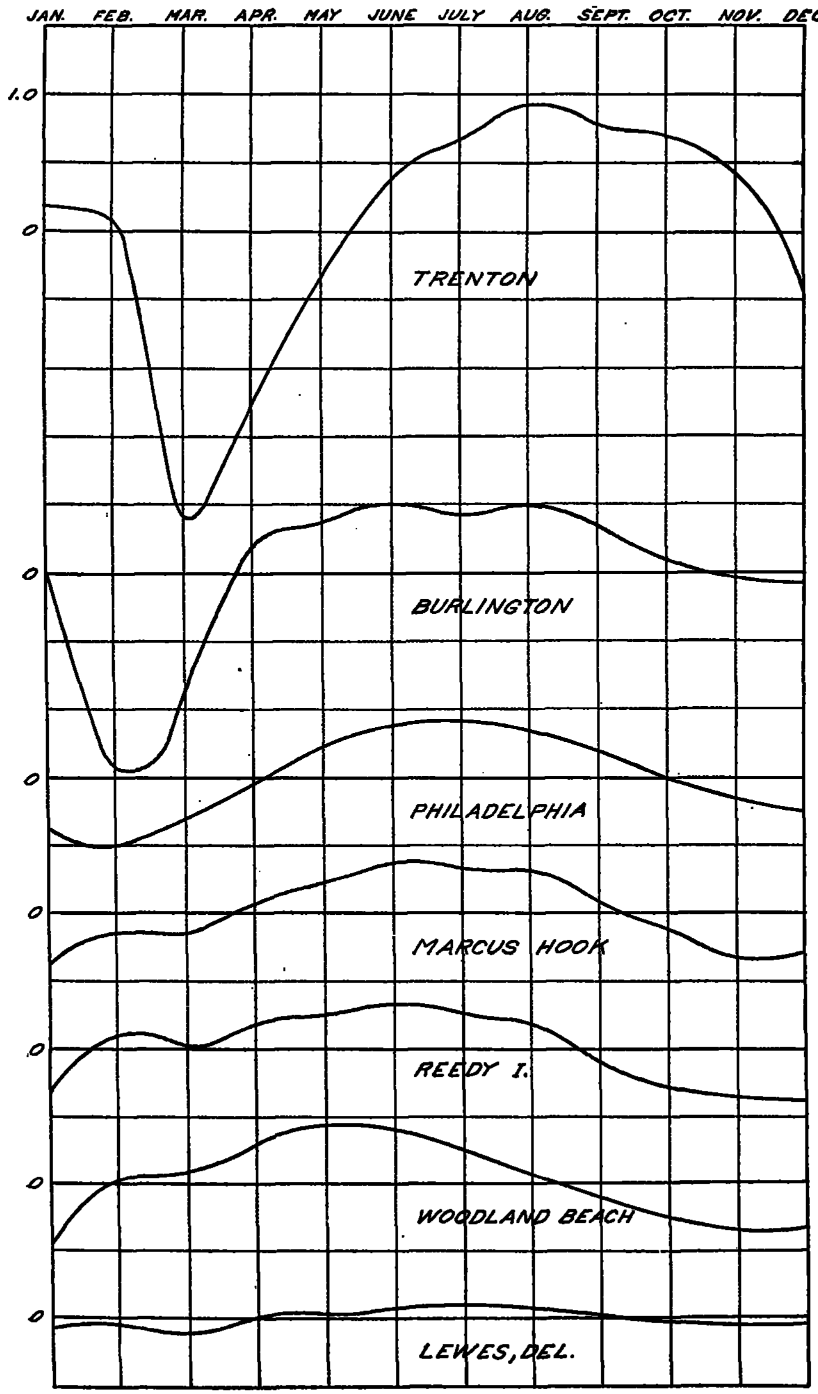

FIG. 23.—Annual variation in range, Delaware Bay and River

after being high during the spring months falls and reaches a secondary minimum in July. This is in contrast to the annual variation of the high water plane, in which it was noted that this plane remains high during the entire summer. It will be seen, therefore, that there is little resemblance between the high and low water planes, the latter being unlike any of the other tidal planes.

Another dissimilarity between the annual variation of the high and low water planes is observed at Trenton and Burlington, where the drop in the low water plane is sharper, and reaches a minimum in August, whereas the plane of high water does not reach its minimum until October.

19. ANNUAL VARIATION IN RANGE OF TIDE

Figure 23 shows graphically the annual variation in the range of tide for the various stations previously discussed. As in the case of the high and low waters the amount of annual variation of range increases progressively from Lewes to Trenton. At Lewes there is a difference of approximately 0.2 foot between the highest and lowest monthly mean ranges, while at Trenton there is a difference of approximately 3.1 feet. It will be observed that the range of tide is generally highest in the summer and fall and lowest in the winter and spring months. As in the case of the several planes discussed, there is a distinct difference in the form of curve of annual variation for the lower river and bay as distinguished from the upper Delaware River. At the beginning of the freshets in February and March, the range of tide drops sharply to a low level and then rises almost as sharply to the maximum value.

Comparing the curves of annual variation of range with those for annual variation of tide level for Trenton and Burlington, there is manifest a striking relation between the two and we observe that when the range is low in March the tide level is correspondingly high, and when the range is high in the summer and autumn months the tide level is low. Since the tide level is directly proportional to and dependent on the river discharge, it is evident that the range of tide is closely related to the river discharge. Although the river discharge has an influence on the tide at and below Philadelphia, its effect becomes more or less dissipated on reaching the deeper water and wider stream at this point, and from here on to the entrance to the bay its effect is not nearly so marked as in the upper river.

In a previous section mention was made of a method by which the range for a short series of observations was corrected to mean value when simultaneous comparison with a standard station was not possible. This method made use of the annual variation. It has been made evident from the various curves of annual variation that the range of tide, as well as other tidal characteristics, varies more or less regularly throughout the year. It has further been evidenced that the amount and kind of annual variation depend on the location of the station in the river. If then a series of these curves be plotted for stations at frequent intervals along the waterway, it is possible to determine for any series of observations, by interpolation, the per cent any quantity is above or below mean at any particular time of the year. By correcting the observed range of tide by this factor an approximate mean value is obtained.

80035—26——5

20. SUMMARY

In the preceeding discussions there was manifested a progressive change in the tidal characteristics from the entrance to the bay to the extremity of tide water at Trenton. Not only does the range of annual variation increase progressively throughout the waterway, but there is also a difference in the form of the curve for the different sections. For example, it was shown that for the lower river and bay, where the waterway is wide and deep, the graphs for annual variation of various characteristics were distinctly different from that of the upper river, where the waterway is narrow and shoal. We are, therefore, led to the conclusion that in the Delaware waterway the tidal characteristics vary from place to place, and the degree of this variation depends on the relative distance of the place in question from the open ocean.

Part II.—CURRENTS IN DELAWARE BAY AND RIVER

By E. A. Le Lacheur, *Assistant Mathematician, United States Coast and Geodetic Survey*

Part II. of this publication deals with the tidal current in Delaware Bay and River from the entrance to the bay at the Delaware Capes to the head of navigation in the river at Trenton, N. J. The movements of the tidal current in the approaches to Delaware Bay from the Atlantic Ocean are also included because of the relationship between such tidal current movements offshore and those in Delaware Bay proper.

Tidal currents in this waterway are discussed under the following sections:

1.—The current in the approaches to Delaware Bay.

2.—The current in Delaware Bay.

3.—The current in the lower Delaware River.

4.—The current in the Delaware River—vicinity of Philadelphia and Camden.

5.—The current in the Delaware River—Philadelphia to Trenton.

THE CURRENT IN THE APPROACHES TO DELAWARE BAY

For convenience in discussing the tidal current in the approaches to Delaware Bay, the entrance to the bay is defined by a line joining Cape Henlopen Light, Del., and Cape May Light, N. J. Current stations located west of this line are therefore in Delaware Bay and those located east of this line are in the approaches to Delaware Bay. Figure 24 shows the locations of 16 current stations which have been occupied in the approaches to Delaware Bay, the records of which are on file in the office of the Coast and Geodetic Survey.

The tidal current in Delaware Bay and River is of the reversing type—that is, it floods or sets northerly—for a period of about six hours and then ebbs, or sets southerly for the following period of about six hours. Due to fresh water run-off in the river, the period of the ebb is generally increased to about seven hours duration and the flood decreased to about five hours duration. When the current changes from flood to ebb, or vice versa, there is a period of slack water, or time of no current. Theoretically, this change takes place instantly. Actually, however, the period during which the current is so feeble that it may be considered as slack varies from a few minutes duration to half an hour, or even longer. In the case of this reversing type of current, there is an increase in the velocity of the flood or ebb from the time of slack water until about three hours later when the current attains its maximum strength. Then it decreases in velocity over another period of about three hours until the following slack water occurs.

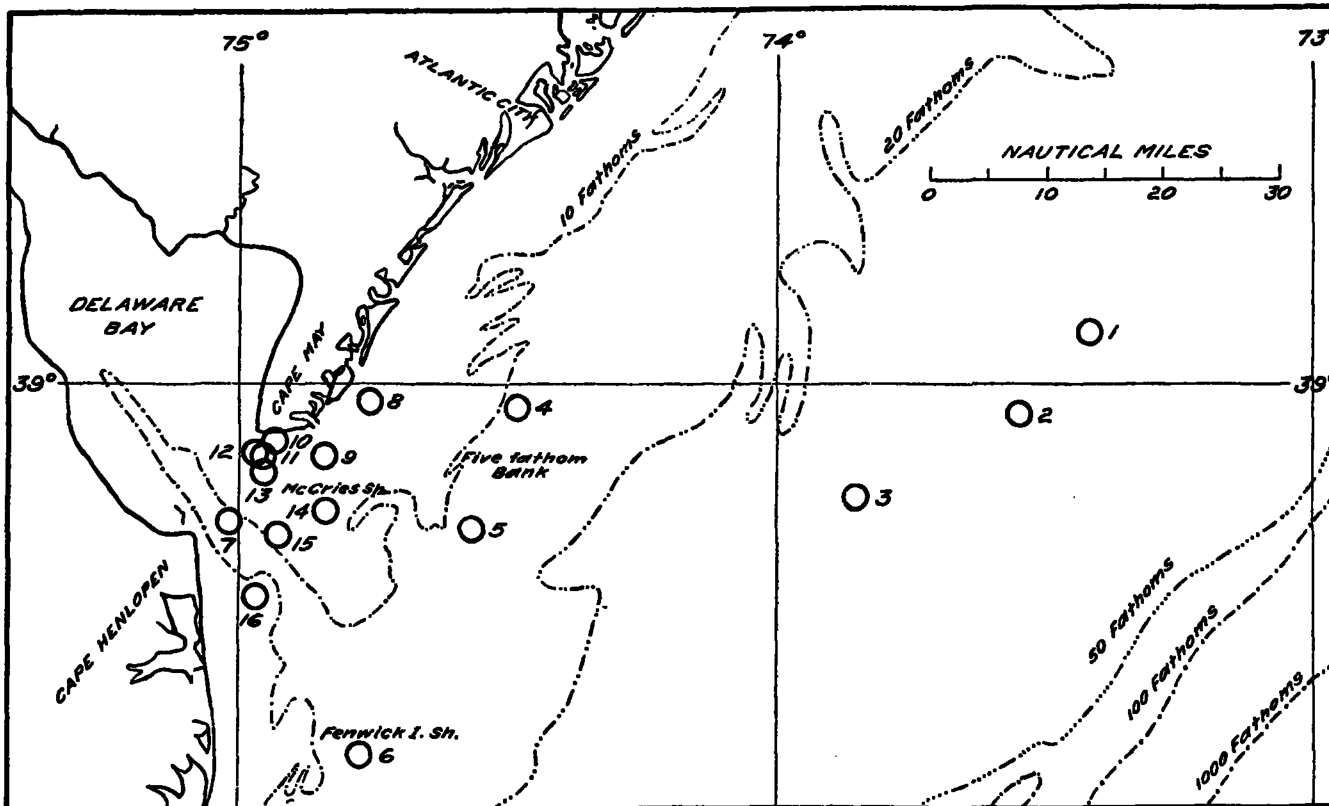

Fig. 24.—Current stations, approaches to Delaware Bay

Offshore, however, away from the immediate influences of the coast, the tidal current is quite different from the current found in the inland tidal waters. Instead of setting in one direction, or flooding, for a period of about six hours, and ebbing in the opposite direction during the following period of about six hours, the tidal current offshore changes in direction and velocity continually, so that in a period of about 12½ hours it will have set in all directions of the compass.

This type of current is called a rotary current in distinction from the reversing type of current found in inland tidal waters such as Delaware Bay and River. For more detailed information on the reversing, or rectilinear, and rotary types of tidal current see pages 114–116 of the Appendix.

At stations 1 to 6, inclusive, the tidal current is distinctly rotary in type, turning clockwise. Twice in a lunar day of 24 hours and 50 minutes the tidal current swings around in a complete ellipse, as shown in Figure D in the Appendix. A characteristic feature of the rotary current is the absence of slack water. The current is always running and varies in velocity and direction hour by hour. It varies from a period of greatest velocity, or maximum current, to a period of least velocity, or minimum current. In half a tidal day, or a period of 12 hours and 25 minutes, two maximum and two minimum velocities of the tidal current occur. These are related to one another in the same way as slack before flood, strength of flood, slack before ebb, and strength of ebb in the case of the reversing type of current. A minimum velocity of the current follows a maximum velocity by an interval of about three hours and is followed in turn by another maximum velocity after a further interval of about three hours.

TABLE 40.—*Current data, stations 1, 2, and 3*

[Referred to time of current at Overfalls Light Vessel]

Station No.	Date of observations	Observations with—	Depth	Tidal current: Strength of flood: Time	Tidal current: Strength of flood: Velocity	Tidal current: Strength of flood: Direction	Tidal current: Minimum before ebb: Time	Tidal current: Minimum before ebb: Velocity	Tidal current: Minimum before ebb: Direction	Nontidal current: Velocity	Nontidal current: Direction	Length of observations
			Feet	*Hours*	*Knots*	*True*	*Hours*	*Knots*	*True*	*Knots*	*True*	*Days*
1	Apr. 26–May 24, 1919.	Pole	7	−1.0	0.05	N. 12° W.	−1.0	0.03	N. 78° E.	0.07	N. 54° W.	29
2	Sept. 10–11, 1879	Can	0	−1.0	0.09	N. 60° W.	−1.0	0.05	N. 21° E.	0.20	S. 41° W.	1
		Pole	10	−1.0	0.12	N. 80° W.	−1.0	0.08	N. 10° E.	0.32	S. 40° W.	1
3	July 21, 1913	Meter	0	−2.1	1.00	S. 82° W.						¼
		do	24	−2.0	0.96	S. 82° W.						¼
		do	144	−3.0	0.62	N. 18° W.						¼

Current data for stations 1, 2, and 3 are given in Table 40. At station 1, located about 65 miles east of Cape May, N. J., current observations by means of pole and log line were made by the officers and crew of the U. S. S. *Falcon*, from February 8 to May 14, 1919. This was a temporary lightship station during that period. Observations were made continuously at hourly intervals, day and night. The current pole used was the Coast and Geodetic Survey standard 15-foot pole, weighted with sheet lead so as to submerge 14 feet. The log line was graduated in knots and tenths of knots for a run of 60 seconds, which was the interval of time used for

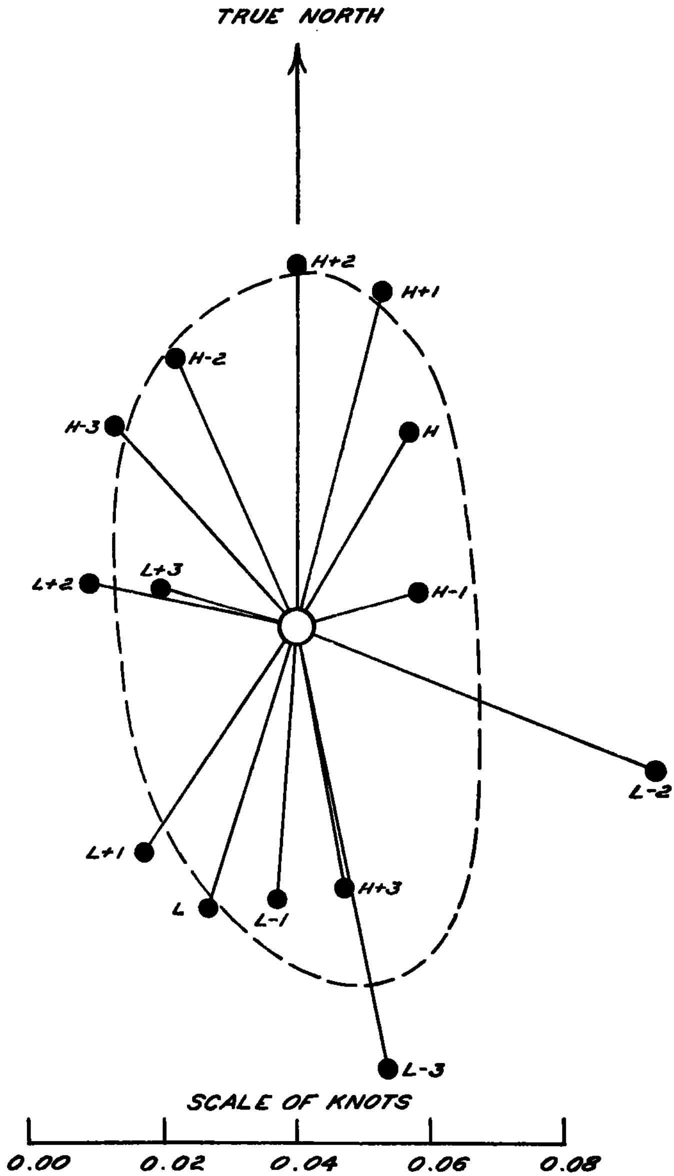

FIG. 25.—Current ellipse from nonharmonic tabulation, U. S. S. *Falcon* temporary light vessel station

each observation. Because of the length of the current pole used, current data for station 1 in Table 40 represents average current conditions at a depth of 7 feet, or, approximately, at the surface.

Figure 25 is a diagrammatic representation of the rotary tidal current at station 1 for a period of a tidal month, 29 days, from April 26 to May 24, 1919, referred to the times of high and low water at Sandy Hook, N. J. The current is rotary, turning clockwise. In the figure, *H* refers to the time of high water at Sandy Hook, while *L* refers to the time of low water at Sandy Hook. The numbers following *H* and *L* refer to hours before and after high or low water at Sandy Hook, the minus (−) sign meaning "earlier than". and the plus (+) sign "later than" those times of high or low water. The velocities of the current hour by hour, as represented by the full black lines in the figure may be scaled off by means of the scale of knots given in the figure. It will be noted that the velocity of the tidal current at any time is extremely small, as one would naturally expect at such a great distance offshore. The tidal current has a maximum velocity of about 0.05 knot, setting northerly or southerly and a minimum velocity of about 0.03 knot, setting easterly or westerly.

In Table 40, the times of maximum and minimum current at stations 1, 2, and 3 are referred to the times of the same phases of the current at Overfalls Light Vessel, located just outside the entrance to Delaware Bay. This is the reference station for the times of the current at all current stations mentioned in this publication. For instance, at station 1, the strength of flood, or maximum current occurs one hour earlier than the time of flood at Overfalls Light Vessel and sets N. 12° W. (true) with a velocity of 0.05 knot per hour. The time of minimum current before ebb at station 1 occurs one hour earlier than slack water before ebb at Overfalls Light Vessel and sets N. 78° E. (true) with a velocity of 0.03 knot per hour. It is to be noted that the tidal current at Overfalls Light Vessel is chiefly of the reversing type because of the nearness of the station to the entrance to Delaware Bay, while the tidal current at stations 1, 2, and 3 is distinctly rotary.

Currents were observed at station 2 for a period of one day, September 10–11, 1879. The current at this station is rotary, turning clockwise. Observations were made by Lieutenant Ackley at the surface with a can and log line and at a depth of 10 feet by means of a 20-foot current pole and log line. The results of these observations are given in Table 40. The set, or nontidal current, due presumably to wind effect was 0.07 knot, N. 54° W. (true) at station 1 and 0.32 knot, S. 40° W. (true) at station 2 during the period of observations at each station. It will be noted in Table 40 that the nontidal current is greater than the tidal current. This is frequently true offshore, and in many cases the weak tidal current is completely masked by the wind.

Observations were made for several hours at station 3 by Dr. H. B. Bigelow, on July 21, 1913. Currents were observed just below the surface and also at depths of 4 and 24 fathoms by means of a Price current meter with telephone attachment. The latter device was used to count the number of revolutions of the rotating cups, which were allowed to rotate through a time interval of five minutes.

In passing, it will be noted that the tidal current at stations 1, 2, and 3, located from 50 to 65 miles offshore is rotary in character, turns clockwise, and is very weak in velocity. The maximum current, corresponding with strength of flood at Overfalls Light Vessel

(Delaware Bay Entrance), sets westerly or northwesterly and occurs from one to two hours earlier than the same phase of the current at Overfalls Light Vessel. The minimum current, corresponding to slack before ebb at Overfalls Light Vessel sets northerly or northeasterly and occurs about an hour earlier than the corresponding phase of the current at Overfalls Light Vessel.

Stations 4, 5, and 6 are Northeast End, Five-Fathom Bank, and Fenwick Island Shoal Light Vessel stations, respectively. Station 6 represents the former location of Fenwick Island Shoal Light Vessel. The vessel is now located about 3 miles to the southward of the location shown in Figure 24. These light vessel stations are located in the approaches to Delaware Bay and are the first aids to navigation picked up by vessels bound to Delaware River ports. Five-Fathom Bank, about 10 miles in length, is located about 20 miles east of Delaware Bay Entrance. Northeast End Light Vessel and Five-Fathom Bank Light Vessel are located, respectively, off the northern and southern limits of this shoal area.

Continuous current observations by means of current pole and log line were made by the officers and crew of Northeast End Light Vessel (station 4) from November 8, 1912 to February 8, 1913, and from September 13, 1918 to October 31, 1919. The total length of observations for these two series is 16.6 months.

TABLE 41.—*Current data, station 4 (Northeast End Light Vessel)*

[Referred to time of current at Overfalls Light Vessel]

Series	Date of observations	Tidal current						Nontidal current	
		Strength of flood			Minimum before ebb				
		Time	Velocity	Direction	Time	Velocity	Direction	Velocity	Direction
		Hours	*Knots*	*True*	*Hours*	*Knots*	*True*	*Knots*	*True*
(*a*)	Nov. 9–Dec. 7, 1912							0.09	S. 77° E.
(*b*)	Dec. 8, 1912–Jan. 5, 1913.	−1.6	0.20	N. 64° W.	−1.4	0.06	N. 26° E.	0.16	N. 61° E.
(*c*)	Jan. 6–Feb. 3, 1913							0.06	S. 79° E.
(*d*)	Sept. 13–Oct. 11, 1918	−1.4	0.24	N. 64° W.	−0.7	0.09	N. 26° E.	0.02	N. 22° E.
(*e*)	Oct. 12–Nov. 9, 1918	−1.1	0.28	N. 58° W.	−0.6	0.08	N. 31° E.	0.01	South.
(*f*)	Nov. 2–30, 1918	−2.1	0.30	N. 54° W.	−0.7	0.10	N. 36° E.	0.05	S. 42° E.
(*g*)	Dec. 1–29, 1918	−1.4	0.29	N. 60° W.	−1.0	0.15	N. 30° E.	0.06	S. 10° W.
(*h*)	Jan. 31–Feb. 28, 1919	−1.3	0.33	N. 65° W.	−1.2	0.16	N. 24° E.	0.16	South.
(*i*)	March 1–29, 1919	−1.2	0.34	N. 68° W.	−1.6	0.18	N. 19° E.	0.14	S. 21° W.
(*j*)	April 1–29, 1919	−1.4	0.35	N. 63° W.	−1.2	0.18	N. 27° E.	0.06	S. 6° E.
(*k*)	May 1–29, 1919	−1.4	0.34	N. 72° W.	−1.2	0.19	N. 18° E.	0.08	S. 21° E.
	Means	−1.43	0.30	N. 63° W.	−1.07	0.13	N. 26° E.	0.05	S. 34° E.

Table 41 gives the current data at station 4 for eleven 29-day series of current observations in 1912, 1913, 1918, and 1919. The tidal current at this station is rotary, turning clockwise. For the tidal current the data are given for the strength of flood and minimum before ebb, since the strength of ebb and minimum before flood are the same, respectively, but with the directions of the current reversed. The time of the current is given with reference to the same phase of the current at Overfalls Light Vessel (Delaware Bay Entrance).

It will be noted from the mean values that the strength of flood at this station occurs about one and one-half hours earlier than the strength of flood at Overfalls Light Vessel. The flood sets northwesterly with a velocity of about 0.3 knot. The minimum before ebb occurs about one hour earlier than slack before ebb at Overfalls Light Vessel and sets northeasterly with a velocity of about 0.1 knot. The nontidal current shows a set of S. 34° E. with a velocity of 0.05 knot for the eleven 29-day periods of observations. The mean values for the velocity and direction of the set, or nontidal current, were derived by resolving the velocities and directions for the eleven 29-day periods.

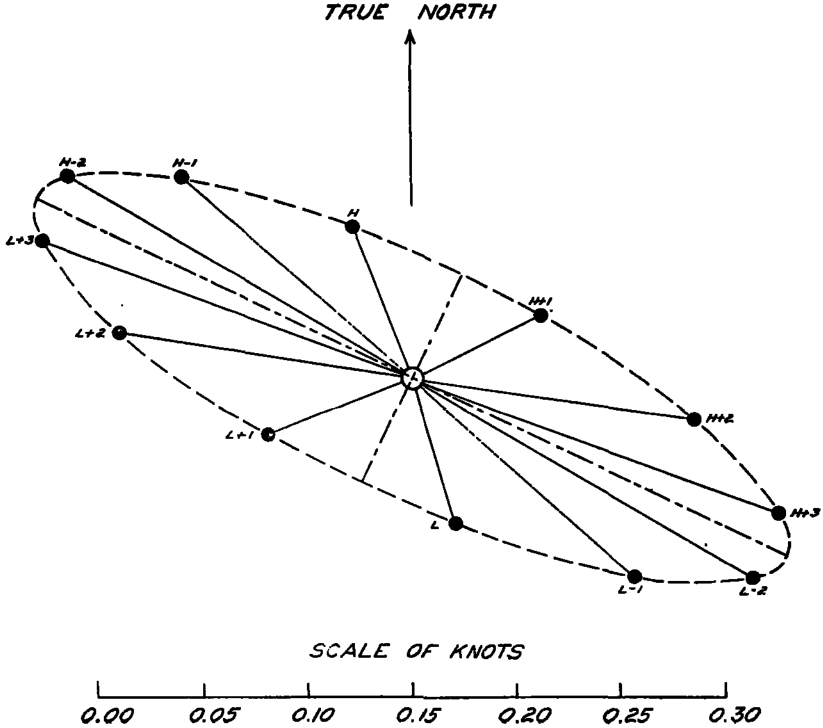

FIG. 26.—Current ellipse for M_2 component, Northeast End Light Vessel

The 87-day series from November 9, 1912, to February 3, 1913, at station 4 has been analyzed harmonically and results from this analysis are given in Table 42.

TABLE 42.—*Harmonic constants, station 4 (Northeast End Light Vessel)*

[From 87-day series, November 9, 1912, to February 3, 1913]

Component	North-and-south (magnetic)		East-and-west (magnetic)	
	H	κ	H	κ
	Knots	*Degrees*	*Knots*	*Degrees*
M_2	0.1179	168.61	0.1692	315.13
M_4	.0116	242.69	.0095	359.20
M_6	.0081	259.05	.0108	344.55
S_2	.0354	181.87	.0259	18.23
S_4	.0078	8.13	.0062	36.76

The current ellipse for the component M_2, Northeast End Light Vessel, based on the data in Table 42 above, is shown in Figure 26. The figure shows the current at station 4 to be relatively weak and rotary in character. The current has been referred to the times of high and low water at Sandy Hook, N. J. It will be noted that the strength of the flood current occurs about two and one-half hours before the time of high water at Sandy Hook and sets N. 65° W., with a velocity of 0.20 knot. The minimum current before ebb occurs about half an hour after the time of high water at Sandy Hook and sets N. 25° E. with a velocity of 0.05 knot.

Continuous current observations by means of current pole and log line were made by the officers and crew of Five Fathom Bank Light Vessel (station 5) from November 5, 1912–February 3, 1913, simultaneously with observations at Northeast End, Overfalls, and Fenwick Island Shoal Light Vessels.

TABLE 43.—*Current data, station 5 (Five-Fathom Bank Light Vessel)*

[Referred to time of current at Overfalls Light Vessel]

Series	Date of observations	Tidal current						Nontidal current	
		Strength of flood			Minimum before ebb				
		Time	Velocity	Direction	Time	Velocity	Direction	Velocity	Direction
		Hours	*Knots*	*True*	*Hours*	*Knots*	*True*	*Knots*	*True*
(a)	Nov. 6–Dec. 4, 1912	−1.1	0.31	N. 68° W.	−0.9	0.08	N. 23° E.	0.13	S. 66° E.
(b)	Dec. 5, 1912–Jan. 2, 1913	−1.5	.34	N. 70° W.	−1.2	.09	N. 20° E.	.14	S. 81° E.
(c)	Jan. 3–31, 1913	−1.2	.32	N. 70° W.	−1.1	.07	N. 20° E.	.07	S. 82° E.
	Means	−1.27	.32	N. 69° W.	−1.07	.08	N. 21° E.	.11	S. 75° E.

Table 43 gives the current data at station 5 for three 29-day series of current observations in 1912 and 1913. The tidal current at this station, as at station 4, is rotary, turning clockwise. For the tidal current the data are given for the strength of flood and minimum before ebb, since the strength of ebb and minimum before flood are the same, respectively, but with the directions of the current reversed. The time of the current is given with reference to the corresponding phase of the current at Overfalls Light Vessel.

It will be noted from the mean values that the strength of flood occurs about one and one-fourth hours earlier than the strength of flood at Overfalls Light Vessel and sets northwesterly with a velocity of about 0.3 knot, similar to that at Northeast End Light Vessel. The minimum before ebb occurs about one hour earlier than slack before ebb at Overfalls Light Vessel and sets northeasterly with a velocity of about 0.1 knot. The nontidal current shows a set S. 75° E. with a velocity of 0.11 knot for the three-month period, November 6, 1912, to January 31, 1913.

Figure 27 is a diagrammatic representation of the tidal current at station 5, Five-Fathom Bank Light Vessel, from a three-month nonharmonic tabulation November 6, 1912, to January 31, 1913. The current has been referred to the times of high and low water at Sandy Hook, N. J. Strength of flood occurs about two and one-fourth hours earlier than the time of high water at Sandy Hook, and sets N. 70° W. with a velocity of 0.3 knot. The minimum before ebb occurs about one hour after the time of high water at Sandy Hook and sets N. 20° E. with a velocity of about 0.1 knot. The tidal current at this station is relatively weak. Currents of a knot or more at stations 4 and 5 occur only with strong winds and are therefore chiefly nontidal.

Offshore tidal observations covering a period of 40 hours were made on the southern end of Five-Fathom Bank (latitude 38° 50.7′ N., longitude 74° 37.8′ W.), about 5 miles northwest of Five-Fathom

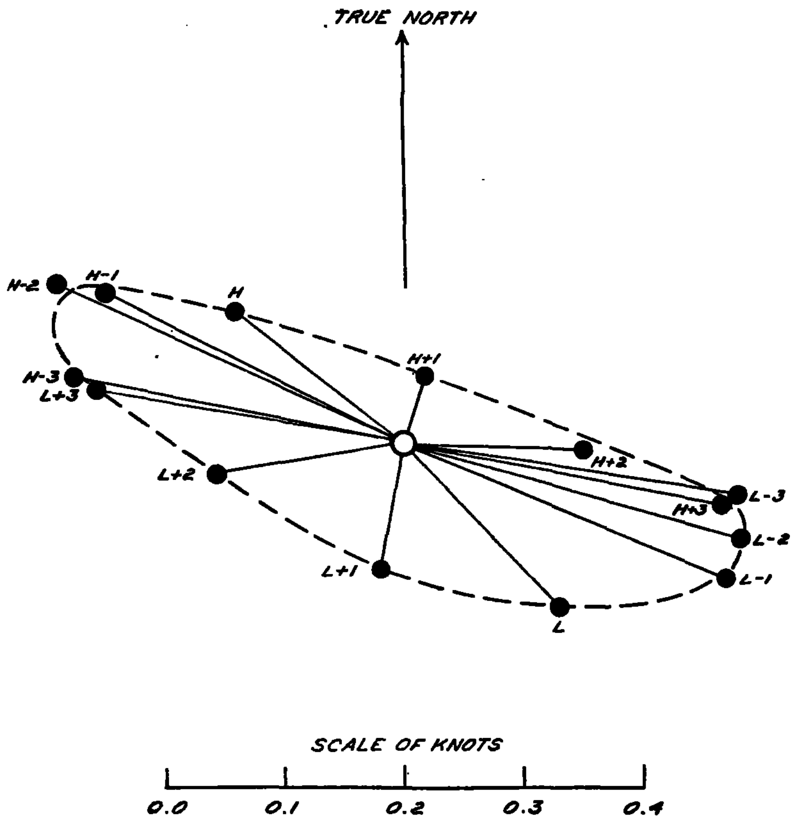

FIG. 27.—Current ellipse from nonharmonic tabulation, Five-Fathom Bank Light Vessel

Bank Light Vessel (current station 5), on September 28–30, 1920. The results of these observations show that the time of tide at Five-Fathom Bank is about 45 minutes earlier than at Breakwater Harbor, Del., and that the mean range of tide, 4.3 feet, is approximately the same at both places. Based on these observations the cotidal hour for Five-Fathom Bank is about XII.2, while that for Breakwater Harbor, Del., is about I.0. The cotidal hour at any place is the time in lunar hours after the moon's transit across the Greenwich meridian at which high water occurs at that place. The cotidal hour at Five-Fathom Bank Light Vessel would be approximately the same as that for Five-Fathom Bank, or XII.2.

The results of an 87-day series of current observations at Five-Fathom Bank Light Vessel in 1912–13 show the cocurrent hour at this station to be X.5. The cocurrent hour at any place is the time in lunar hours after the moon's transit across the Greenwich meridian at which the strength of flood occurs at that place. It will be noted therefore by comparison between the cotidal and cocurrent hours for Five-Fathom Bank Light Vessel that the strength of flood at this station occurs I.7 lunar hours, or 1¾ solar hours, earlier than local high water.

TABLE 44.—*Harmonic constants, station 6 (Fenwick Island Shoal Light Vessel)*

[From 87-day series, Nov. 5, 1912, to Jan. 30, 1913]

Component	North-and-South (magnetic)		East-and-West (magnetic)	
	H	κ	H	κ
	Knots	*Degrees*	*Knots*	*Degrees*
M_2	0.2601	194.16	0.1171	319.88
M_4	.0090	242.28	.0213	322.12
M_6	.0079	256.38	.0118	285.31
S_2	.0543	208.26	.0231	354.01
S_4	.0022	341.08	.0025	180.88

Hourly current observations by means of current pole and log line were made by the officers and crew of Fenwick Island Shoal Light Vessel (station 6) from November 4, 1912, to February 4, 1913. An 87-day series, from November 5, 1912, to January 30, 1913, was analyzed harmonically and the results of this analysis are given in Table 44.

Figure 28 represents the M_2 current ellipse for station 6, Fenwick Island Shoal Light Vessel, derived from the constants above. The velocities and directions of the tidal current are shown for each hour with reference to the times of high and low water at Sandy Hook, N. J., *H* representing the time of high water, and *L* the time of low water. It is obvious that the current at station 6 is rotary, relatively weak, and turns clockwise. The strength of flood occurs about 1 hour before the time of high water at Sandy Hook, or simultaneously with the time of strength of flood at Overfalls Light Vessel. The flood sets N. 20° W. with a velocity of 0.3 knot. The minimum before ebb occurs about 2 hours after the time of high water at Sandy Hook, or simultaneously with the time of slack water before ebb at Overfalls Light Vessel, and sets N. 70° E. with a velocity of 0.1 knot. The velocities and directions of the current derived from the current ellipse of Figure 28 refer to the tidal current only, for the harmonic analysis eliminates the nontidal current. Maximum and minimum currents are represented by dot-and-dashed lines in Figure 28.

Current observations by means of current pole and log line were made hourly by the officers and crew of the Overfalls Light Vessel (station 7) as follows: November 7, 1912, to February 6, 1913; September 13 to December 18, 1918; February 22 to May 2, 1919; July 1, 1919, to January 17, 1920; March 21, 1920, to January 20, 1921; March 13 to July 31, 1921; August 18, 1924, to May 14, 1925. The total length of observations for these seven current series is 38.7 months, or approximately, 3¼ years.

Overfalls Light Vessel is located about 4 miles off Cape Henlopen, Del., and just outside the entrance to Delaware Bay. It is one of the important aids to navigation for vessels bound from and to Delaware Bay. Vessels inward bound pass between Overfalls Light Vessel and Cape Henlopen. Vessels leaving Delaware Bay usually follow the

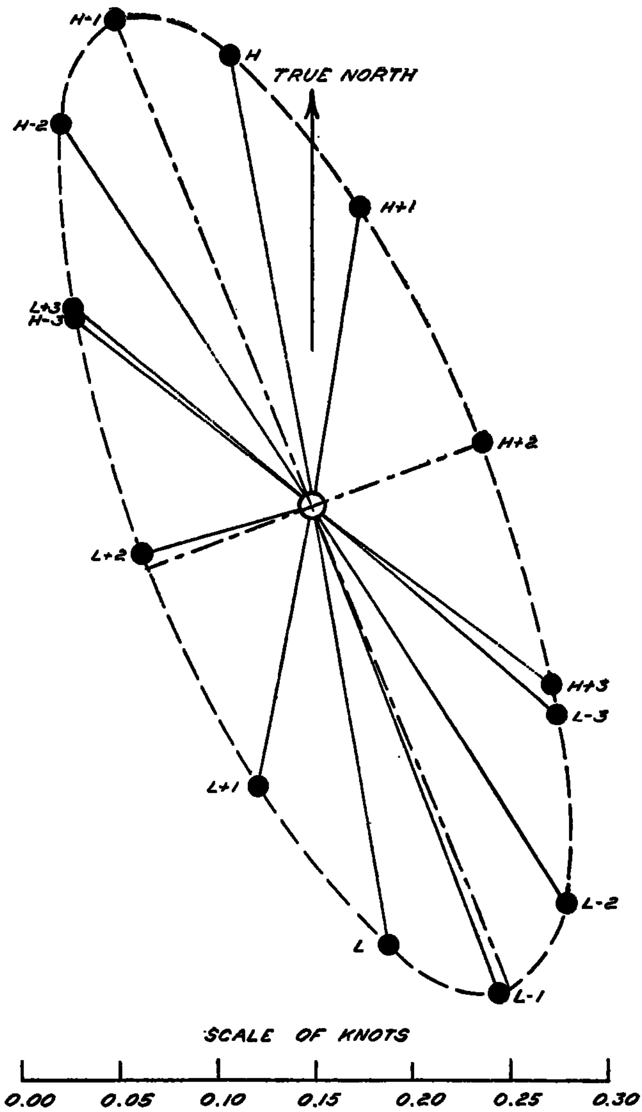

FIG. 28.—Current ellipse for M_2 component, Fenwick Island Shoal Light Vessel

same course, although there is considerable deep water between the light vessel and Overfalls, or South Shoal. Strong tidal currents obtain at Overfalls Light Vessel. The current is chiefly of the reversing, or rectilinear type, due to the position of the light vessel at the entrance to Delaware Bay.

TABLE 45.—*Current data, station 7 (Overfalls Light Vessel)*

[Referred to times of high water and low water at Sandy Hook, N. J.]

Series	Date of observations	Slack	Flood strength			Flood duration	Slack	Ebb strength			Ebb duration
			Time	Direction	Velocity			Time	Direction	Velocity	
		Hours after L.W.	*Hours before H.W.*	*True*	*Knots*	*Hours*	*Hours after H.W.*	*Hours before L.W.*	*True*	*Knots*	*Hours*
(a)	Nov. 8–Dec. 6, 1912	2.4	1.0	N. 30° W.	2.01	5.8	2.1	1.1	S. 48° E.	2.20	6.6
(b)	Dec. 7, 1912–Jan. 4, 1913	2.6	1.0	N. 32° W.	1.96	5.7	2.2	.9	S. 46° E.	2.35	6.7
(c)	Jan. 5–Feb. 2, 1913	2.6	1.0	N. 38° W.	2.06	5.4	1.9	.9	S. 38° E.	2.41	7.0
(d)	Sept. 13–Oct. 11, 1918	1.9	1.2	N. 58° W.	1.73	6.4	2.2	1.6	S. 58° E.	1.48	6.0
(e)	Oct. 3–31, 1918	1.8	1.1	N. 56° W.	1.81	6.5	2.2	1.6	S. 59° E.	1.56	5.9
(f)	Nov. 1–29, 1918	1.8	1.2	N. 59° W.	1.78	6.2	1.9	1.6	S. 53° E.	1.61	6.2
(g)	Mar. 1–29, 1919	2.1	.9	N. 56° W.	1.82	6.1	2.1	1.4	S. 45° E.	1.91	6.3
(h)	Apr. 1–29, 1919	2.0	1.0	N. 51° W.	1.91	6.1	2.0	1.6	S. 50° E.	1.82	6.3
(i)	July 1–29, 1919	2.1	1.0	N. 52° W.	1.96	5.9	1.9	1.5	S. 48° E.	2.26	6.5
(j)	Aug. 1–29, 1919	2.4	.8	N. 59° W.	1.96	5.6	1.9	1.3	S. 49° E.	2.26	6.8
(k)	Sept. 1–29, 1919	2.2	1.1	N. 60° W.	1.88	6.0	2.1	1.5	S. 50° E.	2.00	6.4
(l)	Oct. 1–29, 1919	2.0	1.0	N. 59° W.	1.75	6.2	2.1	1.4	S. 47° E.	1.77	6.2
(m)	Nov. 1–29, 1919	2.0	1.0	N. 61° W.	1.78	6.2	2.1	1.5	S. 49° E.	1.89	6.2
(n)	Dec. 1–29, 1919	2.1	.9	N. 63° W.	1.72	6.1	2.1	1.2	S. 44° E.	2.00	6.3
(o)	Apr. 1–29, 1920	2.3	.9	N. 45° W.	1.95	5.7	1.9	1.0	S. 42° E.	2.42	6.7
(p)	May 1–29, 1920	2.2	1.1	N. 54° W.	1.84	5.9	2.0	1.3	S. 38° E.	2.03	6.5
(q)	June 1–29, 1920	2.2	1.1	N. 51° W.	1.97	6.0	2.1	1.0	S. 43° E.	2.30	6.4
(r)	Dec. 1–29, 1920	2.5	.9	N. 48° W.	1.63	5.8	2.2	1.0	S. 46° E.	1.73	6.6
(s)	Apr. 1–29, 1921	2.1	1.0	N. 59° W.	1.70	5.9	1.9	1.5	S. 44° E.	2.02	6.5
(t)	May 1–29, 1921	2.0	1.2	N. 55° W.	1.83	6.0	1.9	1.3	S. 43° E.	1.84	6.4
(u)	June 1–29, 1921	2.1	1.2	N. 50° W.	1.93	6.1	2.1	1.3	S. 42° E.	1.78	6.3
(v)	July 1–29, 1921	2.1	1.0	N. 48° W.	1.87	6.0	2.0	1.3	S. 43° E.	1.77	6.4
	Means	2.16	1.03	N. 52° W.	1.86	5.98	2.04	1.31	S. 47° E.	1.97	6.42

Table 45 gives the current data at station 7 (Overfalls Light Vessel) for twenty-two 29-day series of current observations in 1912, 1913, 1918, 1919, 1920, and 1921. Since the times of the current at all current stations in this publication have been referred to the times of the current at Overfalls Light Vessel as a standard or reference station, it was necessary in the above table to refer the times of the current at Overfalls Light Vessel to the times of high and low water at Sandy Hook, N. J. It will be noted from the mean results in the table that the time of slack water at the light vessel occurs about 2.1 hours after the times of high and low water at Sandy Hook. The strength of flood occurs one hour before the time of high water at Sandy Hook and sets about N. 50° W. with a velocity of 1.9 knots per hour. The strength of ebb occurs 1⅓ hours before the time of low water at Sandy Hook and sets about S. 50° E. with a velocity of 2.0 knots. The duration of the flood, or northerly current, is about 6.0 hours and of the ebb, or southerly current, 6.4 hours.

Based on tidal observations at Five-Fathom Bank and at Breakwater Harbor, Del., it has been computed that the cotidal hour for Overfalls Light Vessel is about XII.8. The results of several years of current observations at this station show the cocurrent hour to be XI.3. It will be noted, therefore, that the strength of flood at this station occurs I.5 lunar hours, or 1½ solar hours, earlier than local high water. Definitions for "cotidal hour" and "cocurrent hour" are given on pages 71–72, in the discussion of the relationship between the current and tide at Five-Fathom Bank Light Vessel.

Figure 29 is a diagrammatic representation of the tidal current at Overfalls Light Vessel, based upon a resolved, nonharmonic tabulation of currents at this station for a 29-day series, April 1 to 29, 1921, referred to the times of high and low water at Sandy Hook, N. J. The figure shows the current to be only slightly rotary, in a clockwise direction. The nontidal current, setting S. 17° E. with a velocity of 0.12 knot, is shown in the figure by the relationship of the center of circle *C* to the center of the circle from which radiate the full black lines representing the hourly velocities and directions of the

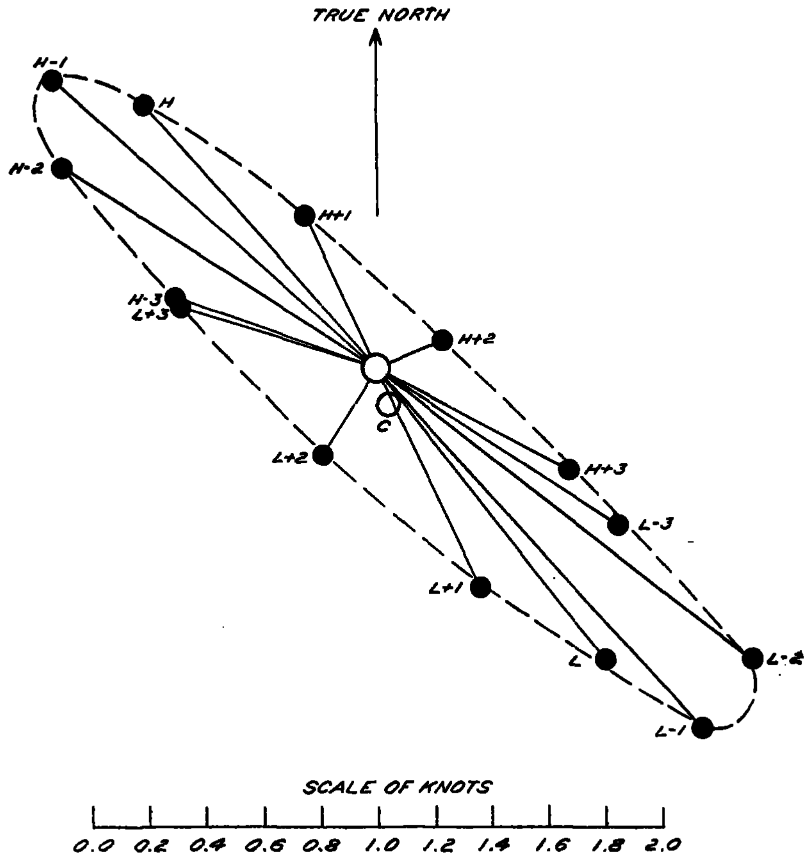

FIG. 29.—Current ellipse from nonharmonic tabulation, Overfalls Light Vessel

current. It will be noted that the strength of flood occurs about 1 hour before high water at Sandy Hook, while slack water before ebb occurs about 2 hours after high water, and the light vessel, swinging to one anchor, then heads toward Cape Henlopen, Del. Actually, a minimum current of about 0.3 knot obtains at this time, setting toward Cape May, N. J. It will also be noted from the figure that the strength of ebb occurs about 1⅓ hours before the time of low water at Sandy Hook, while slack water before flood occurs about 2 hours after low water, and at this time a minimum current of about 0.3 knot sets toward Cape Henlopen, Del.

TABLE 46.—*Current data, station 7 (Overfalls Light Vessel)*

[Referred to times of high water and low water at Sandy Hook, N. J.]

Date of observations	Observations with	Depth	Slack	Flood strength			Slack	Ebb strength			Length of observations
				Time	Direction	Velocity		Time	Direction	Velocity	
		Feet	*Hours after L.W.*	*Hours before H.W.*	*True*	*Knots*	*Hours after H.W.*	*Hours before L.W.*	*True*	*Knots*	*Days*
1924											
Aug. 18-22	Pole	7	2.0	1.2	N. 44° W.	1.96	2.4	1.7	S. 46° E.	1.88	4¼
Do	Meter	7	2.1	1.0		2.09	2.6	1.9		1.91	4
Do	do	15	2.1	1.0		2.13	2.6	1.6		1.86	4
Do	do	35	2.0	1.0		1.97	2.6	1.7		1.57	4
Do	do	55	1.9	.8		1.55	2.6	1.4		1.27	4

While a comprehensive tidal and current survey of Delaware Bay and River was in progress during the summer of 1924, current meter observations, in addition to current pole observations, were obtained at Overfalls Light Vessel (station 7). The results of these observations are shown in Table 46. The observations were made by means of a Price current meter with telephone attachment for recording the velocities of the current at depths of 7, 15, 35, and 55 feet. No observations of subsurface directions of the current are at hand but it is reasonable to assume that the direction of the current at various depths at this station is approximately the same as that for flood and ebb at the surface. The data obtained during the 4-day period of these observations, August 18 to 22, 1925, indicates only a slightly reduced current toward the bottom.

In Table 46 the depths 15, 35, and 55 feet are, respectively, 0.2, 0.5, and 0.8 of the total depth of water at Overfalls Light Vessel, or, approximately, the surface, middle depth, and bottom. It will be noted from the table that the times of slack water (minimum current) and strengths of flood and ebb (maximum current) occur practically simultaneously at all depths. The velocities of flood and ebb, however, generally decrease with the depth.

The greatest flood and ebb velocities observed at Overfalls Light Vessel (station 7) in 1912, 1913, 1918, and 1919, are as follows:

Year	Month and day	Current	Direction	Velocity	Wind	
					Direction	Velocity
			True	*Knots*	*True*	*Miles*
1912	Dec. 11	Flood	N. 44° W.	2.6	S. 38° W.	13
	Dec. 27	Ebb	S. 46° E.	3.6	N. 75° W.	34
1913	Jan. 20	Flood	N. 58° W.	3.2	S. 7° E.	13
	Jan. 12	Ebb	S. 36° E.	3.4	N. 52° W.	34
1918	Nov. 4	Flood	N. 42° W.	2.4	S. 37° W.	13
	Nov. 18	Ebb	S. 70° E.	2.2	S. 37° W.	23
1919	Apr. 30	Flood	N. 53° W.	3.0	S. 8° E.	13
	July 26	Ebb	S. 32° E.	3.2	N. 14° E.	13

Stations 8 to 16, located in rather shoal water near the Delaware Capes, were occupied by the field party of J. R. Goldsborough in the summer of 1847. The current at these stations is chiefly of the reversing, or rectilinear, type. The results of the pole observations at these stations are given in Table 47. The times of slack and strength are given in hours and tenths and are referred to the times of the corresponding phases of the current at Overfalls Light Vessel. The velocities of the current are given in knots and tenths and are corrected to a mean range of tide. The directions of the current are given to the nearest 5°. The duration of the flood and ebb is given in hours and tenths of hours.

TABLE 47.—*Current data, stations 8–16, approaches to Delaware Bay*

[Referred to time of current at Overfalls Light Vessel]

Station No.	Date of observations [1]	Slack	Flood strength			Flood duration	Slack	Ebb strength			Ebb duration	Length of observations
			Time	Direction	Velocity			Time	Direction	Velocity		
	1847	*Hours*	*Hours*	*True*	*Knots*	*Hours*	*Hours*	*Hours*	*True*	*Knots*	*Hours*	*Days*
8	Sept. 17	−1.3	−0.8	N. 50° W.	0.9	6.0	−1.3	−1.4	N. 35° E.	1.2	6.4	½
9	Sept. 15–16	−1.1	−1.5	S. 90° W.	1.2	5.5	−1.6	−2.0	N. 85° E.	1.3	6.9	½
10	Aug. 26	−1.1	−1.8	N. 85° W.	1.4	5.8	−1.3	−1.5	S. 80° E.	1.4	6.6	½
11	Sept. 6–7	−1.1	−1.8	N. 65° W.	1.7	6.0	−1.1	−1.0	S. 50° E.	1.9	6.4	½
12	Aug. 27	−0.4	−1.2	N. 40° W.	2.1	5.2	−1.2	−0.9	S. 65° E.	2.0	7.2	½
13	Sept. 8–9	−1.1	−1.7	N. 65° W.	1.3	5.8	−1.3	−1.4	S. 85° E.	1.7	6.6	½
14	Sept 16–17	−1.1	−1.7	N. 45° W.	1.3	5.8	−1.3	−1.2	S. 80° E.	1.4	6.6	½
15	Sept. 18	−0.6	−0.6	N. 65° W.	1.3	5.7	−0.9	−0.3	N. 85° E.	1.5	6.7	½
16	Sept. 28–29	−0.5	+0.1	N. 25° W.	1.0	5.8	−0.7	+0.3	S. 20° E.	1.2	6.6	½

[1] Party of J. R. Goldsborough.

It will be noted from Table 47 that the duration of ebb at each station is longer than that for the flood, at station 12 being two hours longer. At all stations, slack water before flood occurs from half an hour to one hour earlier than slack before flood at Overfalls Light Vessel. This is due to the shoalness of the water at these stations compared with the much greater depth of water at station 7 (Overfalls Light Vessel).

The times of flood and ebb strengths occur much earlier at these stations than at Overfalls Light Vessel with the exception of station 16. At the latter station, flood and ebb strengths occur a few minutes later than the same phases of the current at station 7. Velocities of flood and ebb strengths at stations 10, 11, 12, and 13 may differ from existing velocities, owing to the changed conditions of the bottom since 1847 when the current observations were made. Many changes have occurred in the extent and position of shoal areas off Cape May since that time.

In general, the tidal current accompanying the tide approaches Delaware Bay Entrance from the northeast. The observations at stations 1 to 5 and also at stations 8 to 15 show that the current is much earlier at these stations than at station 7 (Overfalls Light Vessel). At station 6, (Fenwick Island Shoal Light Vessel) located about 23 nautical miles southeast of station 7, the current is practically simultaneous with that at the latter station, while at station 16, located off Cape Henlopen in much shoaler water, the current is actually later than that at stations 6 and 7. In general, the current in the approaches to Delaware Bay is rotary, turns clockwise, and is very weak. This is especially true beyond the 10-fathom depth curve. Near the entrance to the bay, however, the current increases in strength to about 2.0 knots and becomes chiefly of the reversing, or rectilinear, type. Because of river discharge from Delaware Bay, the duration of ebb for stations near the bay entrance becomes considerably greater than that for the flood.

THE CURRENT IN DELAWARE BAY

Delaware Bay is here understood to comprise the body of water between the States of New Jersey and Delaware, bounded on the south by a line joining Cape May Light, N. J. and Cape Henlopen Light, Del., and extending northward as far as Artificial Island, off Stony Point, N. J. The entrance to the bay, between Capes Henlopen and May is about 10 nautical miles in width. The bay is about 42 nautical miles in length, and has a maximum width of about 23 nautical miles.

The entrance to the bay, except for a 3-mile stretch in the vicinity of Overfalls Light Vessel, off Cape Henlopen, is marked by numerous shoals. Of these, Overfalls, or South Shoal, is the most prominent. These shoals are located chiefly off Cape May, N. J., and are separated by several channels, prominent ones being Cape May Channel and Through Channel.

In general, the water in the eastern part of Delaware Bay is quite shallow, the bottom consisting of extensive flats and shoal areas. The prevailing depths of water are from 7 to 15 feet with many spots of less than 6 feet. The western part of Delaware Bay shows similar characteristics. The eastern and western shores of the bay are low and marshy and are dissected by many small rivers and creeks which are narrow and crooked.

The main shoal area in Delaware Bay is Joe Flogger Shoal, a long, narrow shoal lying about midway between Egg Island Point, N. J., and Murderkill Neck, Del., and extending in a northwest-southeast direction. Lying east of this shoal is the Upper, or Main Ship, Channel, marked by Fourteen-Foot Bank, Miah Maull, and Elbow of Cross Ledge Lights. West of this shoal lies Blake, or Lower, Channel.

Figure 30 shows the locations of 34 current stations occupied in Delaware Bay by the following field parties of the United States Coast and Geodetic Survey: J. R. Goldsborough, in 1847; F. H. Crosby, in 1885; H. L. Marindin, in 1886; and W. H. Overshiner, in 1924. Observations at a majority of these stations were made in the summer of 1924, when the Coast and Geodetic Survey made an extensive tide and current survey of Delaware Bay and River from the Delaware Capes to Trenton, N. J. Currents were observed on cross sections of Delaware Bay in 1924, as follows:

1.—Between Capes Henlopen and May—stations 1, 2, 5, and 7.

2.—Between Jones Neck, Del., and Egg Island Pt., N. J.—stations 24, 25, and 26.

3.—Between Bombay Hook, Del., and Bacon Neck, N. J.—stations 30, 31, and 32.

Station 31 was a control station for current stations occupied in Delaware Bay in 1924, and continuous observations by current pole and log line and also by current meter were made at this station for 32¼ days from August 8 to September 11.

In addition to observations in Delaware Bay proper, current observations were also obtained at Mispillion Creek Entrance, Maurice River Entrance, and Cohansey Creek Entrance. The data

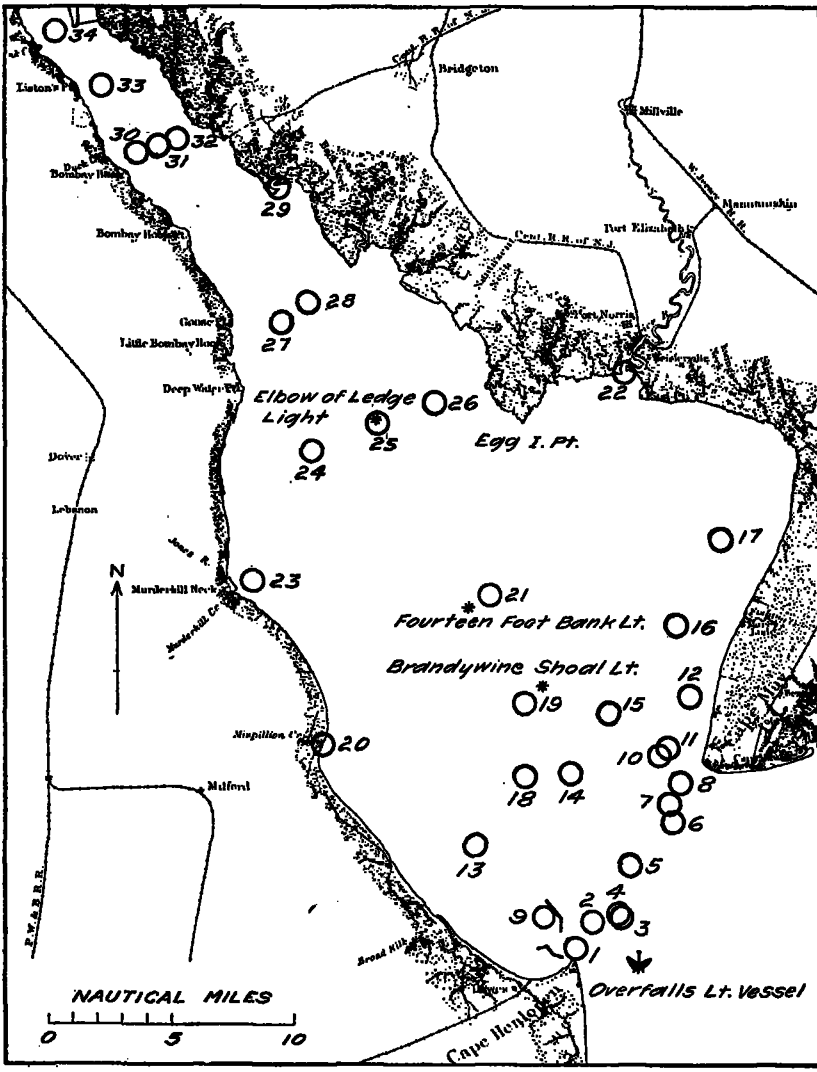

FIG. 30.—Current stations, Delaware Bay

derived from current observations at these 34 stations in Delaware Bay are given in Table 48. For each station these data refer to the tidal current near the surface, at a depth of about 7 feet, and are based on observations made by means of current pole and log line.

TABLE 48.—*Current data, Delaware Bay*

[Referred to time of current at Overfalls Light Vessel]

Station No.	Location	Party of—	Date	Slack	Flood strength			Flood duration	Slack	Ebb strength			Ebb duration	Length of observations
					Time	Direction	Velocity			Time	Direction	Velocity		
				Hours	*Hours*	*True*	*Knots*	*Hours*	*Hours*	*Hours*	*True*	*Knots*	*Hours*	*Days*
1	Off Cape Henlopen	W. H. Overshiner	August, 1924	−0.6	−0.4	N. 65° W.	1.5	6.3	−0.3	−0.6	S. 50° E.	1.7	6.1	1
2	do	do	do	0.3	0.0	N. 25° W.	1.9	6.0	0.3	0.5	S. 30° E.	2.0	6.4	1
3	do	J. R. Goldsborough	September, 1847	−1.1	−1.1	N. 70° W.	1.8	5.9	−1.2	−1.3	S. 40° E.	1.9	6.5	½
4	do	H. L. Marinden	August, 1886	0.1	−0.5	N. 65° W.	1.3	5.5	−0.4	0.4	S. 35° E.	2.1	6.9	2½
5	do	W. H. Overshiner	August, 1924	−0.7	−1.8	N. 35° W.	1.2	6.3	−0.4	−0.4	S. 15° E.	1.7	6.1	1½
6	Off Cape May	J. R. Goldsborough	September, 1847	−1.2	−1.3	N. 60° W.	2.2	6.0	−1.2	−1.2	S. 35° E.	1.7	6.4	½
7	do	W. H. Overshiner	August, 1924	−1.6	−2.3	N. 30° W.	0.8	6.1	−1.5	−2.0	S. 5° E.	1.4	6.3	1
8	do	J. R. Goldsborough	August, 1847	−1.1	−1.9	N. 50° W.	1.1	5.7	−1.4	−1.6	S. 35° E.	1.3	6.7	½
9	Off Cape Henlopen	do	do	−2.0	−2.1	N. 55° W.	1.3	6.6	−1.4	−2.3	S. 65° E.	1.1	5.8	½
10	Off Cape May	do	do	−1.3	−1.6	N. 35° W.	1.6	5.6	−1.7	−2.3	S. 20° E.	1.3	6.8	½
11	do	do	do	−1.6	−2.1	N. 10° W.	1.1	5.9	−1.7	−0.7	S. 5° E.	1.1	6.5	½
12	do	do	do	−1.8	−2.7		1.7	6.2	−1.6	−2.0	S. 5° W.	1.7	6.2	½
13	Off Broadkill Neck	W. H. Overshiner	August, 1924	0.8	−0.1	N. 45° W.	1.0	4.6	−0.6	0.2	S. 55° E.	1.6	7.8	½
14	Off Cape May	J. R. Goldsborough	August, 1874	0.1	−0.6	N. 15° W.	1.7	5.2	−0.7	0.8	S. 20° E.	1.7	7.2	½
15	do	do	do	−0.4	−1.4	N. 5° E.	1.3	4.8	−1.6	−0.8	S. 5° W.	1.8	7.6	½
16	Off Fishing Creek	W. H. Overshiner	August, 1924	−0.6	−1.4	N. 10° E.	1.4	6.0	−0.6	−0.4	S. 20° W.	1.3	6.4	½
17	do	F. H. Crosby	September, 1885	0.1	−0.6	N. 30° E.	0.5	5.1	−0.8	−0.3	S. 30° W.	0.6	7.3	½
18	Off Broadkill Neck	J. R. Goldsborough	August, 1847	1.0	−0.4	N. 35° W.	1.4	5.0	0.0	0.8	S. 25° E.	1.5	7.0	½
19	Off Brandywine Shoal Light	do	do	−0.1	−0.8	N. 25° W.	1.4	5.9	−0.2	−0.1	S. 30° E.	1.5	6.5	½
20	Mispillion Creek Entrance	W. H. Overshiner	August, 1924	0.0	0.6	N. 30° W.	0.6	6.3	0.3	1.0	S. 10° E.	0.6	6.1	½
21	Off 14-Foot Bank Light	do	do	0.4	−0.4	N. 15° W.	1.2	5.5	−0.1	1.2	S. 25° E.	1.6	6.9	1
22	Maurice River Entrance	do	do	0.0	0.5	N. 10° W.	1.1	6.6	0.6	0.9	S. 5° W.	0.8	5.8	1
23	Off Murderkill Neck	do	do	−0.2	−0.2	N. 25° W.	0.5	6.6	0.4	1.2	S. 60° E.	0.5	5.8	1
24	Off Deep Water Point	do	September, 1924	−0.2	0.5	N. 40° W.	0.9	6.5	0.3	−0.2	S. 20° E.	0.7	5.9	1
25	Off Elbow of Cross Ledge Light	do	do	1.3	1.4	N. 35° W.	1.4	5.6	0.9	2.0	S. 15° E.	2.1	6.8	3
26	Off Egg Island Point	do	do	0.6	0.5	N. 25° W.	0.9	6.0	0.6	1.6	S. 25° E.	1.0	6.4	1
27	Off Goose Point	do	August, 1924	1.7	1.5	N. 40° W.	1.4	5.4	1.1	2.2	S. 35° E.	2.0	7.0	½
28	do	do	do	1.8	2.5	N. 25° W.	1.2	5.6	1.4	1.6	S. 35° E.	1.6	6.8	½
29	Cohansey Creek Entrance	do	September, 1924	0.2	0.5	N. 90° W.	1.5			0.1	N. 60° E.	1.1		½
30	Off Bombay Hook	do	August, 1924	2.5	1.5	N. 30° W.	1.9	5.5	2.0	2.7	S. 40° E.	1.7	6.9	1
31	do	do	do	2.5	2.2	N. 40° W.	1.6	5.6	2.1	2.9	S. 40° E.	2.0	6.8	32¼
32	do	do	do	1.5	1.6	N. 30° W.	0.9	5.7	1.2	1.2	S. 45° E.	1.1	6.7	1
33	Off Liston Point	do	September, 1924	2.8	2.2	N. 30° W.	2.0	5.3	2.1	3.3	S. 40° E.	2.5	7.1	½
34	Off Stony Point	do	August, 1924	3.4	2.9	N. 25° W.	2.2	5.4	2.8	3.7	S. 35° E.	2.2	7.0	1

In Table 48 the times of slack water and strengths of flood and ebb are given in hours and tenths of hours and are referred to the times of the corresponding phases of the current at Overfalls Light Vessel. The durations of flood and ebb are also given in hours and tenths of hours and it will be noted from the table that the duration of ebb at nearly all the current stations in Delaware Bay is much greater than that for the flood. The velocities of flood and ebb strengths are given in knots and tenths of knots and are corrected to a mean range of tide. The true directions of the flood and ebb currents at times of strength are given to the nearest 5°.

In general, it will be noted from the table that the current turns earliest in the shallower reaches near the eastern and western shores of the bay and latest in the deeper, central part of the bay. The deeper portion of the bay, referring to Figure 30, is located by connecting with straight lines Overfalls Light Vessel, Brandywine Shoal Light, Fourteen-Foot Bank Light, and Elbow of Cross Ledge Light. These aids to navigation mark the Main Ship Channel, which is a natural channel with a depth at mean low water of 35 feet or more, leading from the entrance of the bay to the vicinity of station 31, where a 32-foot dredged channel begins. This channel has a width of about 2½ miles at the bay entrance between Cape Henlopen and the shoals off Cape May and a least width of about ¼ mile off Elbow of Cross Ledge Light.

It will be noted from Table 48 that at stations 5, 6, 7, 8, 10, and 11, located in the shoal areas and channels of Delaware Bay Entrance in the vicinity of Cape May, N. J., the current turns one-half to one and three-fourths hours earlier than it does at Overfalls Light Vessel. The maximum depth of water at these stations is about 45 feet, while the average depth is considerably less than that.

It will be noted from the table that at stations 2, 3, and 4 the current occurs approximately simultaneous with that at Overfalls Light Vessel. Comparing data for station 2 in Table 48 with that for the control station (station 31), it is found that the current occurs about two hours earlier at the navigable entrance to Delaware Bay than it does off Bombay Hook.

Current stations 14, 19, 21, 25, 28, 31, 33, and 34 were located along the axes of the natural and dredged channels of Delaware Bay. The data in Table 48 show that the current becomes later and later at each of these stations from Delaware Bay Entrance to Artificial Island. At station 34, in mid-channel off Stony Point, N. J., it becomes later by about three hours.

Along the eastern shore of the bay in Bay Shore Channel, Fishing Creek Shoal, and Maurice River Cove the current turns earlier than it does along the axis of the channel. This is shown by the data in Table 48 for stations 12, 16, 17, and 22.

No current stations have been occupied by the Coast and Geodetic Survey in Maurice River Cove, but the following excerpt from a report of a hydrographic survey in Delaware Bay in the vicinity of Maurice River Cove in the summer and fall of 1885 is noteworthy:

> A comparison of all of the stations established in this area as to times of high and low water, together with a perceptible increase of rise and fall observed in the bottom of Maurice River Cove, seems to indicate that the tide (current) flows directly into the bay, following the channels, and turns back into the cove from the vicinity of Brandywine Shoal. This would also account for the fact

that along the east side of Egg Island Point the flood tidal current sets very strong to the southward.[1]

The data in Table 48 for stations located along the western shore show that the current in this part of Delaware Bay also turns earlier than it does along the axis of the channel. At station 24 on the Delaware shore the current turns earlier than it does at stations 25 and 26 on the cross section off Egg Island Point, while at the cross section off Bombay Hook the current turns earlier at station 32 on the New Jersey shore than it does at stations 30 and 31. In general, slack and strength of current along the eastern and western shores of Delaware Bay occur from half an hour to one hour earlier than corresponding phases of the current along the axis of the channel.

The greatest velocities of the current on the flood and ebb occur at stations which are located on the axis of the channel. The average velocity of flood at time of strength at these stations is about 1½ knots, although in the narrow portion of the bay above Bombay Hook the flood attains an average velocity of 2 or more knots per hour. Ebb strength averages about 2 knots at these stations, diminishing to about 1½ knots at channel stations where the bay widens considerably and increasing to about 2½ knots at the head of the bay.

At stations along the eastern and western shores of the bay the strength of flood and ebb averages from one-half to 1 knot, although in freshet seasons stronger ebb currents would obtain at stations located at creek and river entrances.

In general, it will be noted from the data in Table 48 that the duration of ebb for all current stations in Delaware Bay is greater than that of the flood. The average duration of flood at these stations is about 5.8 hours and that for the ebb about 6.6 hours. Thus it will be seen that the duration of ebb near the surface in Delaware Bay exceeds that of the flood by about an hour. This is due primarily to river discharge. Along the axis to the channel the durations of flood and ebb are approximately 5.5 and 6.9 hours, respectively. For stations 20, 22, 23, and 24, however, the period of flood is greater than that of ebb, these periods being 6.5 and 5.9 hours, respectively, the flood running longer than the ebb by about half an hour. A glance at Figure 30 shows that these stations are so located that they receive the full effect of the flood which progresses up the bay from the entrance in a northwesterly direction. The ebb, on the other hand, follows mainly a southeasterly direction along the channel and its effect is not felt so strongly at these stations as it is in the channel, where stronger ebb velocities and longer ebb durations obtain.

The direction of the flood current in Delaware Bay is generally northwesterly as shown by the data in Table 48. This is in conformity with the axes of the natural and dredged channels of the bay. At stations 12, 15, 16, and 17, the flood and ebb currents set northeasterly and southwesterly, respectively, indicating that in the shoal portion of the bay between Cape May and Egg Island Point the current follows the contour of the eastern shore in this part of the bay. At all current stations in Delaware Bay, the ebb sets generally directly opposite to that of the flood.

[1] From U. S. Coast and Geodetic Survey Report for 1886, p. 47.

At the 21 current stations occupied by the field party of W. H. Overshiner in 1924, in Delaware Bay, observations of subsurface currents were also made, a Price current meter with telephone attachment being used for this purpose. These observations were made at three depths—0.2, 0.5, and 0.8 of the depth at each station. The results of these observations are given in Table 49. The velocities have been reduced to a mean range of tide and are given to the nearest hundredth of a knot. The times of the current at each station are referred to the same phases of the current at Overfalls Light Vessel, off the entrance to the bay. The durations of flood and ebb as well as the times of the current at each station are given to the nearest hundredth of an hour, and the directions of the current at flood and ebb strengths are given to the nearest degree.

At most of these stations currents were observed for either a half day or a whole day. Stations 1, 2, 5, 7, 24, 25, 26, 30, 31, and 32 were located on cross sections of the bay. Station 5 at the bay entrance was occupied for 1½ days, station 25, in midchannel off Elbow of Cross Ledge Light, for 3 days, and station 31, the control station, in midchannel off Bombay Hook, for 32¼ days. At all these stations the current is of the reversing, or rectilinear type, and generally the ebb runs longer than the flood by an hour or more. With the exception of a few stations at or near the entrance to the bay, the time of the current is generally later at each station than at the reference station, Overfalls Light Vessel.

In addition to the subsurface velocity determinations at each station, subsurface current directions were also observed by means of a bifilar suspension current direction indicator, a device permitting simultaneous determinations of the direction of the current at the three depths at each station. It will be noted from Table 49 that at times of flood and ebb strengths the directions of the current at subsurface depths are approximately the same as those at the surface.

In general, the velocity of the current decreases as the depth increases in accordance with the distribution of velocity in ordinary hydraulic flow. This is true at Delaware Bay Entrance at times of ebb strength as will be noted in Table 49 for stations 1, 2, 5, and 7. On the flood, however, at stations such as 2 and 5, located at the entrance to a tidal waterway and in the path of the fresh water run-off from this waterway, the velocity shows an increase from the surface downward for a considerable depth. It will be noted from Table 49, that at station 2 the velocity of the flood strengths at the lower depths is greater than that for the ebb strengths. This condition also prevails at the 32-foot depth at station 5.

The difference in the vertical distribution of the current velocity is evidently due to the nontidal or fresh water discharge from the Delaware River. Having a density less than that of sea water, this fresh water tends to remain near the surface. On the ebb both tidal and nontidal waters are moving in the same direction and, therefore, the vertical velocity distribution is similar to that in water under hydraulic motion. On the flood the nontidal water near the surface tends to move seaward, and thus decreases the velocity of the tidal current near the surface. With increased depth the effect of the nontidal water diminishes, and hence the full velocity of the flood current is attained at some distance from the surface.

TABLE 49.—*Current data for various depths, Delaware Bay*

[Referred to time of current at Overfalls Light Vessel]

Station No.	Location	Date	Party of—	Observations with—	Depth	Slack	Flood strength: Time	Flood strength: Direction	Flood strength: Velocity	Flood duration	Slack	Ebb strength: Time	Ebb strength: Direction	Ebb strength: Velocity	Ebb duration	Length of observations
		1924			*Feet*	*Hours*	*Hours*	*True*	*Knots*	*Hours*	*Hours*	*Hours*	*True*	*Knots*	*Hours*	*Days*
1	Off Cape Henlopen	Aug. 21-22	W. H. Overshiner	Pole	7	−0.65	−0.37	N. 65° W.	1.54	6.39	−0.30	−0.55	S. 52° E.	1.71	6.03	1
				Meter	15	−0.60	−0.66	N. 62° W.	1.69	6.19	−0.45	−0.30	S. 54° E.	1.66	6.23	1
				do	38	−0.80	−0.66	N. 62° W.	1.44	6.79	−0.05	−0.30	S. 56° E.	1.69	5.63	1
				do	60	−0.80	−0.92	N. 68° W.	1.37	6.39	−0.45	−0.30	S. 56° E.	1.49	6.03	1
2	do	Aug. 20-21	do	Pole	7	0.30	0.00	N. 27° W.	1.87	6.04	0.30	0.45	S. 32° E.	2.04	6.38	1
				Meter	14	0.80	−0.17	N. 31° W.	1.89	5.34	0.10	0.25	S. 35° E.	2.07	7.08	1
				do	35	0.58	−0.12	N. 30° W.	1.77	5.56	0.10	0.25	S. 28° E.	1.64	6.86	1
				do	56	−0.35	−0.72	N. 35° W.	1.46	6.49	0.10	0.05	S. 33° E.	1.13	5.93	1
5	do	Aug. 21-23	do	Pole	7	−0.67	−1.77	N. 36° W.	1.20	6.28	−0.43	−0.35	S. 16° E.	1.67	6.14	1½
				Meter	8	−0.60	−1.37	N. 33° W.	1.35	5.77	−0.87	−0.38	S. 16° E.	1.73	6.65	1½
				do	20	−0.60	−1.27	N. 33° W.	1.32	5.92	−0.72	−0.68	S. 20° E.	1.47	6.50	1½
				do	32	−0.53	−0.77	N. 36° W.	1.28	6.14	−0.43	−0.28	S. 20° E.	1.21	6.28	1½
7	Off Cape May	Aug. 22-23	do	Pole	7	−1.60	−2.32	N. 30° W.	0.84	6.14	−1.50	−1.95	S. 7° E.	1.44	6.28	1
				Meter	5	−1.30	−1.57	N. 42° W.	0.89	5.89	−1.45	−1.40	S. 18° E.	1.36	6.53	1
				do	14	−1.30	−1.57	N. 38° W.	0.94	6.34	−1.00	−1.20	S. 16° E.	1.34	6.08	1
				do	22	−1.20	−1.57	N. 38° W.	0.91	6.24	−1.00	−1.20	S. 16° E.	1.19	6.18	1
13	Off Broad Kill Neck	Aug. 26-27	do	Pole	7	0.80	−0.07	N. 46° W.	1.04	4.64	−0.60	0.15	S. 53° E.	1.59	7.78	½
				Meter	6	0.80	−0.37	N. 42° W.	1.04	5.64	0.40	0.65	S. 40° E.	1.59	6.78	½
				do	15	0.60	−0.57	N. 42° W.	1.03	5.64	0.20	0.65	S. 42° E.	1.28	6.78	½
				do	24	0.40	−0.87	N. 33° W.	0.96	5.94	0.30	0.65	S. 42° E.	0.76	6.48	½
16	Off Cape May	Aug. 28-29	do	Pole	7	−0.40	−1.37	N. 8° E.	1.40	5.84	−0.60	−0.35	S. 21° W.	1.30	6.58	½
				Meter	5	−0.20	−0.87	N. 8° E.	1.30	5.64	−0.60	−0.35	S. 31° W.	1.45	6.78	½
				do	12	−0.30	−0.87	N. 8° E	1.11	6.14	−0.20	0.15	S. 21° W.	1.16	6.28	½
				do	20	−0.30	−0.87	N. 8° E.	1.07	5.94	−0.40	0.15	S. 21° W.	0.92	6.48	½
20	Mispillion Creek Entrance.	Aug. 25	do	Pole	2	0.00	0.67	N. 31° W.	0.65	6.34	0.30	1.03	S. 9° E.	0.65	6.08	½
				Meter	3	0.40	1.37	N. 27° W.	1.03	6.34	0.70	0.23	S. 8° E.	1.18	6.08	½
21	Off 14-Foot Bank Light	Aug. 27-28	do	Pole	7	0.40	−0.37	N. 14° W.	1.20	6.31	−0.10	1.20	S. 24° E.	1.60	6.11	1
				Meter	8	0.55	−0.07	N. 11° W.	1.31	5.96	−0.15	1.15	S. 15° E.	1.66	6.46	1
				do	19	0.40	−0.42	N. 8° W.	1.17	6.56	0.10	0.70	S. 10° E.	1.27	5.86	1
				do	30	0.20	−0.12	N. 5° W.	0.99	6.26	0.10	0.30	S. 10° E.	0.89	6.16	1
22	Maurice River Entrance.	do	do	Pole	7	0.00	0.47	N. 10° W.	1.10	6.64	0.60	0.88	S. 3° W.	0.79	5.78	1
				Meter	3	0.60	0.00	N. 14° W.	1.06	5.99	0.55	0.68	S. 6° W.	0.99	6.43	1
				do	8	0.55	−0.33	N. 12° W.	0.99	6.04	0.55	0.68	S. 6° W.	0.91	6.38	1
				do	12	0.50	0.12	N. 10° W.	0.98	6.09	0.55	0.68	S. 1° W.	0.81	6.33	1
23	Off Murderkill Neck	Aug. 20-21	do	Pole	2	−0.15	−0.17	N. 26° W.	0.52	6.29	0.40	1.15	S. 62° E.	0.52	6.13	1
				Meter	3	0.00	−0.67	N. 27° W.	0.73	6.39	0.35	0.25	S. 42° E.	0.83	6.03	1
				do	6	0.00	−0.67	N. 24° W.	0.68	6.39	0.35	0.25	S. 42° E.	0.78	6.03	1
24	Off Deep Water Point	Sept. 3-4	do	Pole	7	−0.20	0.52	N. 39° W.	0.94	6.54	0.30	−0.22	S. 22° E.	0.74	5.88	1
				Meter	3	0.65	0.27	N. 44° W.	1.03	5.84	0.45	0.53	S. 29° E.	0.88	6.58	1
				do	7	0.35	0.52	N. 46° W.	0.99	6.19	0.50	0.78	S. 27° E.	0.74	6.23	1
				do	11	0.65	0.52	N. 46° W.	0.94	5.84	0.45	0.78	S. 27° E.	0.64	6.58	1
25	Off Elbow of Cross Ledge Light.	Sept. 2-5	do	Pole	7	1.27	1.38	N. 34° W.	1.42	5.67	0.90	2.00	S. 17° E.	2.11	6.75	3
				Meter	9	1.22	1.00	N. 26° W.	1.54	5.92	1.10	1.88	S. 21° E.	1.97	6.50	3
				do	22	0.98	0.42	N. 26° W.	1.62	6.34	1.18	1.87	S. 19° E.	1.46	6.08	3
				do	35	0.85	0.68	N. 44° W.	1.53	6.36	1.17	1.87	S. 20° E.	1.22	6.06	3
26	Off Egg Island Point	Sept. 8-9	do	Pole	7	0.65	0.52	N. 23° W.	0.89	5.99	0.60	1.63	S. 23° E.	0.97	6.43	1
				Meter	4	0.85	0.72	N. 22° W.	1.19	6.09	0.90	1.48	S. 12° E.	1.21	6.33	1
				do	11	0.75	0.72	N. 23° W.	1.14	6.14	0.85	1.23	S. 19° E.	1.24	6.28	1
				do	18	0.75	0.72	N. 23° W.	1.19	6.14	0.85	1.23	S. 19° E.	1.09	6.28	1
27	Off Goose Point	Aug. 30	do	Pole	7	1.70	1.47	N. 39° W.	1.45	5.44	1.10	2.23	S. 37° E.	2.00	6.98	½
				Meter	5	1.70	1.47	N. 39° W.	1.54	5.34	1.00	1.13	S. 44° E.	2.14	7.08	½
				do	11	1.60	0.97	N. 44° W.	1.52	5.54	1.10	2.23	S. 42° E.	1.52	6.88	½
				do	18	1.50	0.47	N. 44° W.	1.39	5.54	1.00	2.48	S. 46° E.	1.19	6.88	½
28	do	do	do	Pole	7	1.80	2.47	N. 25° W.	1.19	5.64	1.40	1.63	S. 35° E.	1.64	6.78	½
				Meter	6	1.80	1.97	N. 40° W.	1.29	4.84	0.60	1.63	S. 35° E.	1.64	7.58	½
				do	15	1.50	1.77	N. 36° W.	1.07	5.14	0.60	1.98	S. 42° E.	1.27	7.28	½
				do	24	1.10	1.47	N. 39° W.	0.95	5.84	0.90	2.18	S. 45° E.	0.95	6.58	½
29	Cohansey River Entrance.	Sept. 8	do	Pole	7	0.20	0.47	N. 89° W.	1.50	-----	-----	0.13	N. 61° E.	1.10	-----	½
				Meter	6	1.00	0.97	S. 76° W.	1.13	6.54	1.50	1.13	N. 65° E.	0.83	5.88	½
				do	15	0.80	1.47	S. 81° W.	1.33	6.84	1.60	0.63	N. 81° E.	0.63	5.58	½
				do	24	0.60	0.97	S. 56° W.	1.38	7.24	1.80	0.13	N. 86° E.	0.63	5.18	½
30	Off Bombay Hook	Aug. 18-19	do	Pole	7	2.50	1.52	N. 32° W.	1.87	5.54	2.00	2.73	S. 41° E.	1.72	6.88	1
				Meter	4	2.60	2.02	N. 32° W.	1.97	5.34	1.90	2.98	S. 33° E.	2.02	7.08	1
				do	9	2.50	2.02	N. 32° W.	1.92	5.49	1.95	2.98	S. 33° E.	1.82	6.93	1
				do	14	2.45	2.02	N. 32° W.	1.82	5.54	1.95	2.98	S. 33° E.	1.62	6.88	1
31	do	Aug. 8-Sept. 11	do	Pole	7	2.53	2.17	N. 39° W.	1.63	5.58	2.07	2.88	S. 42° E.	1.97	6.84	32¼
				Meter	8	2.57	2.12	N. 45° W.	1.65	5.57	2.10	2.95	S. 40° E.	1.91	6.85	32¼
				do	20	2.17	1.85	N. 50° W.	1.42	5.99	2.12	2.77	S. 27° E.	1.36	6.43	32¼
				do	32	1.95	1.98	N. 48° W.	1.18	6.24	2.15	2.83	S. 42° E.	0.96	6.18	32¼
32	do	Aug. 18-19	do	Pole	7	1.50	1.57	N. 31° W.	0.89	5.74	1.20	1.23	S. 44° E.	1.09	6.68	1
				Meter	2	1.80	1.37	N. 31° W.	0.96	5.39	1.15	0.73	S. 41° E.	1.23	7.03	1
				do	6	1.65	1.37	N. 30° W.	0.84	5.54	1.15	0.73	S. 40° E.	1.14	6.88	1
				do	10	1.65	1.37	N. 30° W.	0.89	5.54	1.15	1.23	S. 40° E.	1.06	6.88	1
33	Off Liston Point	Sept. 9-10	do	Pole	7	2.80	2.17	N. 29° W.	2.03	5.34	2.10	3.33	S. 40° E.	2.48	7.08	½
				Meter	7	2.40	2.37	N. 29° W.	1.83	5.84	2.20	2.53	S. 45° E.	2.68	6.58	½
				do	18	2.50	1.97	N. 29° W.	1.78	5.84	2.30	2.33	S. 49° E.	2.28	6.58	½
				do	28	2.40	1.97	N. 29° W.	1.67	5.94	2.30	3.13	S. 43° E.	1.97	6.48	½
34	Off Stony Point	Aug. 15-16	do	Pole	7	3.40	2.88	N. 24° W.	2.15	5.39	2.75	3.73	S. 36° E.	2.25	7.03	1
				Meter	7	3.20	2.67	N. 21° W.	2.20	5.59	2.75	3.78	S. 38° E.	2.15	6.83	1
				do	18	3.15	2.88	N. 21° W.	2.16	5.64	2.75	3.78	S. 24° E.	2.11	6.78	1
				do	28	3.20	2.88	N. 16° W.	2.00	5.59	2.75	4.03	S. 18° E.	1.90	6.83	1

In consequence of the diminution of the flood strength near the surface by fresh water, an increase in the duration of the flood period may be expected with increasing depth. This is unmistakably shown in the current data for station 2 in Table 49. The station is located in mid-channel, in deep water off Cape Henlopen. It will be noted that at the surface the ebb runs about 20 minutes longer than the flood, while at a depth of 56 feet the flood runs longer than the ebb by about half an hour. Similar current conditions are to be noted at stations 21, 25, and 31, all located in mid-channel.

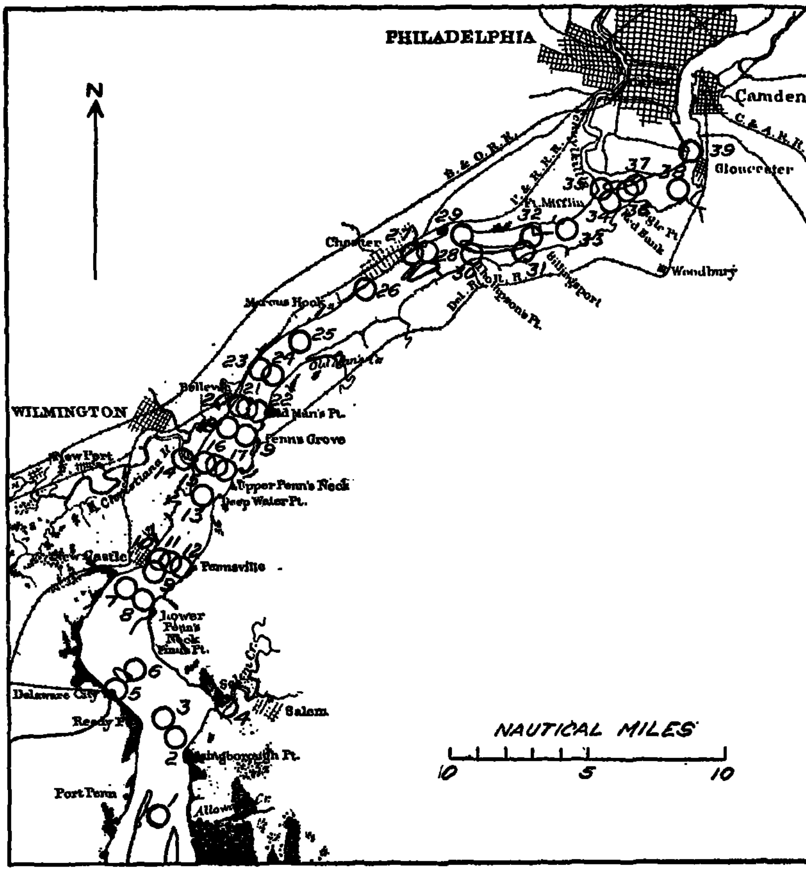

FIG. 31.—Current stations, lower Delaware River

THE CURRENT IN THE LOWER DELAWARE RIVER

The lower Delaware River is here understood to comprise the navigable waterway between the States of New Jersey, Delaware, and Pennsylvania from the northern limits of Delaware Bay to the vicinity of Philadelphia, Pa., and Gloucester, N. J. This portion of the Delaware River is about 43 nautical miles in length. Off Stony Point, N. J., in the vicinity of Artificial Island, the river has a width of about $2\frac{1}{2}$ nautical miles. Off Deepwater Point, N. J., it narrows in width to about three-fourths of a nautical mile. A deep, dredged channel extends from the mouth of the river to Philadelphia. This channel is generally 800 feet wide in the straight reaches and 1,000 feet wide in the bends, and is flanked on either side by numerous small shoals and islands.

Figure 31 shows the locations of 39 current stations occupied in the lower Delaware River. Observations at all of these stations, with the exception of those at station 9, located off New Castle, Del., were made in the summer of 1924, by the party of W. H. Overshiner. Station 9 was occupied by the party of H. L. Marinden in 1886. Currents were observed on cross sections of the lower Delaware River in 1924 as follows:

1.—Between New Castle, Del., and Pennsville, N. J.—Stations 10, 11, and 12.
2.—Off Christiana River entrance—Stations 15, 16, and 17.
3.—Off Oldmans Point, N. J.—Stations 20, 21, and 22.

Station 21 was the control station for this portion of the river in 1924, and observations by current pole and log line and also by current meter were made at this station for 18½ days from July 28 to August 9 and from September 10 to 17.

In addition to observations in the Delaware River proper, current observations were also obtained at Salem River Entrance, Christiana River, Schuylkill River Entrance, and at several water-front stations off docks and piers at South Chester, Chester, League Island Navy Yard, and Greenwich Point, Philadelphia. The data derived from current observations at these 39 stations in the lower Delaware River are given in Table 50. For each station these data refer to the tidal current near the surface, at a depth of about 7 feet, and are based on observations made by means of current pole and log line.

Table 50.—*Current data, lower Delaware River*

[Referred to time of current at Overfalls Light Vessel]

Station No.	Location	Party of—	Date	Slack	Flood strength			Flood duration	Slack	Ebb strength			Ebb duration	Length of observations
					Time	Direction	Velocity			Time	Direction	Velocity		
				Hours	*Hours*	*True*	*Knots*	*Hours*	*Hours*	*Hours*	*True*	*Knots*	*Hours*	*Days*
1	Off Reedy Island	W. H. Overshiner	September, 1924	2.9	2.5	N. 15° E.	1.7	5.6	2.5	3.6	S. 15° W.	2.2	6.8	½
2	Off Elsingborough Point	do	August, 1924	3.4	2.9	North	1.5	5.4	2.8	3.7	S. 5° E.	1.6	7.0	1
3	Off Reedy Point	do	do	3.4	2.6	do	1.9	5.4	2.8	2.9	S. 20° E.	1.7	7.0	½
4	Salem River Entrance	do	do	3.4	2.9	East	1.0	5.2	2.6	4.3	S. 50° W.	1.0	7.2	½
5	Off Delaware City, Del	do	do	3.7	3.4	N. 60° W.	1.6	5.3	3.0	4.1	S. 50° E.	1.7	7.1	1
6	Off Finns Point	do	do	3.8	3.7	N. 35° W.	2.0	5.2	3.0	4.4	S. 30° E.	1.9	7.2	1
7	Off Penns Neck	do	September, 1924	3.9	3.8	N. 60° E.	1.6	5.9	3.8	4.6	S. 40° W.	1.4	6.5	¼
8	do	do	do	3.7	3.6	N. 60° E.	1.9	5.7	3.4	4.1	S. 45° W.	1.8	6.7	½
9	Off New Castle, Del	H. L. Marinden	August, 1886	3.8	3.6	N. 65° E.	2.6	5.8	3.6	4.1	S. 45° W.	2.0	6.6	7
10	do	W. H. Overshiner	August, 1924	3.8	3.5	N. 45° E.	2.2	5.8	3.6	4.4	S. 50° W.	1.6	6.6	1
11	do	do	do	4.2	3.1	N. 40° E.	1.4	5.3	3.5	4.2	S. 45° W.	1.7	7.1	1
12	do	do	do	4.0	3.9	N. 50° E.	1.6	5.4	3.4	3.9	S. 45° W.	1.6	7.0	1
13	Off Deepwater Point	do	do	4.2	3.7	N. 20° E.	2.2	5.5	3.7	4.4	S. 25° W.	1.8	6.9	1
14	Christiana River	do	do	3.4	2.8	N. 50° W.	0.6	5.2	2.6	2.3	S. 45° E.	0.8	7.2	1
15	Off Christiana River Entrance	do	September, 1924	4.0	4.1	N. 10° E.	0.9	5.6	3.6	3.5	S. 15° W.	0.8	6.8	½
16	do	do	August, 1924	4.5	3.7	N. 15° E.	1.3	5.2	3.7	3.9	S. 15° W.	1.4	7.2	½
17	do	do	do	4.3	3.7	N. 20° E.	1.3	5.3	3.6	4.4	S. 35° W.	1.2	7.1	½
18	Off Pennsgrove, N. J	do	do	4.3	4.1	N. 30° E.	1.4	5.5	3.8	4.8	S. 25° W.	1.6	6.9	1
19	do	do	do	4.2	4.2	N. 10° E.	1.6	5.7	3.9	4.8	S. 40° W.	1.6	6.7	1
20	Off Oldmans Point	do	do	4.4	4.2	N. 35° E.	1.7	5.5	3.9	4.3	S. 35° W.	1.3	6.9	1
21	do	do	July, 1924	4.7	4.1	N. 25° E.	1.6	5.3	4.0	5.1	S. 35° W.	1.7	7.1	18½
22	do	do	August, 1924	4.6	4.0	N. 15° E.	1.5	5.4	4.0	4.9	S. 30° W.	1.5	7.0	1
23	Off Oldmans Creek	do	do	4.9	4.3	N. 45° E.	1.6	5.3	4.2	4.5	S. 40° W.	1.4	7.1	1
24	do	do	do	4.5	4.1	N. 30° E.	1.5	5.7	4.2	4.5	S. 65° W.	1.0	6.7	1
25	Off Marcus Hook, Pa	do	do	4.6	4.0	N. 45° E.	1.6	5.5	4.1	5.3	West	1.4	6.9	½
26	Off South Chester, Pa	do	September, 1924	4.1	3.3	N. 45° E.	0.5	5.7	3.8	4.2	S. 30° W.	0.1	6.7	¾
27	Off Chester, Pa	do	do	4.8	4.4	N. 65° E.	0.1	5.0	3.8	4.9	S. 50° W.	1.2	7.4	½
28	Off Eddystone, Pa	do	August, 1924	4.9	4.6	N. 65° E.	1.8	5.6	4.5	4.7	S. 55° W.	1.7	6.8	1
29	Off Darby Creek Entrance	do	September, 1924	4.3	5.5	N. 60° E.	1.1	6.1	4.4	3.5	S. 65° W.	0.7	6.3	½
30	Off Thompsons Point	do	July, 1924	5.2	5.0	S. 85° E.	1.7	5.1	4.3	5.9	West	1.8	7.3	½
31	Off Billingsport, N. J	do	do	5.3	5.1	N. 75° E.	1.8	5.8	5.1	5.5	S. 80° W.	1.8	6.6	1
32	do	do	September, 1924	4.8	4.8	S. 60° E.	0.9	5.6	4.4	4.1	N. 75° W.	0.9	6.8	½
33	Off Hog Island	do	July, 1924	5.4	5.0	N. 40° E.	1.2	5.2	4.6	5.3	S. 60° W.	1.7	7.2	½
34	Off Red Bank, N. J	do	do	5.3	4.4	N. 75° E.	1.6	6.0	5.3	6.3	S. 65° W.	1.5	6.4	1
35	Schuylkill River Entrance	do	do	4.2	4.4	N. 20° W.	0.5	6.1	4.3	4.5	S. 10° W.	0.3	6.3	1
36	Off League Island Navy Yard	do	September, 1924	4.7	4.5	East	1.0	6.5	5.2	5.1	S. 80° W.	0.3	5.9	½
37	do	do	do	3.9	3.4	S. 75° E.	0.3	7.0	4.9	5.8	S. 30° W.	0.2	5.4	½
38	Off Horseshoe Shoal	do	July, 1924	5.6	5.1	N. 35° E.	1.3	5.8	5.4	5.8	S. 50° W.	1.3	6.6	1
39	Off Greenwich Point	do	September, 1924	5.1	3.9	N. 5° E.	0.6	5.1	4.2	4.4	S. 10° W.	0.5	7.3	½

In Table 50 the times of slack water and strengths of flood and ebb are given in hours and tenths of hours and are referred to the times of the corresponding phases of the current at Overfalls Light Vessel. The durations of flood and ebb are also given in hours and tenths of hours, and it will be noted from the table that the duration of ebb at nearly all of the current stations in the lower Delaware River is much greater than that for the flood. The velocities of flood and ebb strengths are given in knots and tenths of knots and are corrected to a mean range of tide. The true directions of the flood and ebb at times of strength are given to the nearest 5°.

It will be noted from Table 50 that the time of any particular phase of the current in mid-channel occurs later in going upstream from Reedy Island to Philadelphia. For instance, at station 1, off Reedy Island, slack before flood occurs 2.9 hours after the time of slack before flood at Overfalls Light Vessel. At station 38, off Horseshoe Shoal Bell Buoy, however, the same phase of the current occurs 5.6 hours later than the time of slack before flood at the reference station, Overfalls Light Vessel. Therefore, slack before flood off Horseshoe Shoal Bell Buoy occurs 2.7 hours later than it does off Reedy Island.

In general it will be noted from the table that the current turns earliest in the shallower reaches near the shores of the river, at creek entrances, and at dock stations, and latest in mid-channel.

A four-year series of tidal observations has been made at the Government Pier, Lewes, Del. (Station B, fig. 10), and also at Reedy Island Quarantine Station (Station B, fig. 12). The results of these observations show that high tide at the latter station occurs about two and one-fourth hours later than it does at Lewes, Del., while low tide at Reedy Island occurs about three and one-half hours later than it does at Lewes, Del. It will be noted from Table 50 that the time of flood strength in mid-channel, off Reedy Island, occurs two and one-half hours later than the time of flood strength at Delaware Bay Entrance (Overfalls Light Vessel). Flood strength, therefore, off Reedy Island, occurs about the time of local high water. It will likewise be noted from Table 50 that the strength of ebb in mid-channel occurs about three and one-half hours later than at Delaware Bay Entrance (Overfalls Light Vessel). Ebb strength, therefore, off Reedy Island, occurs about the time of local low water. The tidal movement in the lower Delaware River, as deduced from the relation of the time of current to the time of tide, is therefore of the progressive-wave type.

The results of a three-months series of tidal observations at Edgemoor, Del. (Station I, fig. 12), compared with several years of observations at Lewes, Del. (Station B, fig. 10), show that high and low water occur three and three-fourths and five hours later, respectively, at Edgemoor than at Lewes. Flood and ebb strengths at current station 18, Figure 31, in mid-channel off Edgemoor, occur four and four and three-fourths hours later, respectively, than the same phases of the current at Overfalls Light Vessel. This relationship between the times of current and tide at Delaware Bay Entrance and in mid-channel off Edgemoor also shows the tidal movement in the lower Delaware River to be of the progressive-wave type.

However, the results of a three-months series of tidal observations at Baldwins, Pa. (Station L, fig. 12), compared with a long series of observations at Lewes, Del. (Station B, fig. 10), show that high and low water occur four and one-fourth and 6 hours later, respectively, at the former station than at the latter, while flood and ebb strengths at current station 28, Figure 31, in mid-channel about a mile south of Baldwins, occur four and one-half and four and three-fourths hours later, respectively, than the corresponding phases of the current at Overfalls Light Vessel. The strength of flood therefore comes approximately at the time of local high water, but the strength of ebb occurs about one and one-fourth hours earlier than the time of local low water.

Comparative tide and current observations therefore show that in the lower Delaware River from Reedy Island to Marcus Hook, Pa., the strengths of flood and ebb currents occur approximately at local high and low tides, respectively, for any given point. From Chester Island to Philadelphia, however, such a relationship between the time of current and tide does not hold true, the difference in time between maximum current and maximum tide ranging from about half an hour to one and one-half hours.

In general, it will be noted from Table 50 that the current turns later and later at mid-channel stations from Reedy Island to Philadelphia. The current turns earlier near the shore than it does in mid-channel, as shown by a comparison of the time of current at the cross sections off New Castle (stations 10, 11, and 12), off the Christiana River Entrance (stations 15, 16, and 17), and off Oldmans Point (stations 20, 21, and 22).

Station 14 was located in the Christiana River along the eastern edge of the channel at a bend in the river about 1,600 yards from Christiana North Jetty Light. It will be noted that the time of current at this station is about an hour earlier at slack and strength than it is in the Delaware River off the entrance to the Christiana River.

It will be noted from the table that the current turns earlier at dock stations than it does at stations in mid-channel as shown by the data for stations alongside docks at Chester, South Chester, League Island Navy Yard, and Greenwich Point

At the entrance to the Schuylkill River the current turns about an hour earlier than it does in the main ship channel of the Delaware River. This will be noted from Table 50 by comparing the data for station 35 with that for station 34. The latter station was located in The Elbow.

The axis of the lower Delaware River lies in a general northeast-southwest direction. Therefore, the flood sets generally northeasterly and the ebb southwesterly. The dredged channel, however, is crooked, owing to numerous bends in the river. At stations located in mid-channel the current sets about fair with the axis of the channel.

The velocities of flood and ebb at mid-channel current stations in the lower Delaware River average about 2.0 knots, the ebb being generally somewhat greater in velocity than the flood. However, at station 9, off New Castle, Del., the flood strength, 2.6 knots, is greater than that of the ebb. This is in agreement with the data for station 10, off New Castle, one of the stations located on a cross section of the river. A glance at Figure 31 shows that the full effect of the flood is felt along the Delaware shore north of Bulkhead Shoal, while the effect of the ebb is felt in mid-channel. Likewise, the fact that flood strength is considerably greater than ebb strength at station 24, off Oldmans Creek, is no doubt due to interference with the ebb caused by Marcus Hook Bar, a sand bar several miles in extent.

It will be noted from the table that the duration of ebb is much greater than that of flood, being approximately one and one-fourth hours greater. For the 39 current stations in the lower Delaware River the average durations of flood and ebb are 5.6 and 6.8 hours, respectively.

At all of the stations listed in Table 50 with the exception of station 9 subsurface current velocity observations were also made by means of current meters. Generally, these observations were made at three depths—two-tenths, five-tenths, and eight-tenths of the depth at each station except at shallow creek entrances. The direction of the subsurface current at these depths was determined by means of a bilfilar direction indicator at all stations listed in Table 50, except stations 9, 26, 27, and 39.

The data derived from these observations are given in Table 51. The times of slack and strength of current are given in hours and hundredths of hours, since differences in time of current at various depths at the same station are frequently small. The velocities of the current at times of flood and ebb strengths are given in knots and hundredths of knots, and have been corrected to a mean range of tide at each station. For comparative purposes, pole observations are listed for every station except station 37 where it was not possible to use the current pole. Generally, a 15-foot pole, submerged to a depth of 14 feet and giving current determinations at an average depth of 7 feet, was used. Owing to shoal water at station 32, a 4-foot pole was used, giving current data at an average depth of 2 feet for that station.

Table 51.—*Current data, lower Delaware River*

[Referred to time of current at Overfalls Light Vessel]

Station No.	Location	Date	Party of—	Observations with—	Depth	Slack	Flood strength: Time	Flood strength: Direction	Flood strength: Velocity	Flood duration	Slack	Ebb strength: Time	Ebb strength: Direction	Ebb strength: Velocity	Ebb duration	Length of observations
		1924			*Feet*	*Hours*	*Hours*	*True*	*Knots*	*Hours*	*Hours*	*Hours*	*True*	*Knots*	*Hours*	*Days*
1	Off Reedy Island	Sept. 9	W. H. Overshiner.	Pole	7	2.90	2.47	N. 14° E.	1.70	5.64	2.50	3.63	S. 14° W.	2.25	6.78	½
				Meter	9	3.00	2.97	N. 21° E.	1.62	5.54	2.50	3.13	S. 22° W.	2.02	6.88	½
				do	22	2.90	2.47	N. 24° E.	1.55	5.74	2.60	3.13	S. 32° W.	1.55	6.68	½
				do	36	2.70	2.47	N. 14° E.	1.46	5.94	2.60	4.13	S. 27° W.	1.26	6.48	½
2	Off Elsingborough Point.	Aug. 15–16	do	Pole	7	3.45	2.92	N. 1° E.	1.52	5.34	2.75	3.68	S. 4° E.	1.62	7.08	1
				Meter	7	3.45	2.82	North	1.66	5.34	2.75	3.88	S. 2° E.	1.61	7.08	1
				do	18	3.35	2.77	N. 2° E.	1.71	5.54	2.85	3.73	S. 3° W.	1.33	6.88	1
				do	29	3.30	2.72	North	1.56	5.59	2.85	3.52	S. 4° W.	1.11	6.83	1
3	Off Reedy Point	Aug. 14–15	do	Pole	7	3.40	2.57	N 1° W.	1.86	5.44	2.80	2.93	S. 21° E.	1.66	6.98	½
				Meter	7	3.30	2.57	N. 7° E.	2.32	5.94	3.20	2.93	S. 14° E.	1.72	6.48	½
				do	16	3.20	2.57	N. 7° E.	2.28	5.94	3.10	3.23	S. 12° E.	1.58	6.48	½
				do	26	3.20	2.57	N. 14° E.	2.12	6.04	3.20	3.03	S. 12° E.	1.32	6.38	½
4	Salem River Entrance	do	do	Pole	7	3.40	2.87	East	1.02	5.24	2.60	4.33	S. 51° W.	1.00	7.18	½
				Meter	2	3.20	3.07	S. 84° E.	1.10	5.34	2.50	4.48	S. 50° W.	1.10	7.08	½
				do	6	3.20	3.07	S. 80° E.	1.01	5.34	2.50	4.48	S. 50° W.	1.09	7.08	½
				do	10	3.10	3.07	S. 80° E.	1.02	5.64	2.70	4.58	S. 50° W.	0.93	6.78	½
5	Off Delaware City, Del.	Aug. 13–14	do	Pole	7	3.70	3.37	N. 58° W.	1.63	5.34	3.00	4.13	S. 48° E.	1.73	7.08	1
				Meter	5	3.85	3.27	N. 40° W.	1.82	5.29	3.10	4.58	S. 37° E.	1.80	7.13	1
				do	12	3.85	3.00	N. 40° W.	1.72	5.29	3.10	4.38	S. 41° E.	1.72	7.13	1
				do	19	3.80	3.17	N. 36° W.	1.59	5.34	3.10	4.68	S. 43° E.	1.66	7.08	1
6	Off Finns Point	do	do	Pole	7	3.75	3.72	N. 33° W.	2.05	5.24	2.95	4.43	S. 31° E.	1.92	7.18	1
				Meter	8	3.70	3.32	N. 30° W.	2.04	5.69	3.35	3.93	S. 21° E.	1.97	6.73	1
				do	21	3.60	3.22	N. 30° W.	1.93	5.79	3.35	4.18	S. 32° E.	1.73	6.63	1
				do	33	3.50	3.22	N. 29° W.	1.67	5.84	3.30	4.13	S. 32° E.	1.52	6.58	1
7	Off Penns Neck	Sept. 10	do	Pole	7	3.90	3.82	N. 60° E.	1.57	5.94	3.80	4.63	S. 39° W.	1.42	6.48	½
				Meter	6	3.80	3.67	N. 62° E.	1.59	5.94	3.70	4.13	S. 35° W.	1.47	6.48	½
				do	16	3.80	4.22	N. 67° E.	1.46	5.94	3.70	4.53	S. 31° W.	1.41	6.48	½
				do	25	3.80	4.22	N. 67° E.	1.35	6.04	3.80	4.63	S. 30° W.	1.13	6.38	½
8	do	do	do	Pole	7	3.70	3.57	N. 60° E.	1.93	5.74	3.40	4.13	S. 46° W.	1.83	6.68	½
				Meter	8	3.80	3.07	N. 51° E.	1.98	5.34	3.10	4.33	S. 49° W.	1.88	7.08	½
				do	20	3.60	3.07	N. 56° E.	1.88	5.54	3.10	4.53	S. 60° W.	1.63	6.88	½
				do	32	3.70	3.27	N. 58° E.	1.68	5.44	3.10	4.63	S. 58° W.	1.43	6.98	½
10	Off New Castle, Del	Aug. 11–12	do	Pole	7	3.75	3.47	N. 44° E	2.19	5.94	3.65	4.43	S. 48° W.	1.57	6.48	1
				Meter	4	3.80	3.77	N. 52° E.	1.90	5.84	3.60	4.13	S. 53° W.	1.52	6.58	1
				do	11	3.70	3.47	N. 50° E.	2.08	6.04	3.70	3.88	S. 52° W.	1.30	6.38	1
				do	18	3.70	3.22	N. 56° E.	2.12	5.99	3.65	3.93	S. 55° W.	1.10	6.43	1
11	do	Aug. 12–13	do	Pole	7	4.25	3.12	N. 42° E.	1.37	5.29	3.50	4.18	S. 43° W.	1.70	7.13	1
				Meter	7	4.20	3.12	N. 51° E.	1.36	5.39	3.55	4.03	S. 55° W.	1.69	7.03	1
				do	17	4.10	3.22	N. 50° E.	1.32	5.54	3.60	4.43	S. 59° W.	1.67	6.88	1
				do	27	4.00	3.72	N. 46° E.	1.32	5.59	3.55	4.13	S. 58° W.	1.49	6.83	1
12	do	do	do	Pole	7	4.05	3.87	N. 49° E.	1.57	5.34	3.35	3.93	S. 46° W.	1.55	7.08	1
				Meter	5	4.20	3.52	N. 53° E.	1.66	5.19	3.35	4.53	S. 47° W.	1.46	7.23	1
				do	12	4.15	3.52	N. 53° E.	1.54	5.34	3.45	4.53	S. 52° W.	1.36	7.08	1
				do	20	3.95	3.62	N. 51° E.	1.41	5.59	3.50	4.53	S. 52° W.	1.14	6.83	1
13	Off Deepwater Point	Aug. 11–12	do	Pole	7	4.15	3.67	N. 18° E.	2.25	5.59	3.70	4.43	S. 24° W.	1.78	6.83	1
				Meter	11	4.10	3.47	N. 26° E.	2.11	5.84	3.90	4.23	S. 24° W.	1.78	6.58	1
				do	28	4.05	3.57	N. 24° E.	1.87	5.89	3.90	4.28	S. 24° W.	1.55	6.53	1
				do	44	4.00	3.62	N. 19° E.	1.56	5.94	3.90	4.23	S. 27° W.	1.23	6.48	1
14	Christiana River	Aug. 8–9	do	Pole	7	3.35	2.77	N. 51° W.	0.62	5.34	2.65	2.33	S. 43° E.	0.82	7.08	1
				Meter	4	3.15	3.02	N. 64° W.	0.71	5.94	3.05	2.33	S. 46° E.	0.96	6.48	1
				do	9	3.40	3.02	N. 67° W.	0.73	5.69	3.05	2.33	S. 58° E.	0.91	6.73	1
				do	14	3.25	3.02	N. 74° W.	0.69	5.89	3.10	2.33	S. 50° E.	0.91	6.53	1
15	Off Christiana River Entrance.	Sept. 10–11	do	Pole	7	4.03	4.07	N. 12° E.	0.94	5.59	3.58	3.53	S. 17° W.	0.79	6.83	½
				Meter	3	4.43	3.57	N. 11° E.	1.27	5.44	3.83	4.03	S. 17° W.	0.87	6.98	½
				do	7	4.43	4.07	N. 12° E.	1.18	5.49	3.88	4.03	S. 17° W.	0.83	6.93	½
				do	10	4.33	4.07	N. 12° E.	0.95	5.59	3.88	4.03	S. 17° W.	0.75	6.83	½
16	do	Aug. 7–8	do	Pole	7	4.53	3.67	N. 17° E.	1.33	5.19	3.68	3.93	S. 13° W.	1.38	7.23	½
				Meter	8	4.63	3.67	N. 19° E.	1.18	5.19	3.78	3.93	S. 12° W.	1.33	7.23	½
				do	20	4.33	3.87	N. 18° E.	1.09	5.29	3.58	3.93	S. 17° W.	1.14	7.13	½
				do	32	4.33	3.77	N. 19° E.	0.91	5.19	3.48	4.00	S. 27° W.	0.76	7.23	½
17	do	do	do	Pole	7	4.33	3.67	N. 22° E.	1.33	5.29	3.58	4.43	S. 36° W.	1.23	7.13	½
				Meter	6	4.43	4.07	N. 30° E.	1.23	5.39	3.78	4.43	S. 40° W.	1.33	7.03	½
				do	15	4.43	3.87	N. 27° E.	1.14	5.39	3.78	4.43	S. 38° W.	1.14	7.03	½
				do	24	4.43	3.67	N. 23° E.	1.04	5.39	3.78	4.43	S. 48° W.	1.04	7.03	½
18	Off Pennsgrove, N. J.	Aug. 6–7	do	Pole	7	4.28	4.12	N. 32° E.	1.45	5.54	3.78	4.83	S. 26° W.	1.60	6.88	1
				Meter	8	4.33	4.12	N. 23° E.	1.31	5.54	3.83	5.08	S. 30° W.	1.41	6.88	1
				do	20	4.28	4.12	N. 20° E.	1.13	5.54	3.78	4.83	S. 22° W.	1.38	6.88	1
				do	32	4.23	4.07	N. 25° E.	1.00	5.59	3.78	4.58	S. 28° W.	1.10	6.83	1
19	do	do	do	Pole	7	4.28	4.22	N. 12° E.	1.56	5.69	3.93	4.83	S. 41° W.	1.64	6.73	1
				Meter	4	4.38	4.07	N. 12° E.	1.52	5.74	4.08	4.83	S. 34° W.	1.59	6.68	1
				do	11	4.38	4.07	N. 12° E.	1.45	5.74	4.08	4.83	S. 33° W.	1.52	6.68	1
				do	18	4.28	4.07	N. 15° E.	1.38	5.84	4.08	4.83	S. 36° W.	1.38	6.58	1
20	Off Oldmans Point	Aug. 5–6	do	Pole	7	4.43	4.17	N. 34° E.	1.70	5.49	3.88	4.28	S. 34° W.	1.27	6.93	1
				Meter	7	4.53	4.27	N. 28° E.	1.70	5.49	3.98	4.68	S. 24° W.	1.30	6.93	1
				do	18	4.58	4.37	N. 26° E.	1.52	5.39	3.93	4.68	S. 26° W.	1.17	7.03	1
				do	28	4.48	4.67	N. 28° E.	1.15	5.49	3.93	4.68	S. 29° W.	0.95	6.93	1
21	do	July 28–Aug. 9, Sept. 10–17.	do	Pole	7	4.68	4.12	N. 26° E.	1.62	5.38	4.02	5.12	S. 34° W.	1.71	7.04	18½
				Meter	6	4.60	3.98	N. 24° E.	1.66	5.39	3.95	4.95	S. 32° W.	1.69	7.03	18½
				do	15	4.58	3.98	N. 27° E.	1.55	5.43	3.97	5.02	S. 35° W.	1.58	6.99	18½
				do	24	4.55	4.05	N. 23° E.	1.36	5.44	3.95	5.13	S. 31° W.	1.36	6.98	18½
22	do	Aug. 5–6	do	Pole	7	4.58	4.02	N. 15° E.	1.53	5.49	4.03	4.93	S. 32° W.	1.53	6.93	1
				Meter	5	4.58	4.02	N. 3° E.	1.53	5.44	3.98	4.38	S. 33° W.	1.48	6.98	1
				do	12	4.58	3.92	N. 8° E.	1.44	5.39	3.93	4.93	S. 26° W.	1.54	7.03	1
				do	19	4.53	4.02	N. 8° E.	1.35	5.44	3.93	4.68	S. 34° W.	1.30	6.98	1
23	Off Oldmans Creek	Aug. 4–5	do	Pole	7	4.88	4.27	N. 46° E.	1.55	5.34	4.18	4.53	S. 40° W.	1.45	7.08	1
				Meter	8	4.58	3.92	N. 42° E.	1.41	5.34	3.88	4.73	S. 36° W.	1.36	7.08	1
				do	20	4.63	3.92	N. 46° E.	1.28	5.29	3.88	4.73	S. 39° W.	1.23	7.13	1
				do	32	4.63	4.07	N. 46° E.	1.09	5.29	3.88	4.73	S. 42° W.	1.04	7.13	1

TABLE 51.—*Current data, lower Delaware River*—Continued

Station No.	Location	Date	Party of—	Observations with—	Depth	Slack	Flood strength: Time	Flood strength: Direction	Flood strength: Velocity	Flood duration	Slack	Ebb strength: Time	Ebb strength: Direction	Ebb strength: Velocity	Ebb duration	Length of observations
		1924			*Feet*	*Hours*	*Hours*	*True*	*Knots*	*Hours*	*Hours*	*Hours*	*True*	*Knots*	*Hours*	*Days*
24	Off Oldmans Creek	Aug. 4-5	W. H. Overshiner	Pole	7	4.48	4.12	N. 28° E.	1.50	5.74	4.18	4.48	S. 64° W.	0.95	6.68	1
				Meter	4	4.58	4.42	N. 48° E.	1.43	5.74	4.28	4.48	S. 75° W.	0.91	6.68	1
				do	11	4.58	4.42	N. 45° E.	1.28	5.79	4.23	4.48	S. 76° W.	0.83	6.63	1
				do	18	4.53	4.42	N. 38° E.	1.15	5.74	4.23	4.48	S. 54° W.	0.75	6.68	1
25	Off Marcus Hook, Pa	Aug. 1	do	Pole	7	4.60	3.97	N. 46° E.	1.63	5.54	4.10	5.33	S. 89° W.	1.43	6.88	½
				Meter	7	4.40	4.47	N. 50° E.	1.54	5.84	4.20	5.33	S. 89° W.	1.44	6.58	½
				do	18	4.40	4.47	N. 50° E.	1.44	5.84	4.20	5.33	S. 89° W.	1.34	6.58	½
				do	29	4.40	4.47	N. 33° E.	1.26	5.64	4.00	4.83	S. 77° W.	1.21	6.78	½
26	Off South Chester, Pa	Sept. 11-12	do	Pole	7	4.10	3.32	N. 46° E.	0.51	5.79	3.85	4.23	S. 30° W.	0.06	6.63	¾
				Meter	4	3.90	3.27	----------	0.68	5.69	3.55	4.23	----------	0.16	6.73	¾
				do	9	3.90	2.97	----------	0.68	5.74	3.60	4.23	----------	0.16	6.68	¾
				do	15	4.00	3.12	----------	0.53	5.54	3.50	4.23	----------	0.15	6.88	¾
27	Off Chester, Pa	Sept. 12-13	do	Pole	7	4.80	4.37	N. 63° E.	0.03	5.04	3.80	4.93	S. 50° W.	1.18	7.38	½
				Meter	4	5.00	3.87	----------	0.62	4.84	3.80	4.93	----------	0.82	7.58	½
				do	9	5.10	3.87	----------	0.52	4.84	3.90	4.93	----------	1.02	7.58	½
				do	15	5.20	3.37	----------	0.40	5.04	4.20	4.43	----------	1.30	7.38	½
28	Off Eddystone, Pa	Aug. 1-2	do	Pole	7	4.93	4.62	N. 65° E.	1.81	5.64	4.53	4.73	S. 54° W.	1.69	6.78	1
				Meter	8	4.88	4.37	N. 58° E.	1.75	5.89	4.73	4.73	S. 61° W.	1.55	6.53	1
				do	20	4.88	4.47	N. 59° E.	1.61	5.84	4.68	4.73	S. 66° W.	1.43	6.58	1
				do	32	4.88	4.72	N. 56° E.	1.44	5.84	4.68	4.73	S. 64° W.	1.19	6.58	1
29	Off Darby Creek Entrance.	Sept. 14-15	do	Pole	7	4.33	5.47	N. 59° E.	1.12	6.09	4.38	3.53	S. 65° W.	0.72	6.33	½
				Meter	4	4.53	5.47	N. 74° E.	1.12	6.09	4.58	3.93	S. 80° W.	0.77	6.33	½
				do	10	4.53	5.47	N. 72° E.	1.03	5.99	4.48	3.93	S. 74° W.	0.63	6.43	½
30	Off Thompsons Point	July 31-Aug. 1	do	Pole	7	5.23	4.97	S. 83° E.	1.73	5.09	4.28	5.93	S. 89° W.	1.78	7.33	½
				Meter	7	5.03	4.47	N. 75° E.	1.68	5.39	4.38	5.93	S. 79° W.	1.78	7.03	½
				do	17	5.03	4.47	N. 85° E.	1.68	5.29	4.28	5.93	S. 84° W.	1.78	7.13	½
				do	28	5.03	4.47	S. 85° E.	1.59	5.19	4.18	5.43	S. 89° W	1.39	7.23	½
31	Off Billingsport, N. J	July 30-31	do	Pole	7	5.28	5.12	N. 74° E.	1.79	5.84	5.08	5.53	S. 80° W.	1.79	6.58	1
				Meter	9	5.18	5.12	N. 60° E.	1.75	5.84	4.98	5.53	S. 70° W.	1.65	6.58	1
				do	23	5.18	5.02	N. 64° E.	1.75	5.84	4.98	5.53	S. 72° W.	1.55	6.58	1
				do	37	5.23	5.12	N. 72° E.	1.56	5.74	4.93	5.53	S. 77° W.	1.36	6.68	1
32	do	Sept. 15-16	do	Pole	2	4.83	4.77	S. 61° E.	0.93	5.59	4.38	4.13	N. 76° W.	0.88	6.83	½
				Meter	4	4.93	4.77	S. 55° E.	1.02	5.59	4.48	4.13	N. 75° W.	1.07	6.83	½
				do	10	4.93	4.77	S. 50° E.	1.02	5.59	4.48	3.93	N. 70° W.	0.98	6.83	½
33	Off Hog Island	July 31-Aug. 1	do	Pole	7	5.43	4.97	N. 41° E.	1.19	5.19	4.58	5.33	S. 61° W.	1.69	7.23	½
				Meter	6	5.23	4.97	N. 40° E.	1.49	5.59	4.78	5.83	S. 74° W.	1.54	6.83	½
				do	15	5.23	4.97	N. 40° E.	1.39	5.59	4.78	5.83	S. 79° W.	1.49	6.83	½
				do	24	5.23	4.97	N. 40° E.	1.35	5.69	4.88	5.83	S. 59° W	1.40	6.73	½
34	Off Red Bank, N. J	July 29-30	do	Pole	7	5.33	4.42	N. 74° E.	1.63	6.04	5.33	6.28	S. 66° W.	1.53	6.38	1
				Meter	6	5.38	4.67	N. 60° E.	1.39	5.49	4.83	6.03	S. 57° W.	1.44	6.93	1
				do	15	5.38	4.42	N. 67° E.	1.38	5.49	4.83	5.78	S. 62° W.	1.38	6.93	1
				do	24	5.48	4.42	N. 74° E.	1.21	5.44	4.88	5.78	S. 70° W.	1.19	6.98	1
35	Schuylkill River Entrance.	July 30-31	do	Pole	7	4.23	4.37	N. 20° W.	0.53	6.09	4.28	4.53	S. 9° W.	0.28	6.33	1
				Meter	5	4.48	4.12	N. 6° E.	0.71	5.64	4.08	4.53	S. 6° W.	0.46	6.78	1
				do	12	4.48	4.12	N. 24° E.	0.72	5.64	4.08	4.53	S. 24° W.	0.37	6.78	1
				do	20	4.48	4.12	N. 2° E.	0.76	5.69	4.13	4.53	S. 15° W.	0.36	6.73	1
36	Off League Island Navy Yard.	Sept. 15	do	Pole	7	4.73	4.47	N. 89° E.	0.99	6.49	5.18	5.13	S. 81° W.	0.29	5.93	½
				Meter	7	5.33	4.47	N. 89° E.	0.94	5.89	5.18	5.63	S. 61° W.	0.59	6.53	½
				do	18	5.33	4.77	N. 89° E.	1.37	5.89	5.18	5.63	S. 56° W.	0.52	6.53	½
				do	30	5.23	4.97	N. 89° E.	1.56	6.09	5.28	5.63	S. 51° W.	0.41	6.33	½
37	do	Sept. 16	do	Meter	6	3.93	3.37	S. 76° E.	0.29	6.99	4.88	5.83	S. 31° W.	0.17	5.43	½
				do	15	3.83	3.17	S. 36° E.	0.23	7.29	5.08	5.63	S. 46° W.	0.16	5.13	½
				do	24	3.53	2.57	S. 86° E.	0.23	7.69	5.18	5.33	----------	0.13	4.73	½
38	Off Horseshoe Shoal	July 29-30	do	Pole	7	5.58	5.07	N. 34° E.	1.28	5.89	5.43	5.78	S. 52° W.	1.28	6.53	1
				Meter	8	5.63	4.82	N. 44° E.	1.48	5.74	5.33	6.28	S. 56° W.	1.25	6.68	1
				do	20	5.63	4.82	N. 36° E.	1.43	5.74	5.33	6.28	S. 54° W.	1.23	6.68	1
				do	32	5.63	5.07	N. 32° E.	1.29	5.74	5.33	6.53	S. 52° W.	1.09	6.68	1
39	Off Greenwich Point	Sept. 16	do	Pole	7	5.13	3.87	N. 5° E.	0.57	5.09	4.18	4.43	S. 8° W.	0.47	7.33	½
				Meter	4	5.03	4.37	----------	0.82	5.39	4.38	4.43	----------	0.47	7.03	½
				do	9	5.13	3.87	----------	0.72	5.39	4.48	4.43	----------	0.57	7.03	½
				do	14	5.63	4.37	----------	0.62	4.49	4.08	4.43	----------	0.47	7.93	½

It will be noted from Table 51 that the time of slack before flood generally becomes earlier from the surface downward, while the time of slack before ebb occurs about the same time from the surface to the bottom. It will also be noted that the velocities of flood and ebb at times of strength generally decrease as the depth increases. This is true for most stations listed in the table. Notable exceptions to this general rule are to be found on inspecting the data for flood at station 36 and ebb at station 27. These were dock stations located at League Island Navy Yard, Philadelphia, Pa., and the Sun Ship Co. Pier, East Chester, Pa., respectively. In general, the velocity of flood decreases slowly with depth, and at some stations actually increases in strength. On the contrary, the ebb generally decreases in strength rapidly with increasing depths. Near the surface the velocity of ebb is considerably augmented by fresh-water discharge. At the surface the duration of ebb is considerably greater than that of flood, but with increasing depth the duration of flood generally increases while that of the ebb decreases. At all stations in the lower Delaware River listed in Table 51, however, with the exception of station 37, the duration of ebb at the bottom depths is greater than that of the flood.

THE CURRENT IN THE DELAWARE RIVER—VICINITY OF PHILADELPHIA AND CAMDEN

This section of the Delaware River comprises that portion of the river along the water fronts of Philadelphia, Pa., and Camden, N. J., from Kaighn Point, N. J., to Port Richmond and Petty Island. From Kaighn Point to Cooper Point, N. J., the Delaware River averages about half a nautical mile in width from shore to shore and is of considerable depth.

Figure 32 shows the locations of nine current stations in this section of the Delaware River, at which observations were made between the years 1886 and 1924. Stations 1 and 9 were dock stations along the Philadelphia water front occupied in September, 1924. In July of the same year currents were observed on a cross section between Philadelphia and Camden at stations 5, 6, and 7, where the new bridge between these cities is at present under process of construction. Current pole observations were made in mid-channel, off Cooper Point, N. J. (station 8), in the summer of 1886, while in 1902 slack water observations were made on a cross section between Philadelphia and Camden at stations 2, 3, and 4. The data derived from current observations at these nine stations in the Delaware River are given in Table 52. These data refer to the tidal current near the surface at a depth of about 7 feet and are based mainly on observations made by means of current pole and log line.

In Table 52 the times of slack water and strengths of flood and ebb are given in hours and tenths of hours and are referred to the times of the corresponding phases of the current at Overfalls Light Vessel. The durations of flood and ebb are also given in hours and tenths of hours and it will be noted from the table that the duration of ebb at all stations is much greater than that of flood. The velocities of flood and ebb strengths are given in knots and tenths of knots and have been corrected to a mean range of tide at each station. The true directions of the flood and ebb at times of strength are given to the nearest 5°.

It will be noted from Table 52 that the current turns about a third of an hour earlier on the flood and ebb along the Camden water front than it does in mid-channel or along the Philadelphia water front. Strengths of flood and ebb occur considerably earlier at dock stations along the Philadelphia water front than in mid-channel.

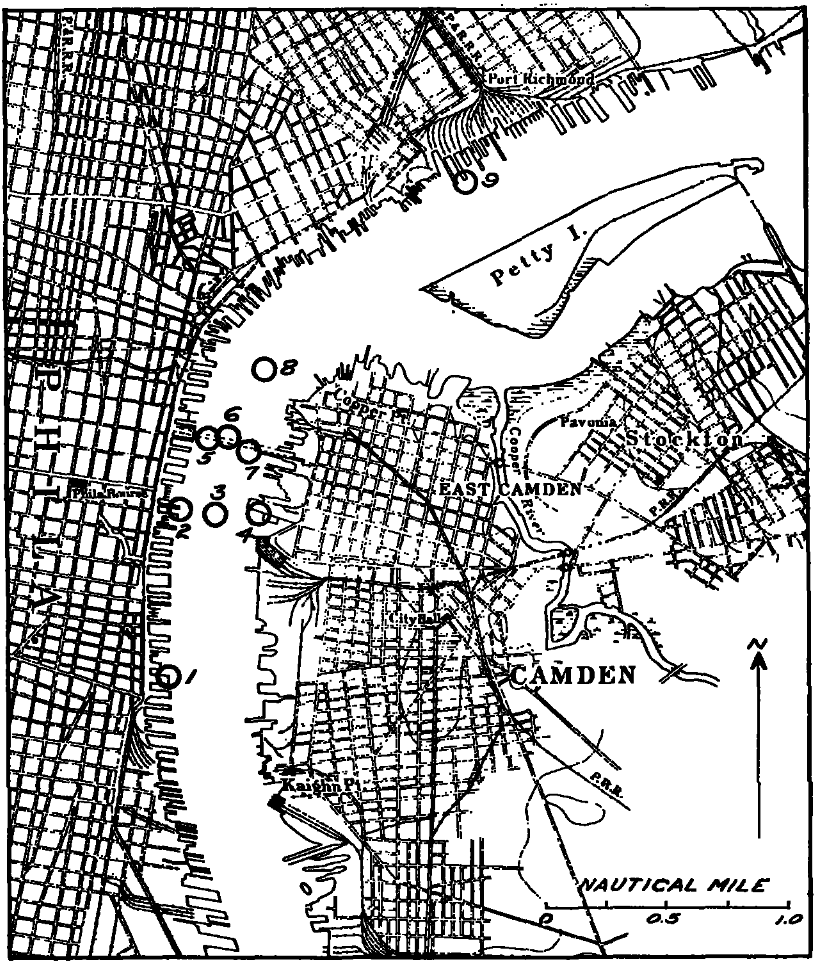

FIG. 32.—Current stations, vicinity of Philadelphia and Camden

Along the water front the velocity of flood and ebb at strength is about one knot. In midstream, flood and ebb strengths average about 1¾ knots. The direction of flood and ebb in midstream varies considerably in this portion of the Delaware River owing to the bend in the river. Thus the directions of flood and ebb in midstream at the Philadelphia-Camden Bridge and off Cooper Point differ by about 40°.

TABLE 52.—*Current data, Delaware River, vicinity of Philadelphia and Camden*

[Referred to time of current at Overfalls Light Vessel]

Station No.	Location	Party of—	Date	Slack	Flood strength			Flood duration	Slack	Ebb strength			Ebb duration	Length of observations
					Time	Direction	Velocity			Time	Direction	Velocity		
				Hours	*Hours*	*True*	*Knots*	*Hours*	*Hours*	*Hours*	*True*	*Knots*	*Hours*	*Days*
1	Off Pier 38, Philadelphia	W. H. Overshiner	September, 1924	5.8	5.1	N. 45° W.	0.6	5.2	5.1	5.2	S. 45° E.	0.8	7.2	½
2	Off Chestnut Street Pier	F. A. Kummell	January, 1902	5.8				5.2	5.0				7.2	157
3	do	do	do	6.1				5.2	5.3				7.2	157
4	do	do	May, 1902	5.6				5.2	4.8				7.2	48
5	Philadelphia-Camden Bridge	W. H. Overshiner	July, 1924	6.0	5.5	N. 15° E.	1.8	5.5	5.6	6.3	S. 10° W.	1.7	6.9	1
6	do	do	do	5.9	5.7	N. 25° E.	1.7	5.5	5.4	5.8	S. 5° W.	1.4	6.9	1
7	do	do	do	5.4	5.6	N. 30° E.	1.6	5.7	5.1	5.6	S. 15° W.	1.1	6.7	1
8	Off Cooper Point	H. L. Marinden	July, 1886	6.0	5.5	N. 60° E.	1.8	5.4	5.3	6.3	S. 55° W.	1.7	7.0	10¼
9	Off Port Richmond	W. H. Overshiner	September, 1924	6.0				4.8	4.8	4.9	S. 60° W.	0.2	7.6	½

TABLE 53.—*Current data, Delaware River, vicinity of Philadelphia and Camden*

[Referred to time of current at Overfalls Light Vessel]

Station No.	Location	Date	Party of—	Observations with—	Depth	Slack	Flood strength: Time	Flood strength: Direction	Flood strength: Velocity	Flood duration	Slack	Ebb strength: Time	Ebb strength: Direction	Ebb strength: Velocity	Ebb duration	Length of observations
		1924			*Feet*	*Hours*	*Hours*	*True*	*Knots*	*Hours*	*Hours*	*Hours*	*True*	*Knots*	*Hours*	*Days*
1	Off Pier 38, Philadelphia	Sept. 16-17	W. H. Overshiner	Pole	7	5.83	5.07	N. 47° W.	0.59	5.29	5.08	5.23	S. 47° E.	0.74	7.13	½
				Meter	9	5.73	5.57	----------	0.73	5.39	5.08	5.73	----------	0.88	7.03	½
				do	22	5.73	5.57	----------	0.69	5.39	5.08	5.73	----------	0.69	7.03	½
				do	36	5.73	5.57	----------	0.69	5.29	4.98	5.73	----------	0.49	7.13	½
5	Philadelphia-Camden Bridge.	July 28-29	do	Pole	7	5.93	5.47	N. 14° E.	1.76	5.49	5.38	6.28	S. 9° W.	1.71	6.93	1
				Meter	7	5.63	5.22	N. 5° E.	1.72	5.99	5.58	6.28	S. 8° W.	1.67	6.43	1
				do	18	6.03	5.22	N. 12° E.	1.62	5.54	5.53	6.28	S. 13° W.	1.57	6.88	1
				do	29	6.03	5.22	N. 15° E.	1.47	5.59	5.58	6.28	S. 18° W.	1.37	6.83	1
6	do	July 25-26	do	Pole	7	5.83	5.67	N. 25° E.	1.68	5.64	5.43	5.83	S. 6° W.	1.38	6.78	1
				Meter	6	5.83	5.07	N. 15° E.	1.68	5.59	5.38	5.83	S. 4° E.	1.43	6.83	1
				do	16	5.88	5.07	N. 20° E.	1.63	5.59	5.43	5.83	S. 2° E.	1.28	6.83	1
				do	25	5.93	5.07	N. 25° E.	1.48	5.54	5.43	5.58	S. 18° W.	1.18	6.88	1
7	do	do	do	Pole	7	5.43	5.57	N. 28° E.	1.63	5.69	5.08	5.58	S. 14° W.	1.13	6.73	1
				Meter	5	5.63	5.32	N. 8° E.	1.43	5.54	5.13	5.83	S. 14° W.	1.18	6.88	1
				do	12	5.58	5.07	N. 1° E.	1.27	5.54	5.08	5.83	S. 14° W.	1.12	6.88	1
				do	20	5.73	5.32	N. 8° E.	1.22	5.34	5.03	5.83	S. 6° W.	0.97	7.08	1
9	Off Port Richmond	Sept. 16-17	do	Pole	7	5.93	------	----------	------	4.89	4.78	4.93	S. 60° W.	0.24	7.53	¼
				Meter	4	5.53	5.67	N. 65° E.	0.24	5.64	5.13	4.43	S. 65° W.	0.39	6.78	½
				do	10	5.53	5.67	N. 55° E.	0.24	5.64	5.13	4.43	S. 73° W.	0.39	6.78	½
				do	16	5.63	5.67	N. 60° E.	0.24	5.54	5.13	4.43	S. 60° W.	0.39	6.88	½

The duration of ebb greatly exceeds that of flood at all stations in this portion of the Delaware River. Based on a long series of slack-water observations on a cross section of the river off Chestnut Street Pier, Philadelphia, the durations of flood and ebb in this section of the river are 5.2 and 7.2 hours, respectively.

At current stations 1, 5, 6, 7, and 9, listed in Table 52, subsurface current velocity observations were also made by means of current meters with telephone attachment for counting the number of revolutions of the current meter cups at each subsurface depth. Generally, these observations were made at three depths — two-tenths, five-tenths, and eight-tenths of the depth at each station. The direction of the subsurface current at these depths at stations 5, 6, 7, and 9 was determined by means of a bifilar direction indicator.

The data derived from these observations are given in Table 53. The times of slack and strength of current, referred to the same phases of the current of Overfalls Light Vessel (Delaware Bay Entrance), are given in hours and hundredths of hours, which permits differences in the time of current at various subsurface depths at each station to be readily seen. The velocities of the current at times of flood and ebb strengths are given in knots and hundredths of knots and have been corrected to a mean range of tide at each station. For comparative purposes, pole observations are listed for each of these stations. A 15-foot pole, submerged to a depth of 14 feet and giving current determinations at an average depth of 7 feet, was used.

At the dock stations, 1 and 9, where observations were made for but 13 hours, it will be noted that the times of slack and strength of current occur about simultaneously at all three meter depths. At times of flood strength at stations 1 and 9 the current attains about the same velocity at all depths. This is likewise true of the ebb at the latter station. At station 1, however, the velocity of the ebb decreases as the depth increases.

The data for stations 5, 6, and 7 show that the current at all depths turns earlier along the Camden water front than it does in mid-channel or along the Philadelphia water front. Likewise the velocities of the current at times of strength of flood and ebb are less for each depth along the Camden water front than they are in mid-channel or in the deeper water along the Philadelphia water front.

THE CURRENT IN THE DELAWARE RIVER—PHILADELPHIA TO TRENTON

This section of the Delaware River which is about 30 nautical miles in length, is crooked, and has many bars and shoals. By means of dredging, the channel has been improved so that the river is navigable for steamers, schooners, and barges to 14 feet draft from the Pennsylvania Railroad bridge at Fisher Point, N. J., to the city of Trenton, N. J. The river is also the approach to the Delaware and Raritan Canal which has its entrance at Bordentown, N. J., about 4 miles below Trenton.

No current observations prior to 1924 for this section of the Delaware River are on file in the office of the Coast and Geodetic Survey. In the summer of 1924 the party of W. H. Overshiner occupied six current stations from Fisher Point, N. J., to Bordentown, N. J.

The locations of these stations are shown in Figure 33. Currents were observed both by means of current pole and current meter. The data derived from current observations at these six stations in the Delaware River are given in Table 54. These data refer to the tidal current near the surface at a depth of about 7 feet, except at station 3, and are based mainly on observations made by means of current pole and log line.

In Table 54 the times of slack water and strengths of flood and ebb are given in hours and tenths of hours and are referred to the

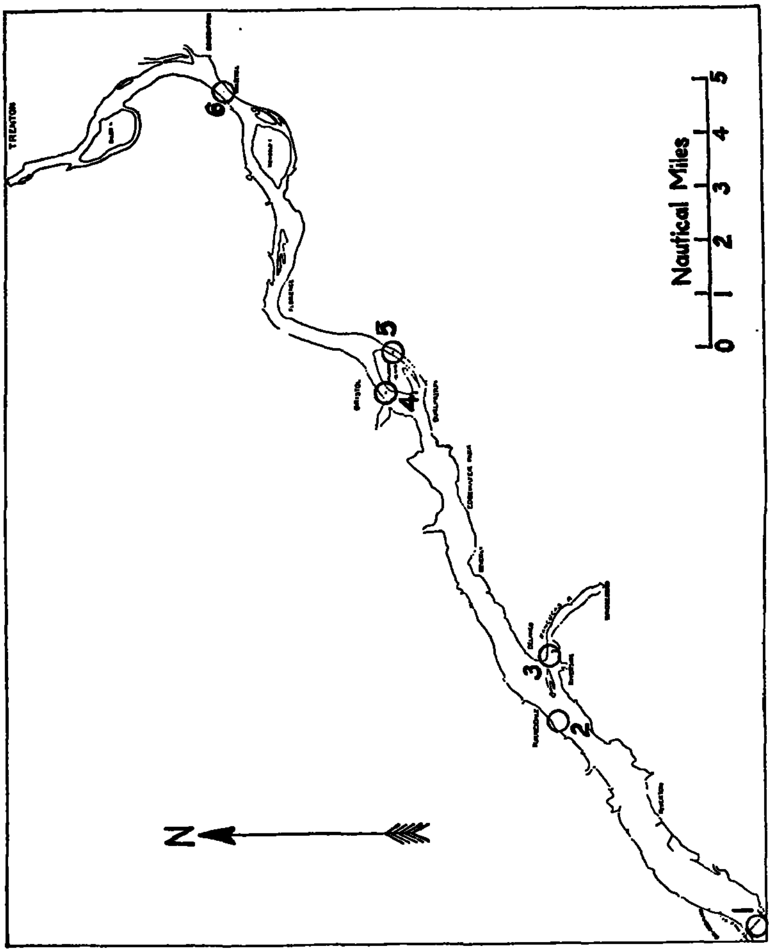

FIG. 33.—Current stations, Delaware River, Philadelphia to Trenton

times of the corresponding phases of the current at Overfalls Light Vessel (Delaware Bay Entrance). The durations of flood and ebb are also given in hours and tenths of hours and it will be noted from the table that the duration of ebb at all stations except at station 3 exceeds that of the flood by one and three-fourth hours or more, due to fresh water run-off in the river. The velocities of flood and ebb strengths are given in knots and tenths of knots and have been corrected to a mean range of tide at each station. The true directions of flood and ebb strengths are given to the nearest 5°.

Table 54.—*Current data, Delaware River, Philadelphia to Trenton*

[Referred to time of current at Overfalls Light Vessel]

Station No.	Location	Date[1]	Slack	Flood strength			Flood duration	Slack	Ebb strength			Ebb duration	Length of observations
				Time	Direction	Velocity			Time	Direction	Velocity		
		1924	*Hours*	*Hours*	*True*	*Knots*	*Hours*	*Hours*	*Hours*	*True*	*Knots*	*Hours*	*Days*
1	Off Fisher Point, N. J	July 21–29	6.3	5.6	N. 70°E.	1.3	5.3	5.6	5.8	S. 30°W.	1.2	7.1	8
2	Off Torresdale, Pa	July 21–22	6.7	6.6	N. 35°E.	1.6	5.3	6.0	6.5	S. 65°W.	1.6	7.1	1
3	Rancocas River Entrance	do	6.2	5.8	N. 85°E.	1.0	6.2	6.4	5.9	N. 85°W.	0.8	6.2	1
4	Off Bristol, Pa	July 22–23	7.4	6.1	N. 55°E.	1.2	5.0	6.4	6.3	S. 50°W.	1.0	7.4	1
5	Off Burlington Island	do	7.5	6.5	N. 30°E.	1.3	4.9	6.4	6.8	S. 30°W.	1.2	7.5	1
6	Off Whitehill, N. J	July 23–24	7.6	6.4	N. 50°E.	0.8	4.8	6.4	7.9	S. 40°W.	0.6	7.6	1

[1] Party of W. H. Overshiner.

Current station 1, located in midstream off Fisher Point, N. J., was the control station for current stations occupied in this portion of the Delaware River. The current turns about one and one-fourth hours earlier on the flood at this station than it does in midstream off Whitehill, N. J. On the ebb, the current turns about three-fourths hour earlier at the former station than at the latter. The flood attains its strength off Whitehill about three-fourths hour after the time of flood strength at the control station off Fisher Point, while ebb strength at the former station occurs about two hours later than it does at the control station. Off Whitehill, the current begins to ebb about the same time that it starts to flood at the reference station, Overfalls Light Vessel. When the current begins to flood off Whitehill, the current at Overfalls Light Vessel is approximately at quarter ebb stage, having been ebbing for one and one-half hours.

The flood and ebb at each station sets approximately fair with the direction of the channel, the former setting northeasterly and the latter southwesterly. At strength, the current averages about one and one-fourth knots in velocity in this stretch of the Delaware River. It is noteworthy that at five of the six current stations, including the control station itself, the velocity at flood strength exceeded that at ebb strength, and at the remaining station the velocity of the current at flood strength equaled that at ebb strength. It should be borne in mind, however, that the observational period at all stations except the control station was short, being about 26 hours at each station, and also that the observations were made during the month of July and therefore at a time when the ebb would not be materially influenced by fresh water discharge.

At the Rancocas River Entrance the durations of flood and ebb are about equal, but in the Delaware River proper the duration of ebb greatly exceeds that of flood. The average durations of flood and ebb at the five stations in this section of the Delaware River are 5.1 and 7.3 hours, respectively.

In addition to current observations by means of pole and log line at the six stations in this section of the Delaware River, meter observations were also made at various depths to determine the time and velocity of the current at two-tenths, five-tenths, and eight-tenths of the depth at each station. At stations 1, 2, 5, and 6 the directions of the current at these depths were determined by means of a bifilar direction indicator. The data derived from these observations are given in Table 55.

In Table 55, the times of slack and strength of current, referred to the same phases of the current at Overfalls Light Vessel (Delaware Bay Entrance), are given in hours and hundredths of hours. The durations of flood and ebb for various depths are also given in hours and hundredths of hours. The velocities of the current at times of flood and ebb strengths are given in knots and hundredths of knots and have been corrected to a mean range of tide at each station. For comparative purposes, pole observations are listed for each of these stations. A 15-foot pole, weighted with lead so as to submerge to a depth of 14 feet and giving current determinations at an average depth of 7 feet, was used at all stations except station 3, which was located at the entrance to Rancocas River. At this station a 4-foot pole was used.

TABLE 55.—*Current data, Delaware River, Philadelphia to Trenton*

[Referred to time of current at Overfalls Light Vessel]

Station No.	Location	Date	Party of—	Observations with—	Depth	Slack	Flood strength			Flood duration	Slack	Ebb strength			Ebb duration	Length of observations
							Time	Direction	Velocity			Time	Direction	Velocity		
		1924			*Feet*	*Hours*	*Hours*	*True*	*Knots*	*Hours*	*Hours*	*Hours*	*True*	*Knots*	*Hours*	*Days*
1	Off Fisher Point, N. J.	July 21–29	W. H. Overshiner	Pole	7	6. 15	5. 63	N. 72° E.	1. 27	5. 54	5. 65	5. 77	S. 28° W.	1. 23	6. 88	8
				Meter	6	6. 25	5. 78	N. 83° E.	1. 31	5. 49	5. 70	5. 48	S. 35° W.	1. 28	6. 93	8
				do	15	6. 22	5. 82	N. 80° E.	1. 22	5. 50	5. 68	5. 57	S. 36° W.	1. 20	6. 92	8
				do	24	6. 20	5. 88	N. 73° E.	1. 12	5. 51	5. 67	5. 55	S. 36° W.	1. 05	6. 91	8
2	Off Torresdale, Pa	July 21–22	do	Pole	7	6. 73	6. 57	N. 34° E.	1. 58	5. 34	6. 03	6. 53	S. 64° W.	1. 63	7. 08	1
				Meter	7	6. 63	6. 07	N. 48° E.	1. 58	5. 34	5. 93	6. 53	S. 83° W.	1. 43	7. 08	1
				do	16	6. 68	6. 07	N. 64° N.	1. 38	5. 34	5. 98	6. 53	S. 88° W.	1. 33	7. 08	1
				do	26	6. 63	6. 07	N. 58° E.	1. 17	5. 19	5. 78	6. 53	S. 88° W.	1. 12	7. 23	1
3	Rancocas River Entrance.	do	do	Pole	2	6. 18	5. 82	N. 85° E.	0. 97	6. 24	6. 38	5. 88	N. 85° W.	0. 82	6. 18	1
				Meter	3	6. 68	6. 07		1. 02	5. 44	6. 08	6. 13		0. 92	6. 98	1
				do	8	6. 68	6. 07		0. 97	5. 44	6. 08	6. 13		0. 87	6. 98	1
				do	12	6. 68	6. 07		0. 83	5. 44	6. 08	6. 13		0. 78	6. 98	1
4	Off Bristol, Pa	July 22–23	do	Pole	7	7. 38	6. 07	N. 53° E.	1. 25	4. 99	6. 33	6. 28	S. 49° W.	1. 05	7. 43	1
				Meter	5	7. 48	6. 47		1. 05	4. 89	6. 33	6. 78		1. 10	7. 53	1
				do	13	7. 48	6. 22		1. 05	4. 94	6. 38	6. 78		1. 05	7. 48	1
				do	21	7. 48	6. 47		0. 90	4. 99	6. 43	6. 78		0. 90	7. 43	1
5	Off Burlington Island	do	do	Pole	7	7. 53	6. 50	N. 28° E.	1. 32	4. 94	6. 43	6. 82	S. 32° W.	1. 15	7. 48	1
				Meter	3	7. 43	6. 30	N. 28° E.	1. 38	5. 14	6. 53	6. 92	S. 29° W.	1. 22	7. 28	1
				do	7	7. 43	6. 15	N. 36° E.	1. 28	5. 14	6. 53	6. 92	S. 51° W.	1. 10	7. 28	1
				do	12	7. 43	6. 00	N. 43° E.	1. 15	5. 14	6. 53	6. 82	S. 57° W.	1. 08	7. 28	1
6	Off Whitehill, N. J	July 23–24	do	Pole	7	7. 58	6. 45	N. 49° E.	0. 78	4. 89	6. 43	7. 92	S. 38° W.	0. 63	7. 53	1
				Meter	3	7. 68	6. 70	N. 38° E.	0. 74	4. 84	6. 48	7. 67	S. 33° W.	0. 64	7. 58	1
				do	7	7. 68	6. 70	N. 56° E.	0. 66	4. 84	6. 48	7. 67	S. 48° W.	0. 64	7. 58	1
				do	12	7. 63	6. 80	N. 62° E.	0. 59	4. 89	6. 48	7. 67	S. 55° W.	0. 59	7. 53	1

At station 1, which was the control station, continuous observations were made for a period of eight days. At stations 2 to 6, inclusive, continuous observations were made for 26 hours at half-hour intervals by means of a Price current meter with telephone attachment for counting the number of revolutions of the meter cups during the observational period of 60 seconds. Pole observations were made hourly as a check on the observations made by means of current meter.

It will be noted from the data in Table 55 that the times of slack water before flood and ebb at various depths is practically simultaneous at each station. This is also true of the time of strength of current at the various depths at each station.

The strengths of flood and ebb at each station decrease generally as the depth increases. At all depths at each station the velocity of flood is generally greater than that of ebb; the duration of ebb, however, is greater at all depths than that of flood.

APPENDIX

GENERAL CHARACTERISTICS OF TIDES AND CURRENTS

[Reprinted from United States Coast and Geodetic Survey Special Publication No. 111]

I. TIDES, GENERAL CHARACTERISTICS

DEFINITIONS

The tide is the name given to the alternate rising and falling of the level of the sea which at most places occurs twice daily. The striking feature of the tide is its intimate relation to the movement of the moon. High water and low water at any given place follow the moon's meridian passage by a very nearly constant interval, and since the moon in its apparent movement around the earth crosses a given meridian, on the average, 50 minutes later each day, the tide at most places likewise comes later each day by 50 minutes on the average. The tidal day, like the lunar day, therefore, has an average length of 24 hours and 50 minutes.

With respect to the tide, the "moon's meridian passage" has a special significance. It refers not only to the instant when the moon is directly above the meridian, but also to the instant when the moon is directly below the meridian, or 180° distant in longitude. In this sense there are two meridian passages in a tidal day, and they are distinguished by being referred to as the upper and lower meridian passages or upper and lower transits.

The interval between the moon's meridian passage (upper or lower) and the following high water is known as the "high water lunitidal interval." Likewise the interval between the moon's meridian passage and the following low water is known as the "low water lunitidal interval." For short they are called, respectively, high water interval and low water interval and abbreviated as follows: HWI and LWI.

In its rising and falling the tide is accompanied by a horizontal forward and backward movement of the water, called the tidal current. The two movements —the vertical rise and fall of the tide and the horizontal forward and backward movement of the tidal current—are intimately related, forming parts of the same phenomenon brought about by the tidal forces of sun and moon.

It is necessary, however, to distinguish clearly between tide and tidal current, for the relation between them is not a simple one nor is it everywhere the same. At one place a strong current may accompany a tide having a very moderate rise and fall while at another place a like rise and fall may be accompanied by a very weak current. Furthermore, the time relations between current and tide vary widely from place to place. For the sake of clearness, therefore, tide should be used to designate the vertical movement of the water and tidal current the horizontal movement.

It is convenient to have a single term to designate the whole phenomenon which includes tides and tidal currents. Unfortunately no such distinct term exists. For years, however, "the tide" or "the tides," or even "flood and ebb," have been used in this general sense, and usually no confusion arises from this usage, since the context indicates the sense intended; but the use of the term tide to denote the horizontal movement of the water is confusing and is to be discouraged.

With respect to the rise and fall of the water due to the tide, high water and low water have precise meanings. They refer not so much to the height of the water as to the phase of the tide. High water is the maximum height reached by each rising tide and low water the minimum height reached by each falling tide.

It is important to note that it is not the absolute height of the water which is in question, for it is not at all infrequent at many places to have the low water of one day higher than the high water of another day. Whatever the height of the water, when the rise of the tide ceases and the fall is to begin, the tide is at high water; and when the fall of the tide ceases and the rise is to begin, the tide is at low water. The abbreviations HW and LW are frequently used to designate high and low water, respectively.

In its rising and falling the tide does not move at a uniform rate. From low water the tide begins rising, very slowly at first, but at a constantly increasing rate for about three hours, when the rate of rise is a maximum. The rise then continues at a constantly decreasing rate for the following three hours, when high water is reached and the rise ceases. The falling tide behaves in a similar manner, the rate of fall being least immediately after high water, but increasing constantly for about three hours, when it is at a maximum, and then decreasing for a period of three hours till low water is reached.

The rate of rise and fall and other characteristics of the tide may best be studied by representing the rise and fall graphically. This may be done by reading the height of the tide at regular intervals on a fixed vertical staff graduated to feet and tenths and plotting these heights to a suitable scale on cross-section paper and drawing a smooth curve through these points. A more convenient method is to make use of an automatic tide gauge by means of which the rise and fall of the tide is recorded on a sheet of paper as a continuous curve drawn to a suitable scale. Figure A shows a tide curve for Fort Hamilton, N. Y., for July 4, 1922.

In Figure A the figures from 0 to 24, increasing from left to right, represent the hours of the day beginning with midnight. Numbering the hours consecutively to 24 eliminates all uncertainty as to whether morning or afternoon is meant and has the further advantage of great convenience in computation.

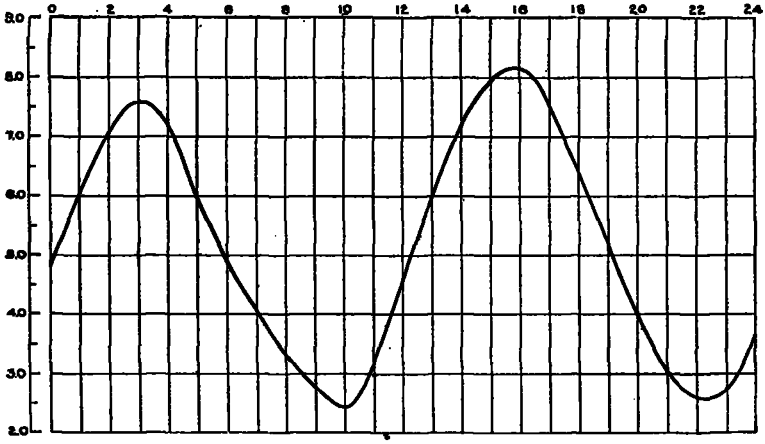

Fig. A.—Tide curve for Fort Hamilton, N. Y., July 4, 1922

The figures on the left, increasing upward from 2.0 to 9.0, represent the height of the tide in feet as referred to a fixed vertical staff. The tide curve presents the well-known form of the sine or cosine curve.

The difference in height between a high water and a preceding or following low water is known as the "range of tide" or "range." The average difference in the heights of high and low water at any given place is called the mean range.

THE TIDE-PRODUCING FORCES

The intensity with which the sun (or moon) attracts a particle of matter on the earth varies inversely as the square of the distance. For the solid earth as a whole the distance is obviously to be measured from the center of the earth, since that is the center of mass of the whole body. But the waters of the earth, which may be considered as lying on the surface of the earth, are on the one side of the earth nearer to the heavenly bodies and on the other side farther away than the center of the earth. The attraction of sun or moon for the waters of the ocean is thus different in intensity from the attraction for the solid earth as a whole, and these differences of attraction gives rise to the forces that cause the ocean waters to move relative to the solid earth and bring about the tides. These forces are called the tide-producing forces.

The mathematical development of these forces shows that the tide-producing force of a heavenly body varies directly as its mass and inversely as the cube of its distance from the earth. The sun has a mass about 26,000,000 times as great as that of the moon; but it is 389 times as far away from the earth. Its tide-producing force is therefore to that of the moon as 26,000,000 is to $(389)^3$, or somewhat less than one-half.

When the relative motions of the earth, moon, and sun are introduced into the equations of the tide-producing forces, it is found that the tide-producing forces of both sun and moon group themselves into three classes: (*a*) Those having a period of approximately half a day, known as the semidiurnal forces; (*b*) those having a period of approximately one day, known as diurnal forces; (*c*) those having a period of half a month or more, known as long-period forces.

The distribution of the tidal forces over the earth takes place in a regular manner, varying with the latitude. But the response of the various seas to these forces is very profoundly modified by terrestrial features. As a result we find the tides, as they actually occur, differing markedly at various places, but apparently with no regard to latitude.

The principal tide-producing forces are the semidiurnal forces. These forces go through two complete cycles in a tidal day, and it is because of the predominance of these semidaily forces that there are at most places two complete tidal cycles, and therefore two high and two low waters in a tidal day.

VARIATIONS IN RANGE

The range of the tide at any given place is not constant but varies from day to day; indeed, it is exceptional to find consecutive ranges equal. Obviously, changing meteorological conditions will find reflection in variations of range, but the principal variations are due to astronomic causes, being brought about by variations in the position of the moon relative to earth and sun.

At times of new moon and full moon the tidal forces of moon and sun are acting in the same direction. High water then rises higher and low water falls lower than usual, so that the range of the tide at such times is greater than the average. The tides at such times are called "spring tides" and the range of the tide is then known as the "spring range."

When the moon is in its first and third quarters, the tidal forces of sun and moon are opposed and the tide does not rise as high nor fall as low as the average. At such times the tides are called "neap tides" and the range of the tide then is known as the "neap range."

It is to be noted, however, that at most places there is a lag of a day or two between the occurrence of spring or neap tides and the corresponding phases of the moon; that is, spring tides do not occur on the days of full and new moon, but a day or two later. Likewise neap tides follow the moon's first and third quarters after an interval of a day or two. This lag in the response of the tide is known as the "age of phase inequality" or "phase age" and is generally ascribed to the effects of friction.

The varying distance of the moon from the earth likewise affects the range of the tide. In its movement around the earth the moon describes an ellipse in a period of approximately 27½ days. When the moon is in perigee, or nearest the earth, its tide-producing power is increased, resulting in an increased rise and fall of the tide. These tides are known as "perigean tides," and the range at such times is called the "perigean range." When the moon is farthest from the earth, its tide-producing power is diminished, the tides at such times exhibiting a decreased rise and fall. These tides are called "apogean tides" and the corresponding range the "apogean range."

In the response to the moon's change in position from perigee to apogee it is found that, like the responses in the case of spring and neap tides, there is a lag in the occurrence of perigean and apogean tides. The greatest rise and fall does not come on the day when the moon is in perigee, but a day or two later. Likewise, the least rise and fall does not occur on the day of the moon's apogee, but a day or two later. This interval varies somewhat from place to place, and in some regions it may have a negative value. This lag is known as the "age of parallax inequality" or "parallax age."

The moon does not move in the plane of the Equator, but in an orbit making an angle with that plane of approximately 23½°. During the month, therefore, the moon's declination is constantly changing, and this change in the position of the moon produces a variation in the consecutive ranges of the tide. When the moon is on or close to the Equator—that is, when its declination is small—consecutive ranges do not differ much, morning and afternoon tides being very much alike. As the declination increases the difference in consecutive ranges increases, morning and afternoon tides beginning to show decided differences, and at the times of the moon's maximum semimonthly declination these differences are very nearly at a maximum. But, like the response to changes in the moon's phase and parallax, there is a lag in the response to the change in declination, this lag being known as the "age of diurnal inequality" or "diurnal age." Like the phase and parallax ages, the diurnal age varies from place to place, being generally about one day, but in some places it may have a negative value.

When the moon is on or close to the Equator and the difference between morning and afternoon tides small, the tides are known as "equatorial tides." At the times of the moon's maximum semimonthly declination, when the differences between morning and afternoon tides are at a maximum, the tides are called "tropic tides," since the moon is then near one of the Tropics.

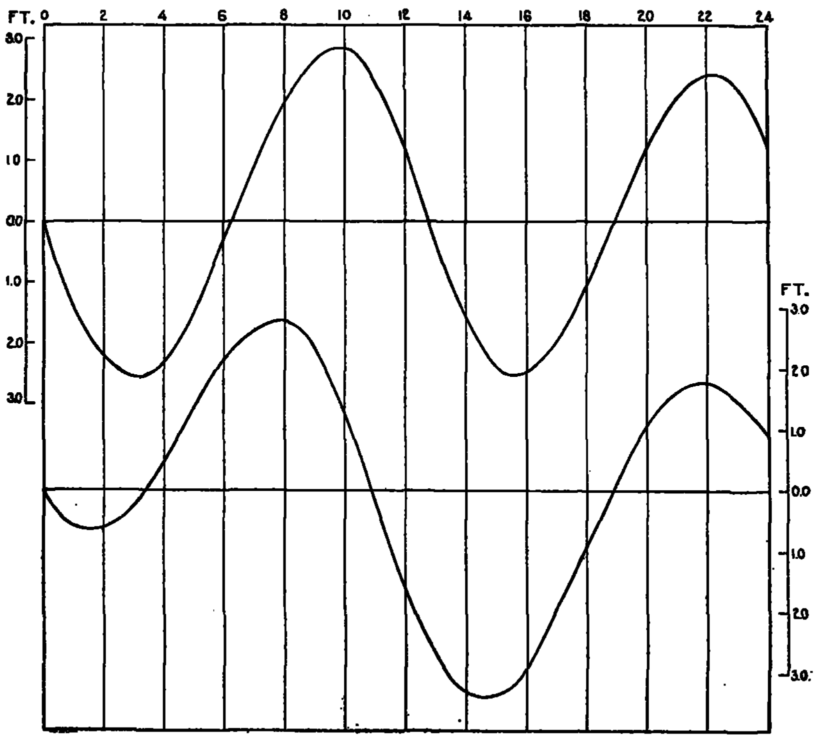

FIG. B.—Tide curves, San Francisco, Calif., October 18 and 24, 1922

The three variations in the range of the tide noted above are exhibited by the tide the world over, but not everywhere to the same degree. In many regions the variation from neaps to springs is the principal variation; in certain regions it is the variation from apogee to perigee that is the principal variation; and in other regions it is the variation from equatorial to tropic tides that is the predominant variation.

The month of the moon's phases (the synodical month) is approximately 29½ days in length; the month of the moon's distance (the anomalistic month) is approximately 27½ days in length; the month of the moon's declination (the tropic month) is approximately 27⅓ days in length. It follows, therefore, that very considerable variation in the range of tide occurs during a year due to the changing relations of the three variations to each other.

DIURNAL INEQUALITY

The difference between morning and afternoon tides due to the declination of the moon is known as diurnal inequality, and where the diurnal inequality is considerable the rise and fall of the tide is affected to a very marked degree both in time and in height. Figure B represents graphically the differences in the tide at San Francisco on October 18 and 24, 1922. On the former date the moon was over the Equator, while on the latter date the moon was at its maximum south declination for the month. The upper diagram thus represents the equatorial tide for San Francisco, while the lower diagram represents the tropic tide.

It will be noted that on October 18 the morning and afternoon tides show very close resemblance. In both cases the rise from low water to high water and the fall from high water to low water took place in approximately six hours. The heights to which the two high waters attained were very nearly the same, and likewise the depressions of the two low waters.

On October 24, when the moon attained its extreme declination for the fortnight, tropic tides occurred. The characteristics of the rise and fall of the tide on that day differ markedly from those on the 18th, when equatorial tides occurred, these differences pertaining both to the time and the height. Instead of an approximately equal duration of rise and of fall of six hours, both morning and afternoon, as was the case on the 18th, we now have the morning rise occupying less time that the afternoon rise and the morning fall more time than the evening fall. Even more striking are the differences in extent of rise and fall of morning and afternoon tides. The tide curve shows that there was a difference of a foot in the two high waters of the 24th and a difference of almost 3 feet in the low waters.

Definite names have been given to each of the two high and two low waters of a tidal day. Of the high waters, the higher is called the "higher high water" and the lower the "lower high water." Likewise, of the two low waters of any tidal day the lower is called "lower low water" and the higher "higher low water."

The diurnal inequality may be related directly to the ratio of the tides brought about, respectively, by the diurnal and semidiurnal tide-producing forces. Those bodies of water which offer relatively little response to the diurnal forces will exhibit but little diurnal inequality, while those bodies which offer relatively considerable response to these diurnal forces will exhibit considerable diurnal inequality. On the Atlantic coast of the United States there is relatively little diurnal inequality, while on the Pacific coast there is considerable inequality.

It is obvious that with increasing diurnal inequality the lower high water and higher low water tend to become equal and merge. When this occurs, there is but one high and one low water in a tidal day instead of two. This occurs frequently at Galveston, Tex., and at a number of other places.

TYPES OF TIDE

From place to place the characteristics of the rise and fall of the tide generally differ in one or more respects; but according to the predominating features the various kinds of tide may be grouped under three types, namely, semidiurnal diurnal, and mixed. Instead of semidiurnal and diurnal the terms semidaily and daily are frequently used.

The semidiurnal type of tide is one in which two high and two low waters occur each tidal day with but little diurnal inequality; that is, morning and afternoon tides resemble each other closely. Figure A may be taken as representing this type of tide and this is the type found on the Atlantic coast of the United States.

In the diurnal type of tide but one high and one low water occur in a tidal day. Do-Son, French Indo-China, may be cited as a place where the tide is always of the daily type; but it is to be noted that there are not many such places. When the moon's decination is zero, the diurnal tidal forces tend to vanish and there are generally two high and two low waters during the day at such times. Galveston, Tex., and Manila, P. I., may be mentioned as ports at which the tide is frequently diurnal, while St. Michael, Alaska, may be cited as a port at which the tide is largely diurnal.

The mixed type of tide is one in which two high and two low waters occur during the tidal day but which exhibits marked diurnal inequality. Several forms may occur under this type. In one form the diurnal inequality is exhibited principally by the high waters; in another form it is the low waters which exhibit the greater inequality; or the diurnal inequality may be features of both high waters and low waters.

It is to be noted that when the tide at any given place is assigned to any particular type, it refers to the characteristics of the predominating tide at that place. At the time of the moon's maximum semimonthly declination the semidiurnal type exhibits more or less diurnal inequality and thus approaches the mixed type; and when the moon is on or near the Equator the diurnal inequality of the mixed type is at a minimum, the tide at such times resembling the semidiurnal type. It is the characteristics of the predominating tide that determine the type of tide at any given place. With the aid of harmonic constants the type of tide may be defined by definite ratios of the semidiurnal to the diurnal constituents.

Type of tide is intimately associated with diurnal inequality, and hence depends on the relation of the semidiurnal to the diurnal tides; and it is due to the variation in this relation that makes possible the various forms of the mixed type of tide.

HARMONIC CONSTANTS

Since the tide is periodic in character, it may be regarded as the resultant of a number of simple harmonic movements. In other words, if h be the height of the tide, reckoned from sea level, then for any time t, we may write $h=A\cos(at+\alpha)+B\cos(bt+\beta)+\ .\ .\ .\ .$ In the above formula each term represents a constituent of the tide which is defined by its amplitude or semirange, A, B, etc., by an angular speed, a, b, etc., and by an angle of constant value, α, β, etc., which determines the relation of time of maximum height to the time of beginning of observation.

We may also regard the matter from another viewpoint and suppose the moon and sun as *tide-producing bodies* to be replaced by a number of hypothetical tide-producing bodies, each of which moves around the earth in the plane of the Equator in a circular orbit with the earth as center. With the further assumption that each of these hypothetical tide-producing bodies gives rise to a simple tide, the high water of which occurs a certain number of hours after its upper meridian passage and the low water the same number of hours after its lower meridian passage, the oscillation produced by each of these simple tides may be written in the form $h=A\cos(at+\alpha)$ as above. The great advantage of so regarding the tide is that it permits the complicated movements of sun and moon relative to the earth to be replaced by a number of simple movements.

Each of the simple tides into which the tide of nature is resolved is called a component tide, or simply a component. The amplitudes or semiranges of the component tides, together with the angles which determine the relation of the high water of each of these component tides to some definite time origin and which are known as the epochs, constitute the harmonic constants.

. The periods of revolution of the hypothetical tidal bodies or the speeds of the various component tides are computed from astronomical data and depend only on the relative movements of sun, moon, and earth. These periods being independent of local conditions are therefore the same for all places on the surface of the earth; what remains to be determined for the various simple constituent tides is their epochs and amplitudes which vary from place to place according to the type, time, and range of the tide. The mathematical process by which these epochs and amplitudes are disentangled from tidal observations is known as the harmonic analysis.

The number of simple constituent tides is theoretically large, but most of them are of such small magnitude that they may for all practical purposes be disregarded. In the prediction of tides it is necessary to take account of 20 to 30, but the characteristics of the tide at any place may be determined easily from the 5 principal ones.

It is obvious that the principal lunar tidal component will be one which gives two high and two low waters in a tidal day of 24 hours and 50 minutes, or more exactly in 24.84 hours. Its speed per solar hour, therefore, is $\frac{2\times360^\circ}{24.84}=28^\circ.98$ This component has been given the symbol M_2. Likewise, the principal solar tidal component is one that gives two high and two low waters in a solar day of 24 hours. Its angular speed per hour is therefore $\frac{2\times360^\circ}{24}=30^\circ.00$. The symbol for this principal solar component is S_2.

Since the moon's distance from the earth is not constant, being less than the average at perigee and greater at apogee, the period from one perigee to another being on the average 27.55 days, we must introduce another hypothetical tidal body, so that at perigee its high water will correspond with the M_2 high water, and at apogee its low water will correspond with the M_2 high water. In other words, the tidal component which is to take account of the moon's perigean movement must, in a period of 13.78 days, lose 180° on M_2, or at the rate of $\frac{180^\circ}{13.78}=13^\circ.06$ per day. Its hourly speed, therefore, is $28^\circ.98-\frac{13^\circ.06}{24}=28^\circ.44$. This component has been given the symbol N_2.

The moon's change in declination is taken account of by two components denoted by the symbols K_1 and O_1. The speeds of these are determined by the following considerations: The average period from one maximum declination to another is a half tropic month, or 13.66 days. The speeds of these two components should, therefore, be such that when the moon is at its maximum declination they shall both be at a maximum, and when the moon is on the Equator they shall neutralize each other; that is, in a period of 13.66 days K_1 shall gain on O_1 one full revolution. The difference in their hourly speeds, therefore, is $\frac{360^\circ}{24\times 13.66}=1^\circ.098$. The mean of the speeds of these two components must be that of the apparent diurnal movement of the moon about the earth, or $\frac{360^\circ}{24.84}=14^\circ.49$. The speeds are therefore derived from the equations $\frac{K_1+O_1}{2}=14^\circ.49$ and $K_1-O_1=1^\circ.098$, from which $K_1=15^\circ.04$ and $O_1=13^\circ.94$.

It is customary to designate the amplitude of any component by the symbol of the component and the epoch by the symbol with a degree mark added. Thus M_2 stands for the amplitude of the M_2 tide and M°_2 for the epoch of this tide. The five components enumerated above are the principal ones. Between 20 and 30 components permit the prediction of the time and height of the tide at any given place with considerable precision.

From the harmonic constants the characteristics of the tide at any place can be very readily determined.[1] The five principal constants alone permit the approximate determination of the tidal characteristics very easily. Thus, approximately, the mean range is $2M_2$, spring range $2(M_2+S_2)$, neap range $2(M_2-S_2)$, perigean range $2(M_2+N_2)$, apogean range $2\ (M_2-N_2)$, diurnal inequality at time of tropic tides $2(K_1+O_1)$, high water lunitidal interval $\frac{M_2{}^\circ}{28.98}$. The various ages of the tide can likewise be readily determined. Approximately, the ages in hours are: Phase age, $S_2{}^\circ-M_2{}^\circ$; parallax age, $2(M_2{}^\circ-N_2{}^\circ)$; diurnal age, $K^\circ{}_1-O^\circ{}_1$. The type of tide, too, may be determined from the harmonic constants through the ratio $\frac{K_1+O_1}{M_2+S_2}$. Where this ratio is less than 0.25, the tide is of the semidiurnal type; where the ratio is between 0.25 and 1.25, the tide is of the mixed type; and where the ratio is over 1.25, the tide is of the diurnal type.

The periods of the various component tides, like the periods of the tide-producing forces, group themselves into three classes. The tides in the first class have periods of approximately half a day and are known as semidiurnal tides; the periods of the tides in the second class are approximately one day, and these tides are known as diurnal tides; the tides in the third class have periods of half a month or more and are known as long-period tides. In shallow waters, due to the effects of decreased depth, the tides are modified and another class of simple tides is introduced having periods of less than half a day, and these are known as shallow-water tides.

The class to which any component tide belongs is generally indicated by the subscript used in the notation for the component tides, the subscript giving the number of periods in a day. With long-period tides generally no subscript is used; with semidiurnal tides the subscript is 2; with diurnal tides the subscript is 1, and with shallow-water tides, the subscript is 3, 4, or more. Thus Sa represents a solar annual component, P_1 a solar diurnal component, M_2 a lunar semidiurnal component, S_4 a solar shallow-water component with a period of one-quarter of a day, and M_6 a lunar shallow-water component with a period of one-sixth of a day.

[1] See R. A. Harris, Manual of Tides, Part III (United States Coast and Geodetic Survey Report for 1894, Appendix 7).

TIDAL DATUM PLANES

Tidal planes of reference form the basis of all rational datum planes used in practical or scientific work. The advantage of the datum plane based on tidal determination lies not only in simplicity of definition, but also in the fact that it may be recovered at any time, even though all bench-mark connections be lost.

The principal tidal plane is that of mean sea level, which may be defined as the plane about which the tide oscillates, or as the surface the sea would assume when undisturbed by the rise and fall of the tide. At any given place this plane may be determined by deriving the mean height of the tide. This is perhaps best done by adding the hourly heights of the tide over a period of a year or more and deriving the mean hourly height. It is to be noted that in such a determination the mean sea level is not freed from the effects of prevailing wind, atmospheric pressure, and other meteorological conditions.

The plane of mean sea level must be carefully distinguished from the plane of half-tide level or, as it is frequently called, mean-tide level. This latter plane is one determined as the half sum of the high and low waters. It is therefore the plane that lies halfway between the planes of mean low water and mean high water. The plane of half-tide level does not, at most places on the open coast, differ by more than about a tenth of a foot from the plane of mean sea level, and where this difference is known the plane of mean sea level may be determined from that of half-tide level. Like all of the tidal planes, the plane of half-tide level should be determined by observations covering a period of a year or more.

For many purposes the plane of mean low water is important. This plane at any given place is determined as the average of all the low waters during a period of a year or more. Where the diurnal inequality in the low waters is small, as on the Atlantic coast of the United States, this plane is frequently spoken of as the "low-water plane" or "the plane of low water"; but strictly it should be called the plane of mean low water.

Where the tides exhibit considerable diurnal inequality in the low waters, as on the Pacific coast of the United States, the lower low waters may fall considerably below the plane of mean low water. In such places the plane of mean lower low water is preferable for most purposes. This plane is determined as the average of all the lower low waters over a period of a year or more. Where the tide is frequently diurnal, the single low water of the day is taken as the lower low water.

The plane of mean high water is determined as the average of all the high waters over a period of a year or more. Where the diurnal inequality in the high waters is small, this plane is frequently spoken of as "the plane of high water" or "the high-water plane." This usage may on occasion lead to confusion, and the denomination of this plane as the plane of mean high water is therefore preferable.

In localities of considerable diurnal inequality in the high waters the higher high waters frequently rise considerably above the plane of mean high water. A higher plane is therefore of importance for many purposes, and the plane of higher high water is preferred. This plane is determined as the average of all the higher high waters for a period of a year or more. Where the tide is frequently diurnal, the single high water of the day is taken as the higher high water.

The tidal planes described above are the principal ones and the ones most generally used. Other planes, however, are sometimes used. Where a very low plane is desired, the plane of mean spring low water is sometimes used, its name indicating that it is determined as the mean of the low waters occurring at spring tides. Another plane sometimes used, which is of interest because based on harmonic constants, is known as the harmonic tide plane and for any given place is determined as $M_2+S_2+K_1+O_1$ below mean sea level.

MEAN VALUES

Since the rise and fall of the tide varies from day to day, chiefly in accordance with the changing positions of sun and moon relative to the earth, any tidal quantities determined directly from a short series of tidal observations must be corrected to a mean value. The principal variations are those connected with the moon's phase, parallax, and declination, the periods of which are approximately 29½ days, 27½ days, and 27⅓ days, respectively.

In a period of 29 days, therefore, the phase variation will have almost completed a full cycle while the other variations will have gone through a full cycle and but very little more. Hence, for tidal quantities varying largely with the phase variation, tidal observations covering 29 days, or multiples, constitute a satisfactory period for determining these quantities. Such are the lunitidal intervals, the mean range, mean high water, and mean low water. For quantities varying largely with the declination of the moon, as, for example, higher high water and lower low water, 27 days, or multiples, constitute the more satisfactory period.

As will be seen in the detailed discussion of the tides at Fort Hamilton, the values determined from two different 29-day or 27-day periods may differ very considerably. This is due to the fact that these periods are not exact synodic periods for the different variations, and to the further fact that variations having periods greater than a month are not taken into account. Furthermore, meteorological conditions, which change from month to month, leave their impress on the tides. For accurate results the direct determination of the tidal datum planes and other tidal quantities should be based on a series of observations that cover a period of a year or preferably three years. Values derived from shorter series must be corrected to a mean value.

Two methods may be employed for correcting the results of short series to a mean value. One method makes use of tabular values, determined both from theory and observation, for correcting for the different variations. The other method makes use of direct comparison with simultaneous observations at some near-by port for which mean values have been determined from a series of considerable length.

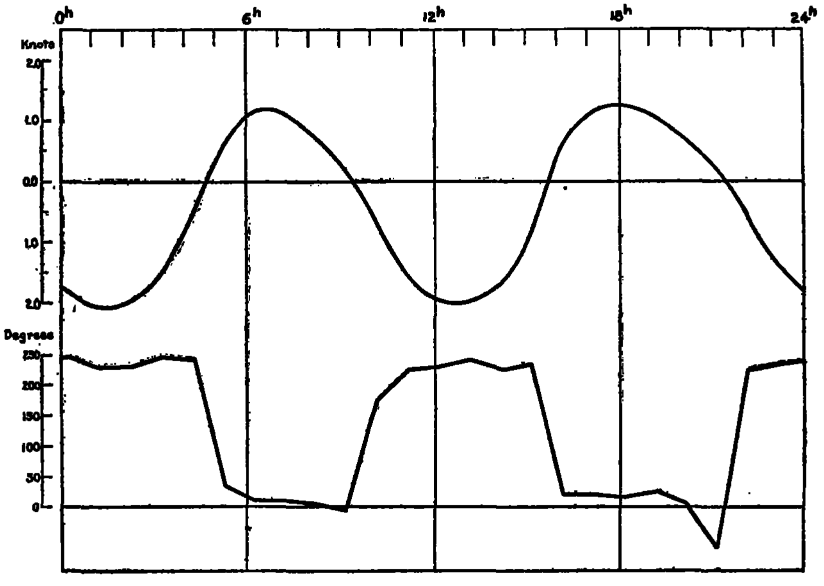

FIG. C.—Velocity and direction curves for current, Hudson River, July 22, 1922

II. TIDAL CURRENTS, GENERAL CHARACTERISTICS

DEFINITIONS

Tidal currents are the horizontal movements of the water that accompany the rising and falling of the tide. The horizontal movement of the tidal current and the vertical movement of the tide are intimately related parts of the same phenomenon brought about by the tide-producing forces of sun and moon. Tidal currents, like the tides, are therefore periodic.

It is the periodicity of the tidal current that chiefly distinguishes it from other kinds of currents, which are known by the general name of nontidal currents. These latter currents are brought about by causes that are independent of the tides, such as winds, fresh-water run-off, and differences in density and temperature. Currents of this class do not exhibit the periodicity of tidal currents.

Tidal and nontidal currents occur together in the open sea and in inshore tidal waters, the actual currents experienced at any point being the resultant of the two classes of currents. In some places tidal currents predominate and in others nontidal currents predominate. Tidal currents generally attain considerable velocity in narrow entrance to bays, in constricted parts of rivers, and in passages from one body of water to another. Along the coast and farther offshore tidal currents are generally of moderate velocity; and in the open sea, calculation based on the theory of wave motion, gives a tidal current of less than one-tenth of a knot.

RECTILINEAR TIDAL CURRENTS

In the entrance to a bay or river and, in general, where a restricted width occurs, the tidal current is of the rectilinear or reversing type; that is, the flood current runs in one direction for a period of about six hours and the ebb current for a like period in the opposite direction. The flood current is the one that sets inland or upstream and the ebb current the one that sets seaward or downstream. The change from flood to ebb gives rise to a period of slack water during which the velocity of the current is zero. An example of this type of current is shown in Figure C, which represents the velocity and direction of the current as observed in the Hudson River off Fort Washington on July 22, 1922.

In Figure C the upper curve represents the velocity of the current in knots, flood being plotted above the axis of X and ebb below the axis. The velocity curve represents approximately the form of the cosine curve. The maximum velocity of the flood current is called the strength of flood and the maximum ebb velocity the strength of ebb. The knot is the unit generally used for measuring the velocity of tidal currents and represents a velocity of 1 nautical mile per hour. Knots may be converted into statute miles per hour by multiplying by 1.15 or into feet per second by multiplying by 1.69.

The lower curve of Figure C is the direction curve of the current, the direction being given in degrees, north being 0°, east 90°, south 180°, and west 270°. The directions are magnetic and represent the direction of the current as derived from hourly observations. During the period of flood the direction curve shows that the current was running practically in the same direction all the time, making an abrupt shift of about 180° to the opposite direction during the period of slack water. For the ebb period the direction curve likewise shows the current to have been running in approximately the same direction with an abrupt change of about 180° during slack.

ROTARY TIDAL CURRENTS

Offshore the tidal currents are generally not of the rectilinear or reversing type. Instead of flowing in the same general direction during the entire period of the flood and in the opposite direction during the ebb, the tidal currents offshore change direction continually. Such currents are therefore called rotary currents. An example of this type of current is shown in Figure D, which represents the velocity and direction of the current at the beginning of each hour of the afternoon on September 24, 1919, at Nantucket Shoals Light Vessel, stationed off the coast of Massachusetts.

The current is seen to have changed its direction at each hourly observation, the rotation being in the direction of movement of the hands of a clock, or from north to south by way of east, then to north again by way of west. In a period of about 12 hours it is seen that the current has veered completely round the compass.

It will be noted that the ends of the radii vectores, representing the velocities and directions of the current at the beginning of each hour, define a somewhat irregular ellipse. If a number of observations are averaged, eliminating accidental errors and temporary meteorological disturbances, the regularity of the curve is considerably increased. The average period of the cycle is, from a considerable number of observations, found to be $12^h\ 25^m$. In other words, the current day, like the tidal day, is $24^h\ 50^m$ in length.

A characteristic feature of the rotary current is the absence of slack water. Although the current generally varies from hour to hour, this variation from greatest current to least current and back again to greatest current does not give rise to a period of slack water. When the velocity of the rotary tidal current is least, it is known as the minimum current, and when it is greatest it is known as the maximum current. The minimum and maximum velocities of the rotary current are thus related to each other in the same way as slack and strength of the rectilinear current, a minimum velocity following a maximum velocity by an interval of about three hours and being followed in turn by another maximum after a further interval of three hours.

VARIATIONS IN STRENGTH OF CURRENT

Tidal currents exhibit changes in the strength of the current that correspond closely with the changes in range exhibited by tides. The strongest currents come with the spring tides of full and new moon and the weakest currents with the neap tides of the moon's first and third quarters. Likewise, perigean tides are accompanied by strong currents and apogean tides by weak currents; and when the moon has considerable variation, the currents, like the tides, are characterized by diurnal inequality.

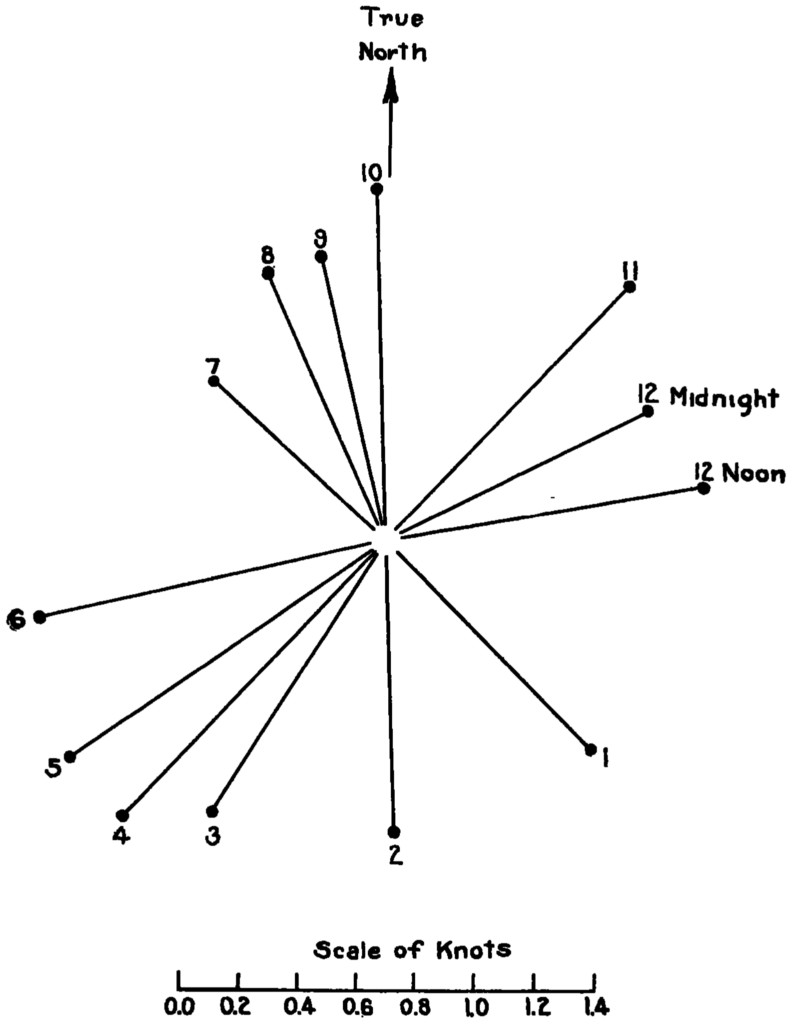

FIG. D.—Rotary current, Nantucket Shoals Light Vessel, afternoon of September 24, 1919

As related to the moon's changing phases, the variation in the strength of the current from day to day is approximately proportional to the corresponding change in the range of the tide. The moon's changing distance likewise brings about changes in the velocity of the strength of the current which is approximately proportional to the corresponding change in the range of the tide; but in regard to the moon's changing declination, tide and current do not respond alike, the diurnal variation in the tide at any place being generally greater than the diurnal variation in the current.

The relations subsisting between the changes in the velocity of the current at any given place and the range of the tide at that place may be derived from general considerations of a theoretical nature. Variations in the current that involve semidiurnal components will approximate corresponding changes in the range of the tide; but for variations involving diurnal components the variation in the current is about half that in the tide.

RELATION OF TIME OF CURRENT TO TIME OF TIDE

In simple wave motion the times of slack and strength of current bear a constant and simple relation to the times of high and low waters. In a progressive wave the time of slack water comes, theoretically, exactly midway between high and low water and the time of strength at high and low water; in a stationary wave slack comes at the times of high and low water, while the strength of current comes midway between high and low water.

The progressive-wave movement and the stationary-wave movement are the two principal types of tidal movements. A progressive wave is one whose crest advances, so that in any body of water that sustains this type of tidal movement the times of high and low water progress from one end to the other. A stationary wave is one that oscillates about an axis, high water occurring over the whole area on one side of this axis at the same instant that low water occurs over the whole area on the other side of the axis.

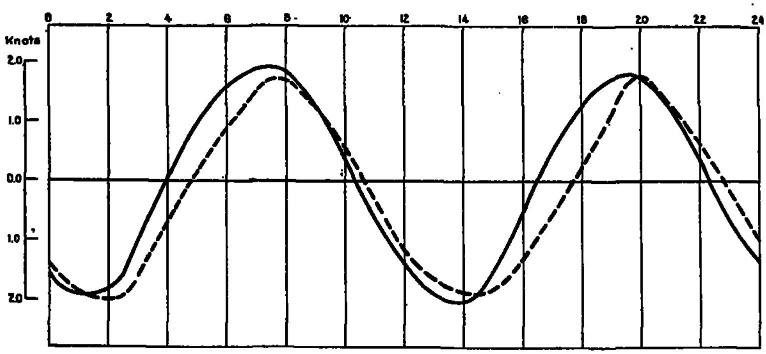

FIG. E.—Tide and current curves, New York Harbor, October 9, 1919

The tidal movements of coastal waters are rarely of simple wave form; nevertheless, it is very convenient in the study of currents to refer the times of current to the times of tide. And where the diurnal inequality in the tide is small, as is the case on the Atlantic coast, the relation between the time of current and the time of tide is very nearly constant. This is brought out in Figure E, which represents the tidal and current curves in New York Harbor for October 9, 1919, the current curve being the dashed-line curve, representing the velocities of the current at a station in Upper Bay, and the tide curve being the full-line curve, representing the rise and fall of the tide at Fort Hamilton, on the eastern shore of the Narrows.

The diagrams of Figure E were drawn by plotting the heights of the tide and the velocities of the current to the same time scale and to such velocity and height scales as will make the maximum ordinates of the two curves approximately equal. The time axis or axis of X represents the line of zero velocity for the currents and of mean sea level for the tide, the velocity of the current being plotted in accordance with the scale of knots on the left, while the height of the tide reckoned from mean sea level was plotted in accordance with the scale in feet on the right.

From Figure E it is seen that the corresponding features of tide and current in New York Harbor bear a very nearly constant time relation to each other, and this constancy in time relation of tides and currents is characteristic of tidal waters in which the diurnal inequality is small. This permits the times of slack and of strength of current to be referred to the times of high and low water. Thus, from Figure E we find strength of ebb occurred about 0.6 hour after the time of low water, both morning and afternoon; slack before flood occurred 2.2 hours before high water; strength of flood 0.4 hour after high water; slack before ebb 3.0 hours before low water. In this connection, however, it is to be noted that the time relations between the various phases of tide and current are subject to the disturbing effects of wind and weather.

Apart from the disturbing effect of nontidal agencies, the time relations between tide and current are subject to variation in regions where the tide exhibits considerable diurnal inequality; as for example, on the Pacific coast of the United States. This variation is due to the fact, previously mentioned, that the diurnal inequality in the current at any given place is, in general, only about half as great as that in the tide. This brings about differences in the corresponding features of tide and current as between morning and afternoon. However, in such cases it is frequently possible to refer the current at a given place to the tide at some other place with comparable diurnal inequality.

EFFECT OF NONTIDAL CURRENT

The tidal current is subject to the disturbing influence of nontidal currents which affect the regularity of its occurrence as regards time, velocity, and direction. In the case of the rectilinear current the effect of a steady nontidal current is, in general, to make both the periods and the velocities of flood and ebb unequal and to change the times of slack water but to leave unchanged the times of flood and ebb strengths. This is evident from a consideration of Figure F, which represents a simple rectilinear tidal current, the time axis of which is the line *A B*, flood velocities being plotted above the line and ebb velocities below.

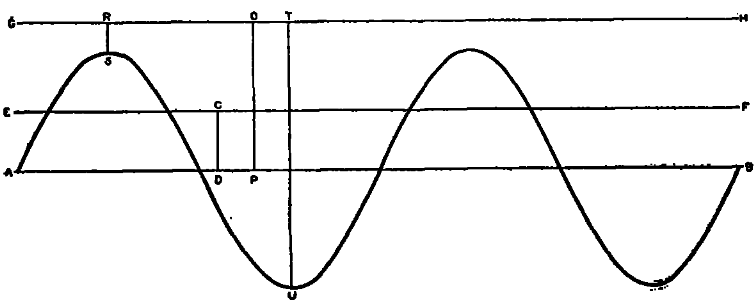

FIG. F.—Effect of nontidal current on tidal current

When unaffected by nontidal currents, the periods of flood and ebb are, in general, equal as represented in the diagram, and slack water occurs regularly three hours and six minutes after the times of flood and ebb strengths. But if we assume a steady nontidal current introduced which has, in the direction of the tidal current, a velocity component represented by the line *CD*, it is evident that the strength of ebb will be increased by an amount equal to *CD*, while the flood strength will be decreased by the same amount. The current conditions may now be completely represented by drawing, as a new axis, the line *EF* parallel to *AB* and distant from it the length of *CD*.

Obviously, if the velocity of the nontidal current exceeds that of the tidal current at the time of strength, the tidal current will be completely masked and the resultant current will set at all times in the direction of the nontidal current. Thus, if in Figure F the line *OP* represents the velocity component of the nontidal current in the direction of the tidal current, the new axis for measuring the velocity of the combined current at any time will be the line *GO* and the current will be flowing at all times in the ebb direction. There will be no slack waters; but at periods 6 hours 12 minutes apart there will occur minimum and maximum velocities represented, respectively, by the lines *RS* and *TU*.

In so far as the effect of the nontidal current on the direction of the tidal current is concerned, it is only necessary to remark that the resultant current will set in a direction which at any time is the resultant of the tidal and nontidal currents at that time. This resultant direction and also the resultant velocity may be determined either graphically by the parallelogram of velocities or by the usual trigonometric computations.

VELOCITY OF TIDAL CURRENTS AND PROGRESSION OF THE TIDE

In the tidal movement of the water it is necessary to distinguish clearly between the velocity of the current and the progression or rate of advance of the tide. In the former case reference is made to the actual speed of a moving particle, while in the latter case the reference is to the rate of advance of the tide phase or the velocity of propagation of wave motion, which generally is many times greater than the velocity of the current.

It is to be noted that there is no necessary relationship between the velocity of the tidal current at any place and the rate of advance of the tide at that place. In other words, if the rate of advance of the tide is known we can not from that alone infer the velocity of the current, nor vice versa. The rate of advance of the tide in any given body of water depends on the type of tidal movement. In a progressive wave the tide moves approximately in accordance with the formula $r=\sqrt{gd}$ in which r is the rate of advance of the tide, g the acceleration of gravity, and d the depth of the waterway. In stationary-wave movement, since high or low water occurs at very nearly the same time over a considerable area, the rate of advance is theoretically very great; but actually there is always some progression present, and this reduces the theoretical velocity considerably.

The velocity of the current, or the actual speed with which the particles of water are moving past any fixed point depends on the volume of water that must pass the given point and the cross section of the channel at that point. The velocity of the current is thus independent of the rate of advance of the tide.

DISTANCE TRAVELED BY A PARTICLE IN A TIDAL CYCLE

In a rectilinear current the distance traveled by the water particles or by any object floating in the water is obviously equal to the product of the time by the average velocity during this interval of time. To determine the average velocity of the tidal current for any desired interval several methods may be used.

If the curve of the tidal current has been plotted, the average velocity may be derived as the mean of a number of measurements of the velocity made at frequent intervals on the curve; as, for example, every 10 or 15 minutes. From the current curve the average velocity may also be determined by deriving the mean ordinate of the curve by use of the planimeter. For a full tidal cycle of flood or ebb, however, since the current curve generally approximates the cosine curve, the simplest method consists in making use of the well-known ratio of the mean ordinate of the cosine curve to the maximum ordinate which is $2\div\pi$, or 0.6366.

The latter method has another advantage in that the velocity of the tidal current is almost invariably specified by its velocity at the time of strength, which corresponds to the maximum ordinate of the cosine curve; hence, the average velocity of the tidal current for a flood or ebb cycle is given immediatley as the product of the strength of the current by 0.6366. And though this method is only approximate, since the curve of the current may deviate more or less from the cosine curve, in general the results will be sufficiently accurate for all practical purposes. For a normal flood or ebb period of 6.2 hours the distance a tidal current with a velocity at strength of 1 knot will carry a floating object is, in nautical miles, $0.6366\times6.2=3.95$, or 24,000 feet.

DURATION OF SLACK

In the change of direction of flow from flood to ebb, and vice versa, the tidal current goes through a period of slack water or zero velocity. Obviously, this period of slack is but momenetary, and graphically it is represented by the instant when the current curve cuts the zero line of velocities. For a brief period each side of slack water, however, the current is very weak, and in ordinary usage "slack water" denotes not only the instant of zero velocity but also the period of weak current. The question is therefore frequently raised, How long does slack water last?

To give slack water in its ordinary usage a definite meaning, we may define it to be the period during which the velocity of the current is less than one-tenth of a knot. Velocities less than one-tenth of a knot may generally be disregarded for practical purposes, and such velocities are, moreover, difficult to measure either with float or with current meter. For any given current it is now a simple matter to determine the duration of slack water, the current curve furnishing a ready means for this determination.

In general, regarding the current curve as approximately a sine or cosine curve, the duration of slack water is a function of the strength of current—the stronger the current the less the duration of slack—and from the equation of the sine curve we may easily compute the duration of slack water for currents of various strengths. For the normal flood or ebb cycle of 6^h 12.6^m we may write the equation of the current curve $y=A \sin 0.4831t$, in which A is the velocity of the current in knots at time of strength, 0.4831 the angular velocity in degrees per minute, and t is the time in minutes from the instant of zero velocity. Setting $y=0.1$ and solving for t (this value of t giving half the duration of slack) we get for the duration of slack the following values: For a current with a strength of 1 knot, slack water is 24 minutes; for currents of 2 knots strength, 12 minutes; 3 knots, 8 minutes; 4 knots, 6 minutes; 5 knots, 5 minutes; 6 knots, 4 minutes; 8 knots, 3 minutes; 10 knots, 2⅓ minutes.

HARMONIC CONSTANTS

The tidal current, like the tide, may be regarded as the resultant of a number of simple harmonic movements, each of the form $y=A \cos (at+\alpha)$; hence, tidal currents may be analyzed in a manner analagous to that used in tides and the harmonic current constants derived. These constants permit the characteristics of the currents to be determined in the same manner as the tidal harmonic constants and they may also be used in the prediction of the times of slack and the times and velocities of the strength of current.

It can easily be shown that in coastal or inland tidal waters the amplitudes of the various current components are related to each other, not as the amplitudes of the corresponding tidal components, but as these latter multiplied by their respective speeds; that is, in any given harbor, if we denote the various components of the current by primes and of the tide by double primes, we have

$$M'_2: S'_2: N'_2: K'_1: O'_1 = m_2M''_2: s_2S''_2: n_2N''_2: k_1K''_1: o_1O''_1$$

where the small italic letters represent, respectively, the angular speed of the corresponding components. This shows at once that the diurnal inequality in the currents should be approximately half that in the tide.

MEAN VALUES

In the nonharmonic analysis of current observations it is customary to refer the times of slack and strength of current to the times of high and low water of the tide at some suitable place, generally near by. In this method of analysis the time of current determined is in effect reduced to approximate mean value, since the changes in the tidal current from day to day may be taken to approximate the corresponding changes in the tide; but the velocity of the current as determined from a short series of observations must be reduced to a mean value.

In the ordinary tidal movement of the progressive or stationary wave types the change in the strength of the current from day to day may be taken approximately the same as the variation in the range of the tide. Hence, the velocity of the current from a short series of observations may be corrected to a mean value by multiplying by a factor equal to the reciprocal of the range of the tide for the same period divided by the mean range of the tide. It is to be noted that in this method of reducing to a mean value, any nontidal currents must first be eliminated and the factor applied to the tidal current alone. This may be done by taking the strengths of the tidal current as the half sum of the flood and ebb strengths for the period in question.

In some places the current, while exhibiting the characteristic features of the tidal current, is in reality a hydraulic current due to differences in head at the ends of a strait connecting two independent tidal bodies of water. East River and Harlem River in New York Harbor and Seymour Narrows in British Columbia are examples of such straits, and the currents sweeping through these waterways are not tidal currents in the true sense, but hydraulic currents. The velocities of such currents vary as the square root of the head, and hence in reducing the velocities of such currents to a mean value the factor to be used is the square root of the factor used for ordinary tidal currents.

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