DEPARTMENT OF COMMERCE
U. S. COAST AND GEODETIC SURVEY
E. LESTER JONES, DIRECTOR

TIDES AND CURRENTS
IN
PORTSMOUTH HARBOR

BY

A. J. HOSKINSON
Junior Hydrographic and Geodetic Engineer,
U. S. Coast and Geodetic Survey
and
E. A. LE LACHEUR
Assistant Mathematician, U. S. Coast and Geodetic Survey

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PREFACE

The growth of commerce, as well as engineering and scientific work during recent years, has created an urgent and constantly growing demand from navigators, engineers, scientists, and the public generally for complete and up-to-date tide and current information of the important waterways of the United States. To meet this demand and to complete and coordinate various tide and current data now on file in the archives of the Coast and Geodetic Survey, this bureau started in 1922 a series of comprehensive tide and current surveys of the important waterways of the country. Several of the more important harbors of the country have at this date been completed, and the work is progressing as rapidly as the available funds permit.

In order to preserve the results of these surveys, combine and compare them with earlier records, and make the results available to all concerned, and at the same time guard against the possible loss or destruction of valuable information by fire or other causes, a special publication for each area has been printed and distributed as soon after the completion of the survey as possible.

The waterways that have been surveyed under this plan and for which information has been published were undertaken in the following order: New York Harbor, Special Publication No. 111; San Francisco Bay, Special Publication No. 115; Delaware Bay and River, Special Publication No. 123; Southeast Alaska, Special Publication No. 127; Boston Harbor, Special Publication No. 142; and the present publication on Portsmouth Harbor and tributaries.

The data and tables presented in this volume are based on the results of all the surveys and observations that have been made in Portsmouth Harbor from 1850 to date, the most recent results being obtained from the tide and current survey of the harbor in 1926.

A discussion of the general characteristics of tides and currents will be found in the appendix of this volume, which is a reprint of the first two sections of Special Publication No. 111.

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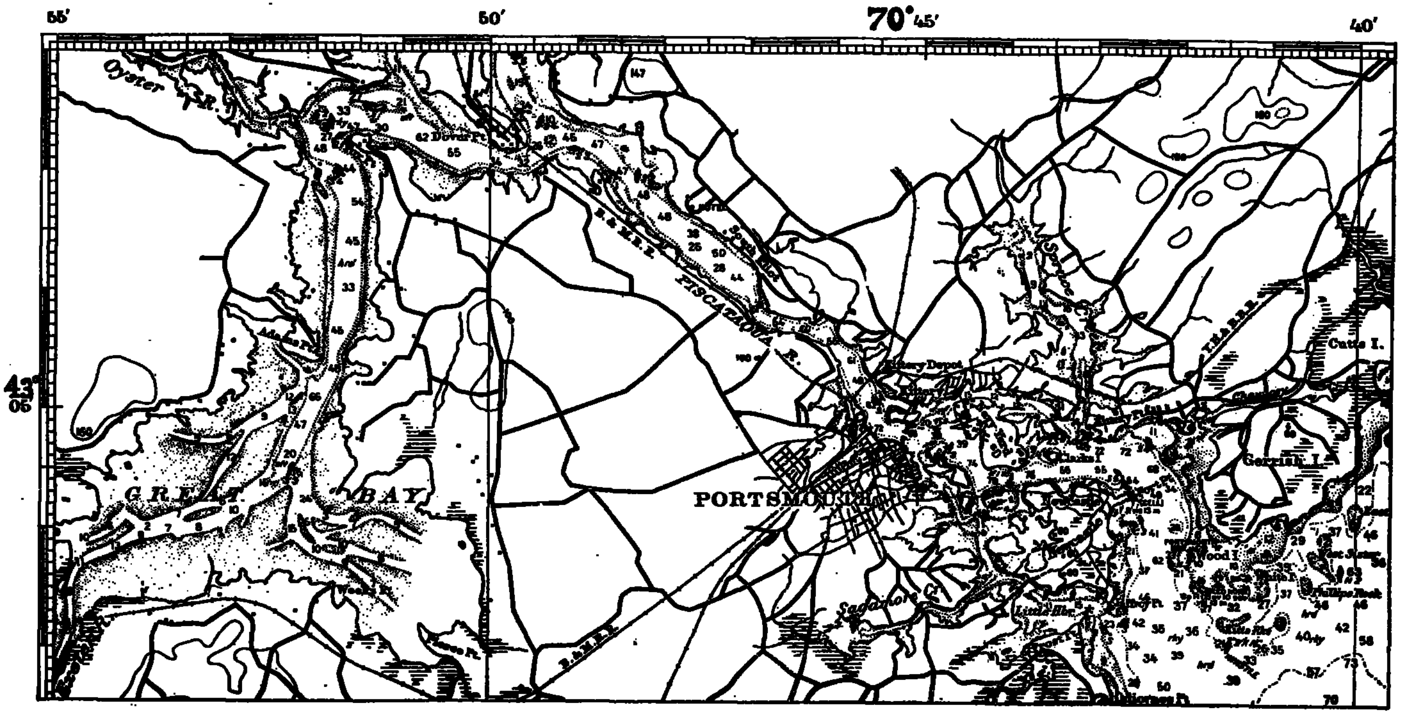

Portsmouth Harbor and tributaries

TIDES AND CURRENTS IN PORTSMOUTH HARBOR

INTRODUCTION

It is not the purpose of this publication to deal with any involved or mathematical theory of tides or tidal currents, but rather to collect, tabulate, and discuss the data from many years of tide and current observations in Portsmouth and Portland Harbors. It is desired to present these results in such form as will be of the most value and interest to scientific and professional organizations as well as the general public, and at the same time tabulate and summarize all of the essential data from the observations so that valuable information would not be lost by destruction of the original records by fire or other causes. Only such mathematical formulas and discussions will be introduced as are necessary to explain or clarify the tables and diagrams presented.

Portsmouth Harbor is one of the important deep-water harbors of the North Atlantic coast. The Government maintains in the harbor one of the important submarine bases on the Atlantic coast. With the modern trend toward larger and faster submarines, an accurate and up-to-date knowledge of the tide and current action in the harbor is a necessary supplement to the successful navigation of this waterway. The current in portions of the harbor approaches a velocity of 6 knots at times of maximum tidal action and in the confined portions of the harbor is a severe hazard to navigation unless accurate information of its action is available.

The earliest tidal observations on record in Portsmouth Harbor were taken at Fort Constitution in 1851, 1852, and 1853. The record is not continuous over the period but consists of a few weeks' continuous record for each of the three years. The main objective of tidal observations at this period was to establish a datum plane to which hydrographic work could be referred. Time at this early date was very uncertain, and the value of time relations from early observations can not, therefore, be given as much weight as observations taken after the standard-time belts were established in 1885.

All of the tidal observations in Portsmouth Harbor have been short-period observations of a few days or weeks. The longest continuous record is from observations at Fort Constitution in 1853 and 1898. But even at this station there has not been a long enough continuous record to establish mean tidal constants from the method of direct tabulation. To determine mean tidal characteristics from the observations it has been necessary to compare each series of observations with some standard station outside of the harbor. The nearest standard station with a tide similar to that at Portsmouth is Portland, Me., which has been used in the comparisons and, as the standard station, will be discussed at some length in this publication.

Late in the year 1926 a standard tide station was established at the Portsmouth Navy Yard, which will be kept in continouus operation for several years. At some future date, when a long series is available from the records of this station, the mean values listed in this publication may be slightly changed. But until this series is available the values in this publication will be accepted as the best available for Portsmouth Harbor.

Part I.—TIDES IN PORTSMOUTH HARBOR AND TRIBUTARIES

By A. J. Hoskinson, *United States Coast and Geodetic Survey*

COMPONENT PARTS

This volume treats of the tides and currents of the navigable portion of Portsmouth Harbor and its tributaries. It is divided into two parts, the first dealing with tides and the second with currents. For the purposes of this publication it is found convenient to divide the waterway into two sections—Portsmouth Harbor proper, and, secondly, Piscataqua River and its tributaries. Strictly speaking, Portsmouth Harbor is the mouth of the Piscataqua River.

PORTSMOUTH HARBOR

Portsmouth Harbor, lying 37 miles southwestward of Cape Elizabeth and about 25 miles northward of Cape Ann Lighthouses, is the only harbor of refuge for deep-draft vessels between Portland, Me., and Gloucester, Mass. For the purposes of this publication the entrance to Portsmouth Harbor may be considered as a cross section between Odiornes Point and the rocky reefs and islands south of Gerrish Island.

Portsmouth Harbor is the approach to the cities of Portsmouth, N. H., and Dover, N. H., and the towns of Newcastle, N. H., Kittery, Me., South Newmarket, N. H., and Exeter, N. H. A part of the boundary line between the States of Maine and New Hampshire is a natural one formed by Portsmouth Harbor and Piscataqua and Salmon Falls Rivers.

Portsmouth has some trade in large coasting vessels and barges, principally in coal. Creosote is imported in large tank steamers. The depths in the harbor are sufficient for the largest ships, and the harbor is open throughout the year. On the north side of the harbor, opposite Portsmouth, is the United States navy yard, which is located on Seavy Island.

Scattered throughout the harbor are a number of islands, many of which are connected with the mainland by means of bridges. The larger and more important islands are Gerrish, Newcastle, and Seavy. Little Harbor, a good anchorage for small ships, lies on the west side of the entrance to Portsmouth Harbor, three quarters of a mile westward of Whaleback Lighthouse. Pepperell Cove, on the eastern side of the harbor, northeastward of Portsmouth Harbor Lighthouse, is also a good anchorage for small coasting vessels and yachts.

Portsmouth is on the south side of the Piscataqua River, about 4 miles above the entrance to the harbor. There are depths from 20 to 30 feet at the wharves. There is no passenger service by water, but there is a small amount of coastwise trade and an occasional foreign arrival.

PISCATAQUA RIVER AND TRIBUTARIES

The Piscataqua River above Portsmouth forms the approach to the Salmon Falls, Cocheco, Bellamy, Oyster, Lamprey, and Exeter Rivers, the towns of Durham, Newmarket, and Exeter, and the city of Dover. These cities and towns are also connected by railroad.

The Piscataqua is a wide, deep, navigable river with tidal currents of considerable velocity. About 3½ miles above Portsmouth, in the vicinity of Dover Point, the Piscataqua River is forked, a northerly branch merging into the Salmon Falls and Cocheco Rivers and a southwesterly branch merging into the Bellamy, Oyster, Lamprey, and Exeter Rivers. South of Fox Point the southwesterly branch of the Piscataqua widens to form Little Bay and Great Bay, which are connected by Furber Strait in the vicinity of Adams Point. Great Bay, a shoal bay about 3½ miles wide with narrow, crooked channels, serves as the approach to the Lamprey and Exeter Rivers.

The channels in the tributaries of the Piscataqua River are narrow and crooked and shoal at the heads. Some of them have been improved by dredging. There is little business by water above Portsmouth, except in small craft and an occasional cargo of coal. The tidal currents are very strong in places.

THE TIDE AT PORTLAND, ME.

THE PORTLAND TIDE STATION

The Portland, Me., tide station is the nearest standard station to Portsmouth Harbor at which tides have been observed for a considerable period of time. Furthermore, the type of tide at Portland, Me., is similar to that at Portsmouth Harbor. Therefore, the tide at Portland, Me., is used as the standard station to which the short series of tides at various paces in Portsmouth Harbor are referred. This makes it necessary to consider in detail the tide at Portland, Me.

The tide station at Portland, Me., is located on the east side of shed No. 6 on the central portion of the Grand Trunk Railroad pier, latitude 43° 39′ 10″ N. and longitude 70° 15′ 07″ W. Observations are made with a United States Coast and Geodetic Survey automatic tide gauge of the three-roller type. Standard time for the meridian 75° W. is used, and all heights are referred to the zero of a tide staff located on piling near the station. It has been necessary to renew the staff from time to time as the numbers became faded or erased through exposure to the elements, but care has been taken to carefully connect by levels the new staff in each case with the permanent bench marks on shore near the station. The zero of the staff is carefully connected by spirit levels with several permanent bench marks in the city of Portland. For convenience in tabulation and for uniformity all of the elevations have been referred to the zero of the staff of 1910.

LUNITIDAL INTERVALS

The lunitidal interval may be defined as the difference in time between the moon's transit over the local meridian and the next succeeding high or low water. From the definition it is evident that there will be two lunitidal intervals; that is, the high-water interval and the low-water interval.

The lunitidal intervals have a definite periodic variation from day to day due largely to the relative positions of the sun and moon with respect to the earth. The controlling factor in the variation is the declination of the moon. In areas where the declination of the moon has a minor effect on the tidal action, as on the North Atlantic coast, the variation in lunitidal interval is small except for those irregular variations caused by wind and weather. From the definition it is evident that, in the computation of lunitidal intervals, the time of the moon's transit and the time of high and low water must be reduced to the local meridian. This reduction is easily made with the help of astronomical tables, but considerable time and labor may be saved in the computations if the daily values of lunitidal intervals are not reduced to the local meridian but are computed as follows: Subtract the time of the moon's transit (meridian of Greenwich given in Nautical Almanac) from the time of high or low water (standard time). This computation will necessarily need correction, since neither the moon's transit nor the time of tide have been reduced to the local meridian. This value may be reduced to the local meridian by applying a correction factor. The daily values are summed for any month and the correction factor applied to the mean. This factor for any month at Portland, Me., is +0.15 hour. This value varies slightly from day to day throughout the month, so that it can not be applied to the daily uncorrected values to obtain the correct interval for that day. If the correct interval for each day is desired, each value must be reduced to the local meridian.

Table 1 is a record of the observations and computation for lunitidal intervals for the month of August, 1926, at Portland, Me. The month of August was selected as an illustration of the intervals because meteorological conditions during the summer months are generally less variable than at other seasons of the year. In column 2 are recorded the times of the moon's transits over the meridian of Greenwich. Those quantities in parentheses are the lower transits of the moon or 180° in longitude from the upper transit. The times of high and low water are recorded in columns 3 and 4 (seventy-fifth meridian time). Column 5 is the difference between columns 3 and 2, being careful to select the transit of the moon just preceding the high water used. Column 6 is obtained by similar methods from columns 4 and 2. The mean of the daily values for the month is reduced to the local meridian by applying the correction factor for Portland (+0.15 hour). The remaining columns in the table will be discussed in later paragraphs.

In Table 2 are recorded the monthly and yearly means of lunitidal intervals for the years 1912 to 1919. There is considerable variation in the monthly values in the table, but the yearly values are very nearly constant. The maximum difference between any two years in the series is only 0.05 hour for the high-water intervals and 0.08 hour for the low-water intervals, and the variation of any yearly value from the mean for the series would be about 0.03 hour, or less than 2 minutes, which is as close as any high or low water can be determined from a tide curve.

The best available values to date for high and low water intervals are the means of the yearly values in Table 2, 11.16 hours for the high-water interval and 4.94 hours for the low-water interval.

DURATION OF RISE AND FALL

The duration of rise is that time during which the tide is increasing in height or it is the difference in time between low water and the next succeeding high water. The duration of fall is the time between high water and the next succeeding low water.

In columns 7 and 8 of Table 1 are given the daily values for duration of rise and fall for the month of August, 1926, at Portland, Me. The variations in these values from day to day are due largely to the variations in meteorological conditions and the effect of the change in declination of the moon, which goes through one complete cycle of change in about 27⅓ days.

In Table 3 are presented the monthly and yearly means for duration of rise and fall for the two years, 1912 and 1919. The values for the duration of rise and fall may be figured either from the daily times of high and low water or from the lunitidal intervals. The monthly and yearly means are most easily computed from the lunitidal intervals as follows: The high-water interval minus the low-water interval equals the duration of rise, and 12.42 hours minus the duration of rise equals the duration of fall (12.42 hours is the average time between an upper and lower transit of the moon).

The values in Table 3 show considerable variation from month to month, as would be expected, since they are computed from the lunitidal intervals, which have a similar variation.

In Table 4 are recorded the yearly means for duration of rise and fall for the years 1912 to 1919. These values are very nearly constant from year to year, as in the case of the lunitidal intervals. The best available values to date for the durations of rise and fall are the means of the yearly values in Table 4, which is 6.21 hours for each interval.

MEAN SEA LEVEL

Engineers, in general, are more interested in mean sea level than in any other tidal datum plane, because of its almost universal adoption as the reference plane for elevations throughout the country. The earliest surveys in this country were generally based on arbitrary datum planes selected by the engineer in charge of the work. This method was satisfactory at that time, but when surveys began to overlap, engineering and legal difficulties were encountered. It soon became apparent that the only permanent solution of these problems was to adopt a universal datum plane for all parts of the country. The natural plane for this purpose is the surface of the sea, but unfortunately the elevation of this plane is not constant but varies from hour to hour, day to day, and year to year, due to tidal action and meteorological changes. Since the plane is variable, some position in its cycle of variation must be selected as the datum. The average height, or the plane or mean sea level, has been selected as the most logical and the most nearly constant position of the plane.

Mean sea level may then be defined as the average height of the sea, or the elevation the water would assume if undisturbed by the rise and fall of the tide. The value of mean sea level may be determined by taking a mean of the hourly heights of the tide over a considerable period of time. The hourly heights may be taken directly from a stationary tide staff or they may be scaled from a tide curve from an automatic tide gauge which has been referred to a tide staff.

or to bench marks on shore. Well-determined values of mean sea level are available at any station where the Coast and Geodetic Survey has tidal observations covering a period of several years and slightly less precise values at many secondary stations where shorter periods of observation are available. The value of mean sea level has been carried throughout the country by a network of lines of precise levels, so that the value of mean sea level is available in most of the larger cities of the country and, when the network of levels is completed, will be available at any important city in the country.

By continued study and comparison of the results of tidal observations from various stations throughout the country, as longer periods of observation become available, a better knowledge of the variations of sea level will be obtained, so that short-period observations may, in the future, be reduced to mean value with increased precision.

The daily values of sea level at Portland, Me., for the month of June, 1919, are tabulated in Table 5. The value for each day is the mean of the 24 hourly heights for that day. Twenty-four hours is not an exact tidal cycle, therefore it is to be expected that the daily values would show considerable variation from day to day. If, however, all of the variation was due to this cause, the daily values would follow a definite periodic variation. A glance at Table 5 shows that the daily values do not have a definite periodic variation but are very irregular. The major part of the variation must then be caused by changes in meteorological conditions, which will be better illustrated in the section entitled "Effect of wind and weather on the tide." The greatest difference between the values of sea level for any two days in the month is 1.1 feet and between any consecutive days is 0.8 foot. If a winter month had been selected when meteorological conditions are more unstable, the variations would have been considerably larger. It is evident from this table that a single day's observations to determine sea level may be in error by a foot or more.

Monthly and yearly values of sea level at Portland, Me., from 1912 to 1925 are tabulated in Table 6. The monthly values are derived as the means of all the hourly heights for the first 29 days of each month and the yearly values as the means of the 12 monthly values for that year. The greatest difference between any two monthly means in a single year is 0.73 foot and between any two consecutive months is 0.65 foot. The greatest difference between any two yearly values in the series is 0.22 foot and between any two consecutive years is 0.12 foot. If the series be divided into 2-year groups, the greatest variation of any group from the mean value would be 0.10 foot; similarly, the variation for any 5-year group would be 0.06 foot, and for 10-year groups, 0.03 foot. If the series at Portland were of longer duration, it is quite probable that the 10-year groups would show slightly more variation, since the margin of overlap in the groups would be reduced. It is interesting to note that the values for any 8, 9, or 10 year group is from 0.01 to 0.03 foot higher than the mean for the entire 14-year series. This would indicate that there is a periodic variation in the yearly values which completes one cycle in less than 14 years. The yearly values show a low in 1913 and an irregular increase to 1919, with a rather rapid decrease to 1922, thus indicating a cycle of about 10 years. When a longer series is available at this station the existence or nonexistence of this cycle will be more definitely established.

The monthly values have a very definite periodic variation throughout the year, as can be seen from an inspection of Table 6 for any year of the series. To represent this periodic variation most accurately, the average value for each month as determined from the 14-year series is shown diagrammatically in Figure 1. By taking the average value of each month for a period of 14 years, most of the irregular variations should be eliminated. The sea-level curve in Figure 1 shows that sea level at Portland, Me., is lowest in the spring months and highest during the midsummer months. There is a second high in the curve in October and a second low in September, thus indicating that there is more than one period involved in the variations. (See Special Publication No. 111, pp. 47 and 48.) The curves of high and low water, also shown in Figure 1, will be discussed in the section entitled "High and low water planes."

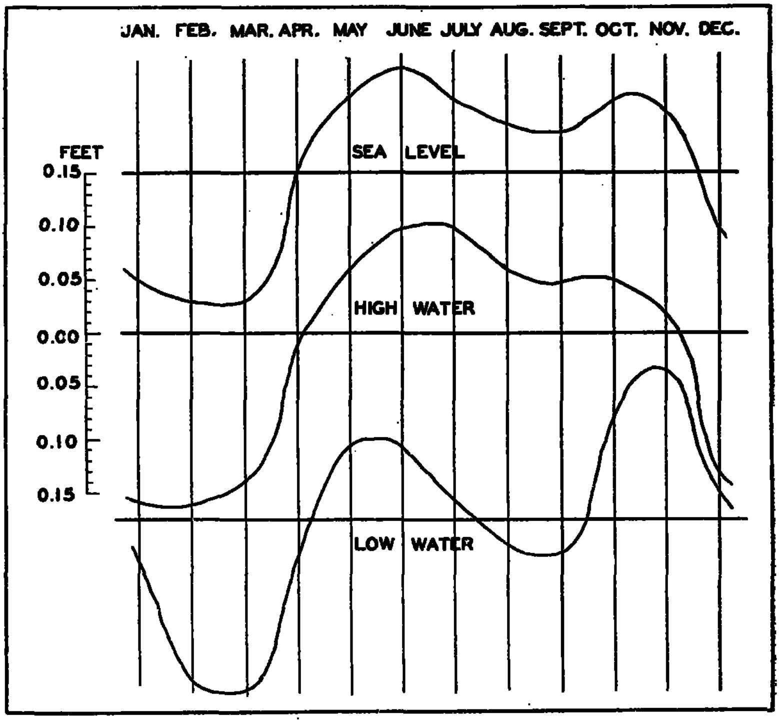

FIG. 1.—Annual variation in sea level, high water and low water at Portland, Me., from 14 years of observations

The best available value for sea level on tide staff at Portland, Me., is the mean of the 14-year series from 1912 to 1926, inclusive, which is 13.11 feet.

THE PLANES OF HIGH AND LOW WATER

The height of high and low water varies from day to day, due largely to the periodic change in position of the moon with respect to the earth and sun. This change in position of the moon may, for ease of discussion, be resolved into three component motions—the phase, the parallax, and the declinational components. Each of these completes one cycle of movement during its lunar month; that is, the synodic the anomalistic, or the tropic month. For simplicity in discussion, each component motion will be discussed as if it were independent of the other two.

During the synodic month (approximately 29½ days in length) the moon passes through its four phases—new moon, first quarter, full moon, and last quarter. At times of new and full moon, or when the moon and sun are acting in conjunction, the high waters rise higher and the low waters fall lower than normal, and tides during this period are called spring tides. When the moon is in its first or last quarter, or when the moon and sun are acting in opposition, the rise and fall of the tide is less than normal, and these tides are called neap tides. The planes of high and low water, usually computed for the synodic month, are spring high water, spring low water, neap high water, and neap low water.

To determine the value for the plane of spring high or low water, the two high or low waters that occur nearest the time of maximum effect will be tabulated for each month, thus giving four values from which to determine the monthly value. The time of maximum effect may be determined by adding the phase age of the tide to the time of new or full moon. The phase age of the tide at Portland, Me., or the time by which the spring tides lag behind their respective positions of the moon, is 34.7 hours, as will be determined later under the section entitled "Tidal harmonic constants."

The planes of neap high and low water are determined in exactly the same way except that the first and last quarters of the moon are substituted for new and full moon.

The heights of the above planes will also be affected by the other component motions of the moon and by meteorological changes. Thus, to get an accurate determination of any plane, several years of observations are necessary.

During the anomalistic month (approximately 27½ days in length) the moon makes one complete circuit of its elliptical path around the earth, passing through perigee (the nearest point to the earth) and apogee (the farthest point from the earth). When the moon is in perigee the tide-producing forces are greater than the average, thus causing an increased rise and fall of the tide. Conversely, when the moon is in apogee the tide-producing forces are less, and the rise and fall of the tide is correspondingly decreased. The tides occurring at these periods are called, respectively, the perigean and apogean tides, and the planes of high and low water usually computed for the anomalistic month are perigean high water, perigean low water, apogean high water, and apogean low water. The value of each plane for any month is determined from the two high or low waters that occur nearest the time of maximum or minimum tidal effect, which will be 56.0 hours after the moon is in either perigee or apogee, 56.0 hours being the parallax age for Portland, Me., or the time by which the perigean or apogean tides lag their respective positions of the moon.

During the tropic month (approximately 27⅓ days) the moon completes one cycle in declination, crossing the Equator twice and passing through its maximum north and south declinations. During the period when the moon is on or near the Equator the two high waters for the day rise to nearly the same height and the two low waters fall to nearly the same level, and the duration of rise and fall between successive tides is uniform. The tides during this period are called the equatorial tides. When the moon is at either its maximum north or south declinational points the two high waters and the two low waters for the day are unequal in height, and the duration of rise and fall is also unequal. This is well illustrated in Figure B of the appendix to this volume. The tides at times of maximum declination of the moon are called tropic tides, since the moon is then near one of the Tropics. The planes of high and low water usually computed for the tropic month are mean higher high water, mean lower low water, tropic higher high water, and tropic lower low water. The planes of lower high water and higher low water may also be computed.

Mean higher high water and mean lower low water for any tropic month are determined as the average of all the higher high waters or lower low waters for the month. Tropic higher high water and tropic lower low water are determined from the two higher high waters or lower low waters that occur nearest the time of greatest diurnal inequality, or 17.5 hours after the moon passes its maximum declinational point, 17.5 hours being the diurnal age for Portland, Me., or the time by which the tropic tides lag behind their respective positions of the moon.

As explained in the appendix, these three component actions are apparent in the tide everywhere but not to the same extent. The diurnal inequality of the tide on the North Atlantic coast is very small as compared with its effect on the Pacific coast. At Portland, Me., the phase component and parallax component are nearly equal.

Since these three lunar months are all of different lengths, there will be many possible combinations of the above planes, as spring perigean tropic higher high water, etc. It is evident then that the mean value for any of the above planes will not be accurately determined until the observations are averaged over a period of sufficient length that all of the combinations will have made one complete cycle or have completed several full cycles. This will be accomplished in a period of about 19 years.

The value for any of the high or low water planes above described may be determined from the harmonic constants and is much less time-consuming than the method of direct tabulation. This method has been used in determining values for these planes at Portland, Me., and the value for each plane will be found in the section entitled "Summary of tidal data," of this volume.

The most important and most widely used planes of high and low water are mean high water and mean low water, which are determined as the average height of all the high or low waters over a considerable period of time.

The plane of mean low water has been adopted as the datum plane for all of the hydrographic work of the Coast and Geodetic Survey on the Atlantic coast and for all heights in the tide and current tables published by this bureau. It is also extensively used as a datum for other engineering and hydrographic work along the coast and inland waterways.

Table 7 is a tabulation of low waters at Portland, Me., monthly and yearly means for the years 1912 to 1925. The monthly means are determined as the average value of all the low waters for the first

29 days of each month, the 1st day of March being added to the February series to complete the 29-day period whenever necessary. The monthly values in the tables show large variations from month to month, the greatest difference between any two months in a single year being 0.87 foot and between any two consecutive months 0.65 foot. These large variations are due to meteorological changes and to the periodic variations introduced by the fact that a 29-day series is not an exact cycle for all of the component motions of the moon previously discussed. The yearly means show much smaller variation, as would be expected, since the meteorological effects will more nearly balance and the periodic effects will be diminished as the various motions of the moon will have more nearly completed even cycles. The maximum difference between any two years in the series is 0.35 foot and between any two consecutive years is 0.19 foot.

If the yearly values of Table 7 are subtracted from the yearly values of sea level in Table 6, the resulting values—low water below sea level—should then be nearly free from meteorological effects, for the effect of wind and weather is largely reflected in the height of sea level and not in an increased rise or fall of the tide. The results of these subtractions are shown in Table 8. The maximum difference between any two years is now 0.27 foot and between any two consecutive years is 0.15 foot. There is also now apparent a definite periodic variation from year to year, with the lowest value in 1913 and the highest about 1922. This periodic variation is caused by the variation in longitude of the moon's node, which makes one complete cycle in a period of 18.6 years. The tidal forces caused by this variation are least in 1913 and greatest in 1922, thus agreeing with the values in Table 8. Factors to reduce the yearly values to a mean have been computed. (See R. A. Harris's Manual of Tides, Pt. III, "Value of F.") After applying these factors, the values in Table 9 are obtained, which should be very nearly constant from year to year. The maximum difference between any two years in the series is now 0.16 foot and between any two consecutive years is 0.12 foot. The maximum variation of any value from the mean for the 14 years, 1912 to 1925, is 0.09 foot. With the exception of the two years, 1912 and 1919, the agreement of mean yearly values to the mean for the 14-year period is very good.

The variations from year to year can be more readily seen at a glance if presented in diagrammatic form, which has been done in Figure 2. Curve *C* represents the yearly means as taken from Table 8, and the periodic variation from year to year is very definite and quite uniform, the "wild" years on the curve being 1912, 1919, and 1920. The value for 1912 may be slightly in error, due to trouble with mud and rust in the float well of the gauge during that year. The value for 1919 is too small and the value for 1920 too large, thus causing a large irregularity in the curve at this point. This irregularity is probably due to meteorological causes during these two years. Other standard stations along the Atlantic coast show a similar variation during these two years, thus supporting the theory of unusual storm action during this period. Curve *D* represents the variation in yearly mean values after applying the factors to correct for longitude of the moon's node. These factors apparently have a slightly overcorrective effect; that is, the values that were on the lower portion of the curve are now above the mean value, while those that were on the upper portion of the curve are now below the mean value. The great irregularity between the years 1919 and 1920 is improved very little on curve *D*, thus indicating that the irregularity is not caused by the periodic variations. The small irregularities from year to year in curves *C* and *D* which impart slight variations in the curves must be due to meteorological changes which have not been entirely eliminated by referring the curves to sea level.

The annual variation of low water from month to month throughout the year is illustrated in Figure 1. In general, the curve shows the same seasonal variations as shown by the sea-level curve, although the second high and second low are more pronounced than on the sea-level curve, indicating that, while the main cause of the variation is meteorological changes which affect sea level, there may also be some other small influence acting on the low waters which is not present in the sea-level curve.

The best available value of mean low water below sea level on the tide staff at Portland, Me., is the mean of the 14 years tabulated in Table 9, or 4.47 feet. Nearly the same value would be obtained by taking a mean of the values in Table 8 for a complete half cycle of the variation from the lowest to the highest portion of the curve, or from the years 1913 to 1922. This mean is also 4.47 feet. The best available value of mean low water on the staff may be obtained by subtracting 4.47 from the accepted value of mean sea level, or 13.11 − 4.47 = 8.64 feet. Nearly the same value may be obtained directly from Table 7 by taking the mean of the yearly values for the years 1913 to 1922. This mean is 8.66 feet, or a difference of 0.02 foot from the accepted value.

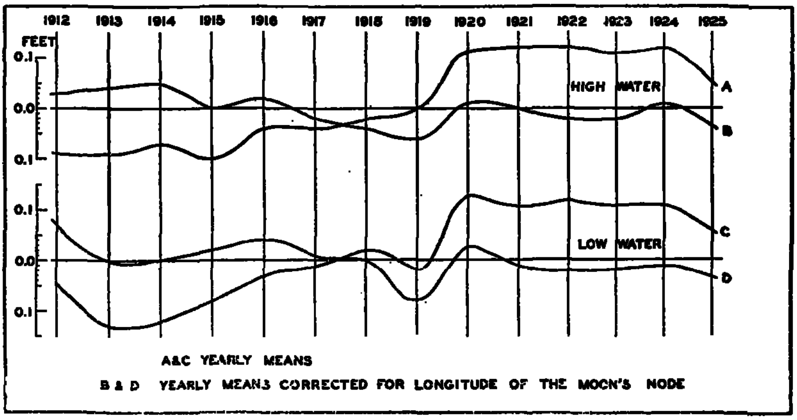

FIG. 2.—Periodic variation in high and low water planes at Portland, Me.

In Table 10 are tabulated the values of high water, monthly and yearly means, for the years 1912 to 1925. The monthly values are determined as the average value of all the high waters for the first 29 days of each month. The maximum difference between any two months in a single year, as shown in Table 10, is 0.70 foot and between any two consecutive months is 0.53 foot. These values are nearly the same as those for the low-water variations. The maximum difference between any two years in the series is 0.36 foot and between any two consecutive years is 0.15 foot.

To eliminate as far as possible the meteorological effects, the yearly values of sea level are subtracted from the yearly means in Table 10. The results are tabulated in Table 11. The variation from year to year is now greatly reduced, and the periodic variation due to the longitude of the moon's node is now evident, which may be eliminated by applying the same factors used in correcting the low waters. The results of this computation are tabulated in Table 12. The yearly variations are illustrated by curves *A* and *B*, Figure 2. The overcorrective effect of the factors to correct for the longitude of the moon's node is also apparent in the high-water curves. The small irregularities caused by wind and weather are also apparent in the high-water curves, the greatest variation being between the years 1919 and 1920, the same as in the low-water curves. The variation in the high-water curve is, however, somewhat less pronounced than on the low-water curve, thus further supporting the theory that the irregularity is caused by meteorological and not astronomical causes, since astronomical forces have an equal effect on both high and low water.

The annual variation in high water from month to month throughout the year is illustrated in Figure 1 and, in general, is similar to the variation of the sea-level and low-water planes. The second high and second low are, however, less pronounced than on either of the other two curves. The greater part of the variation shown by the three curves in Figure 1 is no doubt caused by changes in meteorological conditions during the year. But the fact that the low-water curves and the high-water curves do not follow the sea-level curve exactly would indicate that there might be some other factor present in these two curves. If the values on the sea-level curve are subtracted from those on each of the other two, the resulting curve in each case should show the effect of the forces which cause the differences between the sea-level curve and the other two. The results of these subtractions, which can readily be seen from Figure 1, would give values very close to the datum line in each case. These values would have a slight periodic tendency, however, and the two resulting curves would be complimentary, indicating that the cause was some astronomical force that acted equally on both high and low waters. The probable explanation of this phenomenon is that the values which are computed for a 29-day month are to some extent in error, owing to the fact that a 29-day period is slightly greater than a complete cycle for the parallax variation of the moon. If the curves of Figure 1 were computed using a 19-year series, during which time this variation would be eliminated, the curves would no doubt be more nearly similar.

The best available value to date for mean high water above sea level should be obtained by taking the mean of all the yearly values in Table 12, which is 4.43 feet. Nearly the same value would be obtained by taking the mean of the uncorrected values of Table 11 for the 10-year period, 1913 to 1922, which is also 4.43 feet.

The best available value to date for the staff reading of mean high water is obtained by adding 4.43 feet to the value of mean sea level, or 13.11 + 4.43 = 17.54 feet. Nearly the same value would be obtained by taking the mean of the yearly values of staff readings, given in Table 10 for the 10-year period, 1913 to 1922. This mean is 17.56, or a difference of 0.02 foot from the above value.

On the Atlantic coast the declinational datum planes are of relatively minor importance, since the diurnal inequality in the height of the tides is small. Like other high-water planes, the declinational planes exhibit annual variations and when determined from observations extending over a period of a month or even a year must be reduced to a mean value. These declinational planes may also be derived from the harmonic constants. The harmonic constants from the analysis of a 369-day series at Portland, Me., beginning January 1, 1925, show that the plane of higher high water lies 0.47 foot above the plane of mean high water, or 4.91 feet above mean sea level. The results of this analysis show that the plane of mean high water lies 4.44 feet above mean sea level. However, the value 4.43 feet should be accepted for the height of this plane above mean sea level, since it is based upon 14 years of direct tabulation—1912 to 1925, inclusive. The height of the plane of mean lower high water (3.98 feet above sea level) at Portland, Me., has been obtained from the harmonic constants for the 369-day series in 1925 referred to above.

The plane of mean higher low water (4.15 feet below sea level) at Portland, Me., and also that of mean lower low water (4.82 feet below sea level) have been obtained from the 369-day series in 1925 referred to above. The plane of mean low water (4.47 feet below sea level) has been obtained from 14 years of direct tabulation—1912 to 1925, inclusive.

In the "Summary of tidal data, Portland, Me.," on page 19, the height relations for the planes of tropic higher high water, tropic lower high water, tropic higher low water, tropic lower low water, spring high water, spring low water, neap high water, neap low water, perigean high water, perigean low water, apogean high water, and apogean low water, all referred to sea level, have been derived from harmonic constants for a 369-day series of tides at Portland, Me., beginning January 1, 1925.

Other important tidal datums are those of storm high water and storm low water, which are discussed in the section on "Effect of wind and weather on the tide," and also the plane of half-tide level, which is discussed in the following section.

THE PLANE OF HALF-TIDE LEVEL

The plane of half-tide level (or mean tide level, as it is sometimes called) is that plane which lies exactly halfway between the planes of mean high water and mean low water. The value for this plane will then be determined from the accepted values of mean high and low water as follows: $(17.54+8.64)\div 2=13.09$ feet, which will be the staff reading for half-tide level. This value is 0.02 foot below the value of mean sea level and may also be determined from Tables 12 and 9 thus: $(4.43-4.47)\div 2=-0.02$ foot. Therefore, the plane of half-tide level is 0.02 foot below the sea-level plane. The value of half-tide level for any month or year may be computed by taking the half sum of the values in Tables 7 and 10 for the month or year desired. The value as thus determined will approach very nearly the value of sea level for that period. Thus the variation in sea level, as discussed in a previous section, will also apply to the plane of half-tide level.

The plane of half-tide level is often confused with sea level or taken to be the same plane. This would be true in a simple sine curve, but in the tide curve the rise of high water above sea level is not equal to the fall of low water below sea level. Therefore half-tide level and mean sea level are not the same plane. At open-ocean stations, like Portland, Me., where the two planes lie so close together, one could be substituted for the other for many practical purposes without serious error, but for the sake of clarity it should be emphasized that they are distinct and separate planes.

THE RANGE OF THE TIDE

The range of the tide, which is the difference in elevation between any high water and the corresponding low water, varies from day to day, month to month, and year to year, much the same as the high and low waters from which it is computed. Since there are many planes of high and low water, it is obvious that there will be as many different ranges as there are combinations of high and low water planes. The more important ranges are enumerated as follows: Mean range, spring range, neap range, perigean range, apogean range, and several kinds of tropic and storm ranges.

The most important of the above ranges is the mean range. The value for mean range at Portland, Me., for any month or year from 1912 to 1925 may be easily computed from the tables of mean high and mean low water. This is the only range at Portland that has been computed from the tabulation for the 14-year period. The other ranges have been computed from the harmonic constants, and their values will be found in the table in the section on "Summary of tidal data."

The variation in range from day to day is shown in the last two columns of Table 1. From this table it is evident that in a single month, selected at random, the range varies from 6.7 to 13.3 feet, or a difference between extremes of 6.6 feet. This variation is caused largely by the change in position of the moon with respect to the sun and earth. The declinational effect of the moon can be easily seen from the table. On August 5 and 20 the moon was at its maximum north and south declinations, respectively, and the morning and afternoon ranges for the 5th and 21st should then show the greatest inequality for the month, as is the case. The moon was on the Equator on the 13th and 26th; therefore the morning and afternoon ranges on the 14th and 27th should be very nearly equal, as is evident from the table. On August 8 the moon was new, and on the 23d it was full; therefore the range on the day following these periods should be larger than when the moon is in the first or last quarter, which occurred on the 16th and 30th of the month. This relation also holds in the table, but the maximum of the 24th is more definite than on the 9th. This is caused by the parallax of the moon. On August 10 the moon was in apogee, which causes a decreased range. Thus the maximum effect of the 8th was nearly balanced by the minimum effect of the 10th. On August 23 the moon was in perigee, which caused a maximum range; therefore full moon and perigee acted in conjunction at this period to produce the maximum range for the month. The daily variations that do not follow any of the three periods above described must be caused by varying meteorological conditions.

The variations in range from month to month may be obtained by subtracting the values of Table 7 from the corresponding values in Table 10. The yearly means may be obtained by subtracting the values of Table 7 from those of Table 10, or by adding the values of Table 8 to those of Table 11. The results of these computations are tabulated in Table 13. The values in Table 13 have a definite periodic variation which makes one complete cycle in about 19 years, the lowest value in the cycle occurring in 1913 and the highest value in 1922. This is caused by the variation in longitude of the moon's node, which was discussed in the section on high and low water planes. These yearly values may be corrected to mean values by applying the same factors used to make similar corrections in the high and low waters. The results of this reduction are shown in Table 14. The yearly values should now be very nearly constant, but there is still some irregularity in the values. This may be best illustrated diagrammatically, which has been done in Figure 3. Curve *A* shows very clearly the periodic variation from year to year. Curve *B* shows the variation after applying the correction or longitude of the moon's node. The factor has a slight over-corrective effect, as was noticed in the high and low waters; that is, the values in the upper portion of curve *A* are now too low and those in the lower-portion of the curve are now too high. The small irregularities in the curve must be due to the effects of wind and weather. The most serious of these irregularities occur in 1919 and 1920, the value for 1919 being too low and for 1920 too high. A similar irregularity is noticed at other stations along the Atlantic coast, indicating that it was probably the result of weather conditions during those two years that caused the abrupt irregularities in the curves.

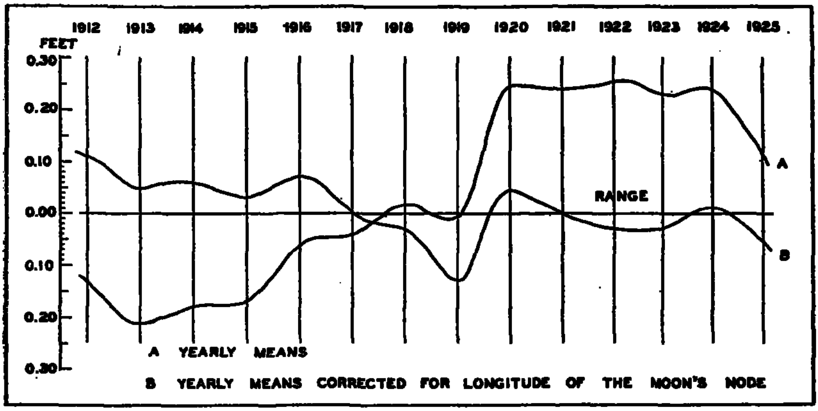

FIG. 3.—Periodic variation in the range of tide at Portland, Me.

The mean of the 14 values in Table 14 should furnish the best available value to date for the mean range at Portland, Me., which is 8.90 feet. The same value may also be obtained by subtracting the accepted value of mean low water from that for mean high water. Nearly the same value should be obtained by taking the mean of the uncorrected ranges in Table 13 for the 10-year period, 1913 to 1922, which is also 8.90 feet. The value of 8.90 feet, as determined from the recent 14-year series, will be accepted as the best available value for the mean range of the tide at Portland, Me.

TIDAL HARMONIC CONSTANTS

The complicated tidal forces are resolved into hypothetical simple forces by the mathematical process of harmonic analysis of the hourly heights of the tide. From this process several constants are derived for any particular place on the earth's surface. These constants are known as harmonic constants and are used primarily in the prediction of tides by setting their values on the tide-predicting machine. This subject is more fully discussed in the appendix of this volume, and a detailed discussion may be found in the Manual of Tides, by R. A. Harris, or in Harmonic Analysis and Prediction of Tides, by Paul Schureman.

Harmonic analyses of the tides at Portland, Me., have been computed for four 369-day periods, the first beginning August 1, 1864, and ending August 4, 1865, the second from January 1, 1915, to January 4, 1916, the third from January 1, 1916, to January 3, 1917, and the fourth from January 1, 1925, to January 4, 1926. The results of the analyses for these four periods are tabulated in Table 15. The amplitudes are expressed in feet, and the epochs (in degrees) are referred to the local meridian. The values inclosed in parentheses are inferred from other constants and are not derived directly from analysis. A number of tidal values may be easily derived from the harmonic constants by means of formulas given in the Manual of Tides.

The ages of the tide are computed as follows:

Phase age in hours equals 0.984 ($S^\circ_2 - M^\circ_2$).

Parallax age in hours equals 1.837 ($M^\circ_2 - N^\circ_2$).

Diurnal age in hours equals 0.911 ($K^\circ_1 - O^\circ_1$).

Substituting the average epoch values of the various constants for Portland, Me., in the above formulas, the phase age equals 34.7 hours, the parallax age equals 56.0 hours, and the diurnal age equals 17.5 hours.

The type of tide may be determined from the ratio $(K_1 + O_1) \div (M_2 + S_2)$. When this ratio is less than 0.25 the tide is of the semidaily type. Substituting the average amplitude values of the constants for Portland, Me., the ratio is 0.16; therefore the tide is of the semidaily type, as may also be seen from the tide curve for any month. The sequence of the tide may also be readily determined, but the formulas are rather involved and will not be reproduced here. The results from the formulas give, as the sequence, higher high water to lower low water. The high and low water planes and ranges may also be computed from the harmonic constants, but the formulas are too involved to present here. The values for the several planes and ranges thus computed will be found in the section on "Summary of tidal data."

EFFECT OF WIND AND WEATHER ON THE TIDE

The effect of wind and weather on the tide is a subject in itself and can, therefore, only be touched upon slightly in this volume. It is not the purpose here to enter into any lengthy or mathematical discussion of meteorological changes and their effects upon the tide, but rather to deal with the subject in a general way in an endeavor to show how some of the irregularities in the tidal observations may be explained, and to emphasize the fact that weather conditions may change to a considerable extent the time and height of any high or low water.

At open-ocean stations where fresh-water discharge is not a factor in tidal action, any high or low water that rises higher or falls lower than can be accounted for from astronomical causes must be due to either meteorological or seismological changes. Seismological changes are rather rare except in those areas of volcanic origin where the volcanic forces are to some extent still active or in localities subject to frequent earthquakes. The station at Portland, Me., does not lie in or near such an area, therefore seismological changes will not be discussed in this volume. The changes in tidal action from this cause have been discussed at some length in Special Publication No. 115, Tides and Currents in San Francisco Bay, and also Special Publication No. 127, Tides and Currents in Southeast Alaska.

Meteorological changes as they affect tidal actions may be divided into two classes somewhat closely related; that is, wind and barometric pressure. The action of the wind upon the surface of the sea is to set up a surface current in the direction of the wind or, to be more exact, somewhat to the right of the direction of the wind in the Northern Hemisphere. The effect of this current, if it is toward the shore, is to pile up the water along the coast and, if it is away from the shore, to draw the water away from the shore line. Since windstorms are generally of much longer duration than the duration of rise or fall of the tide, the net result is that the wind action is largely reflected in changes of sea level, so that the natural tidal forces act from a different datum for the period of the storm. The extent to which wind action influences the tides depends entirely upon the strength and duration of the storm, since it takes some time to set a current in motion and likewise some time for the current to cease flowing after the force of the storm is spent.

Changes in barometric pressure have a direct effect on the height of sea level. An increase in pressure over an area tends to depress sea level, while a decrease in pressure allows sea level to rise. Changes in barometric pressure, like windstorms, are generally of several days' duration, so that the action on the tidal forces is quite similar to the wind action.

The selection of values of high or low water that are indicative of storm action must necessarily be either somewhat arbitrary or else very complicated. No doubt the most accurate method of determining the influence of storm action would be to compare the actual height of every high and low water with the astronomical or theoretical height for that time and from the difference, and also from accurate and complete storm data regarding wind and pressure, determine the influence of storms of various intensities. This method would necessarily be very complicated and too detailed for practical use. From a practical standpoint it is only those storms that produce extreme tides that are of interest, and for the purpose of this discussion this will be the basis of selection.

The highest and lowest tide for each month have been selected and tabulated as extreme monthly tides. The mean of these 12 values for any year is then called the storm high, or storm low, water for that year, and the highest and lowest monthly value for each year is entered as the extreme high or low water for the year. The results of this selection and computation are tabulated in Table 16. The values in the table show somewhat smaller variation from year to year than might be expected from the method of selection. The maximum difference between any two years in the storm high waters is 0.70 foot and in the storm low waters 0.63 foot. The maximum difference between any two yearly values in the highest high or lowest low tides is 1.2 feet for the high waters and 1.0 foot for the low waters. If the series extended over a longer period of time, these values would, no doubt, be somewhat increased.

The average value of storm high water for the 14-year series is 19.69 feet for the staff reading, or 6.58 feet above the plane of mean sea level. The value of mean high water above mean sea level for the same period is 4.43 feet, or a difference of 2.15 feet. All of this difference is not due to storm action, for by the method of selection we find that nearly all of the extreme tides for the months occur on or near the time of maximum astronomical tides for the month. This would be expected, since a small storm at times of maximum rise and fall will give a higher or lower reading than a storm of much greater intensity at times of minimum tidal action. From this information 1.75 feet of the increased rise can be accounted for by astronomical causes, leaving 0.40 foot as the average yearly increase in high water caused by wind and weather. This represents an increased rise above mean sea level of about 6 per cent more than the astronomical tides. The value for low water also shows about 6 per cent depression. The highest tide for the series, 21.1 feet on the staff, or 8.0 feet above mean sea level, is 1.2 feet higher than the astronomical tide for that date, which represents an increased rise of about 18 per cent over the normal tide. The lowest low water for the series shows about 20 per cent increased fall below the normal tide for that day.

The average yearly storm range for the 14-year series will be 19.69 − 6.68, or 13.01 feet. The average extreme range will be 20.47 − 5.93, or 14.54 feet. The greatest range is 21.1 − 5.4, or 15.7 feet, which is about 2.3 feet greater than the greatest possible astronomical range for the series.

In order to show the general meteorological conditions at times of extreme tides, Table 17 has been compiled. The highest and lowest tides of each month at Portland, Me., from January to September, 1926, together with the meteorological conditions on such days are entered in the table. For purposes of comparison, the astronomical, or theoretical, tides for the days of extreme tides have also been entered in the table. From the table it is readily seen that most of the extreme low waters occurred when the barometric pressure was high, while most of the extreme high waters occurred when the barometric pressure was low.

An example of the variation in sea level as a result of changes in barometric pressure is illustrated in Figure 4. In this diagram the daily variation in sea level is represented in one curve and the daily variation in barometric pressure for the same period is represented by another curve. The scale of the sea-level curve is feet and the scale of the pressure curve is inches of mercury. Therefore the amplitudes of the two curves should be nearly the same but of opposite sign. From the curves it is evident that, while the ordinates of the curves as measured from the datum are not equal, every sharp rise or fall in sea level is accompanied by a corresponding rise or fall in pressure. The smaller variations in sea level and pressure do not agree so well as the larger variations. This might be expected, because other causes entering into the variations may easily mask a small variation due to changes in pressure. Most of the small changes in sea level that do not correspond to changes in pressure can be explained by wind action at that time.

From the curves (fig. 4) and the results in Table 17 there can be no doubt about the great effect of pressure and wind action on the tides. In places of small rise and fall, meteorological changes may even be the controlling factors.

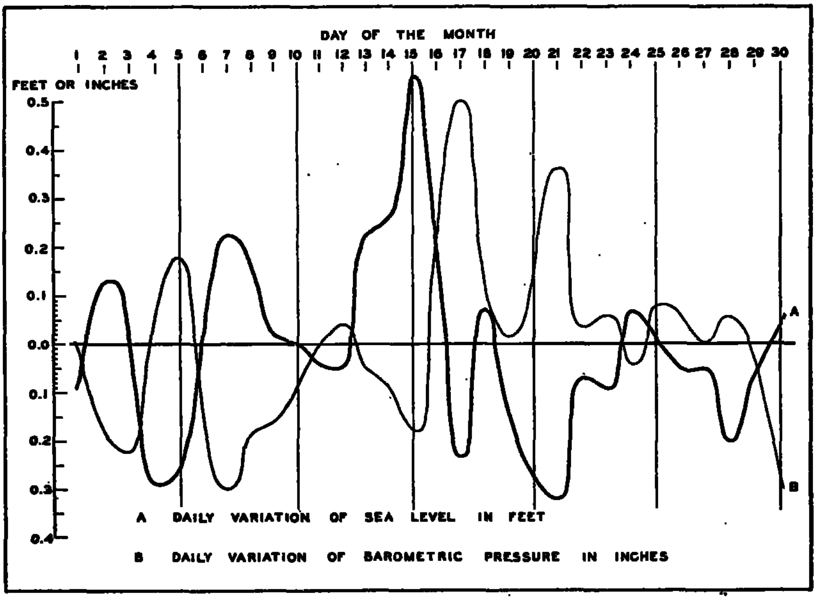

FIG. 4.—Daily variations in sea level as related to variations in barometric pressure at Portland, Me.

SUMMARY OF TIDAL DATA, PORTLAND, ME.

Time relations

	Hours
High-water interval	11. 16
Low-water interval	4. 94
Duration of rise	6. 21
Duration of fall	6. 21
Phase age	34. 7
Parallax age	56. 0
Diurnal age	17. 5

Sequence of tides is HHW to LLW.

Ranges

	Feet
Mean range	8. 90
Great diurnal range	9. 73
Small diurnal range	8. 13
Great tropic range	9. 83
Small tropic range	7. 43
Spring range	10. 28
Neap range	7. 46
Perigean range	10. 72
Apogean range	7. 47
Storm range	13. 01
Extreme range	14. 54
Greatest range	15. 7

Ratios

Spring range÷mean range	1. 16
Neap range÷mean range	0. 84
Perigean range÷mean range	1. 20
Apogean range÷mean range	0. 84
Great diurnal range÷mean range	1. 09
Small diurnal range÷mean range	0. 91
Great tropic range÷mean range	1. 10
Small tropic range÷mean range	0. 83

Height relations

	Feet
Mean high water above sea level	4. 43
Mean higher high water above sea level	4. 91
Mean lower high water above sea level	3. 98
Tropic higher high water above sea level	4. 98
Tropic lower high water above sea level	3. 65
Spring high water above sea level	5. 12
Neap high water above sea level	3. 71
Perigean high water above sea level	5. 34
Apogean high water above sea level	3. 71
Storm high water above sea level	6. 58
Highest high water above sea level	7. 89
Mean higher low water below sea level	4. 15
Mean low water below sea level	4. 47
Mean lower low water below sea level	4. 82
Tropic lower low water below sea level	4. 85
Tropic higher low water below sea level	3. 78
Spring low water below sea level	5. 16
Neap low water below sea level	3. 75
Perigean low water below sea level	5. 38
Apogean low water below sea level	3. 76
Storm low water below sea level	6. 43
Lowest low water below sea level	7. 71
Half-tide level below sea level	0. 02

THE TIDE IN PORTSMOUTH HARBOR AND TRIBUTARIES

The earliest record of tidal observations in Portsmouth Harbor is in 1851, when observations were made at Fort Constitution for a period of several weeks. Since that time there have been many series of observations at various places in the harbor and tributaries, most of which were made in connection with hydrographic or other engineering projects in the harbor where the local tidal action for a short period of time was required. Therefore many of these series of observations are not continuous but are daylight readings on staff gauges, sometimes on successive days and sometimes at broken intervals. There are a few places where a continuous record of several days or weeks is available.

A series of observations was started at Fort Constitution in 1851 to determine tidal characteristics for Portsmouth Harbor. A record was obtained for 86 consecutive days in 1851, 48 days in 1852, and 166 days in 1853. The gauge was then discontinued, and no further record was obtained until 1898. The series in 1853 is the longest complete record available for any portion of the harbor at the present time. A longer partial record is available for the station at the navy yard, Seavy Island, where the naval authorities maintained a gauge for a period of 25 consecutive lunar months to determine the elevation of the high and low water planes at the yard. The time relations for this series are, however, not available.

The locations of stations in Portsmouth Harbor and tributaries where tidal observations have been made are shown in Figures 5 and 6 by means of circles lettered from *A* to *J*, inclusive. At most of these stations two or more short series of observations are available, so that a comparison of tidal constants at different periods may be made. In the tide and current survey of 1926 several of the old stations were reoccupied and a few new stations were established at controlling points in the harbor.

All of the short-period observations in the harbor have been reduced to mean values by comparison with some standard station, or by applying factors to correct them for periodic variations. Portland, Me., has been used as the standard station whenever possible, because of the similarity of the tides at the two stations. Some of the earlier observations in the harbor were taken before the Portland gauge was established, and it is, therefore, impossible to make a direct comparison of the observations with the Portland station, and some other form of reduction has been employed in such cases. Since the times and methods of observations at each station in the harbor are quite different, it seems advisable to discuss first each station separately and later collect and tabulate the accepted values for each station in one table for further comparison and discussion.

STATION A, JAFFREY POINT, N. H.

This station was located on the eastern shore of Little Harbor (latitude 43° 03.3′ N. and longitude 70° 42.9′ W.), on the outer end of the Army pier at Fort Stark. This station is located so near the entrance point of Little Harbor that there should be very little difference between the tidal action at this place and that in the outer harbor.

There are three short periods of observations available at this station, as follows: One series of 10 days in 1903, another of 2 days in 1919, and a third of 6 days in 1926. The tidal characteristics for the two later periods have been reduced to mean values by comparison of simultaneous observations with the Portland station. The observations from the 1903 series have been reduced to mean values by comparison of simultaneous observations with Portsmouth, N. H. (Commercial Wharf). The Portland gauge was not in operation in 1903, and a direct comparison with this station is impossible. The values obtained for the three series by the methods just explained are tabulated in Table 18.

The values of lunitidal intervals for the three periods are very nearly the same, but the value of mean range for the 1903 observations is about 0.5 foot greater than that for either of the other two series, while the results for the two later series are very nearly the same. This difference may be due to the method of indirect comparison or it may be the natural irregularity in the tidal values.

The best available values to date for tidal characteristics at station A should be the weighted means of all the observations. These values are shown in the last line of the table. The values for each series of observations has been weighted in direct proportion to the number of days of observations in the series.

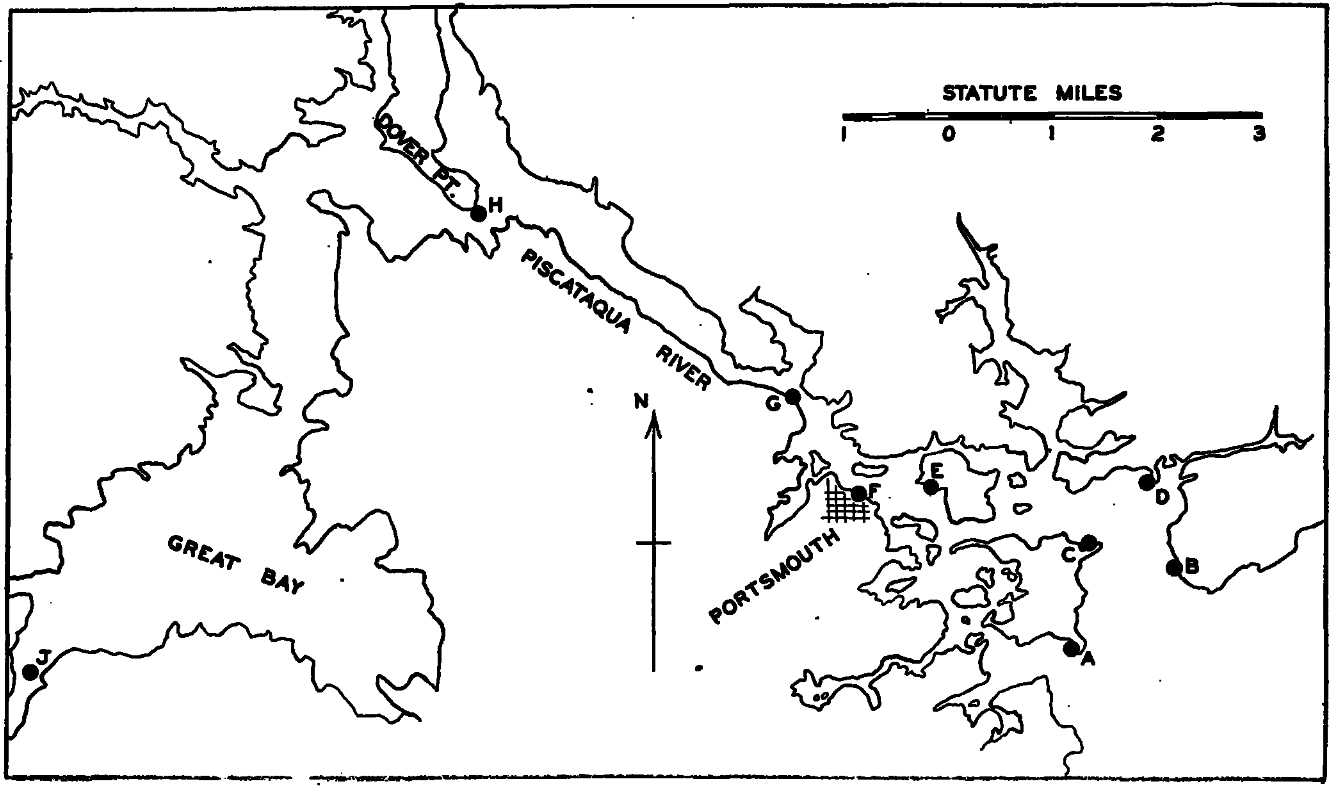

FIG. 5.—Tide stations, Portsmouth Harbor

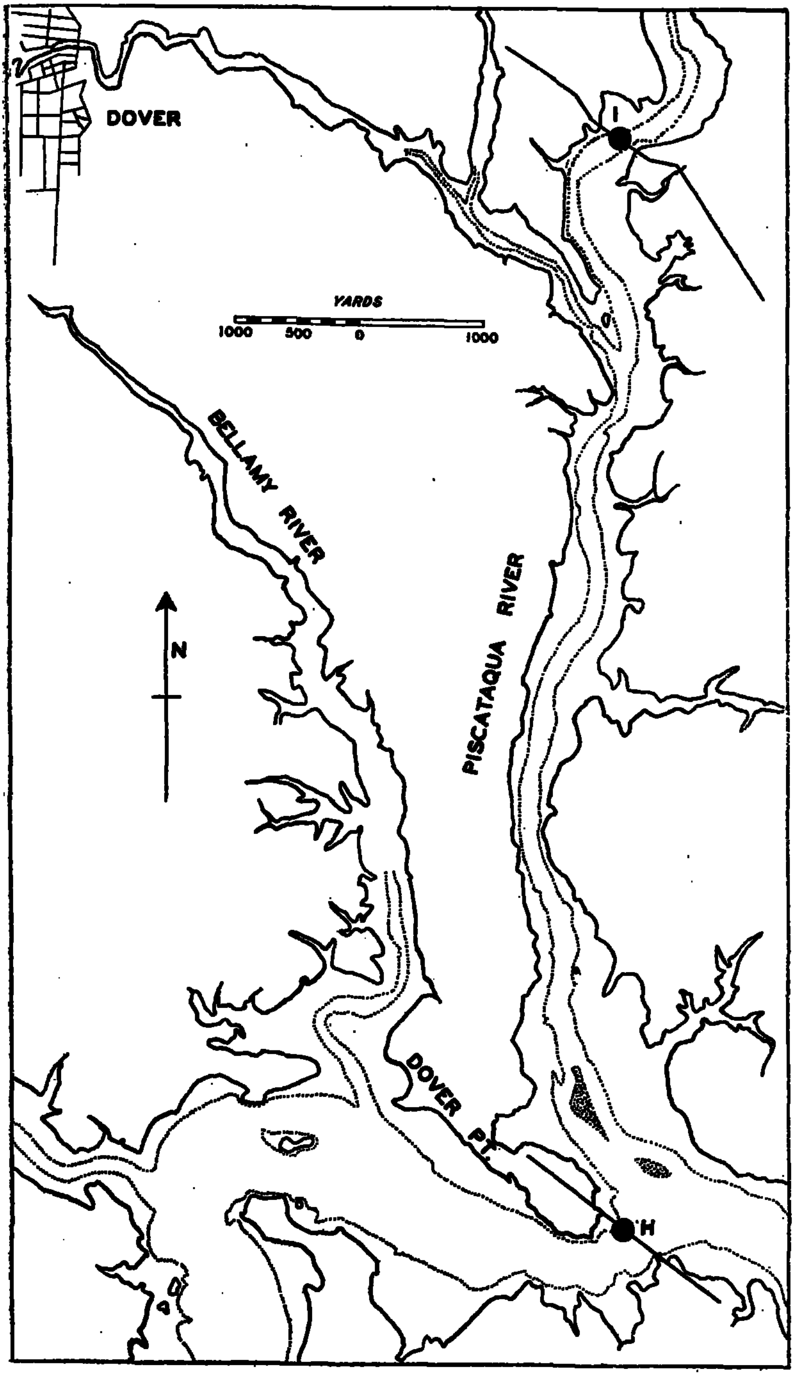

FIG. 6.—Tide stations, Piscataqua River

STATION B, GERRISH ISLAND, ME.

This station was located on the outer end of the Army pier on the western side of Gerrish Island and about ½ mile north of Whaleback Reef Lighthouse. The station is in latitude 43° 04.0′ N. and longitude 70° 41.8′ W. It was established in 1926 in connection with the tide and current survey of that year and was occupied for a period of seven consecutive days. This is the only series of tidal observations that has been taken at this place. The results from this series were reduced to mean values by direct comparison with observations at Portland. The mean values are given in Table 19.

The values of mean range and lunitidal intervals for this station agree closely with those for station A. This might be expected, since the stations are both near the entrance points of the harbor, one on either side, so that the time and height of the tide should be very nearly the same at either station.

STATION C, FORT CONSTITUTION, N. H.

This station was located on the Army pier at Fort Constitution, Newcastle Island (latitude 43° 04.3′ N. and longitude 70° 42.7′ W.). The tidal characteristics at this station are probably better determined than at any other place in the harbor because of the number of series at this place and also the lengths of some of the series. The earliest observations here were taken in 1851, when 86 days of continuous record were obtained. The station was again operated in 1852 and 1853, but, owing to the scale of the gauge being too large, the 1852 observations do not contain the lowest low waters of the series and the value of mean range is, therefore, too small. The following year a new gauge was installed and a record obtained for 166 consecutive days. No further observations were made until 1898, when 74 days of observations were recorded. Since this date there have been several short periods of observations at this station. The results from each series have been reduced to mean values and are tabulated in Table 20, the last line of the table being the weighted means of all the observations since 1885.

The three earliest series were taken before standard-time belts were established in the United States, and the time relations could not, therefore, be given as much weight as those from observations at a later date when the kind of time used was no longer an uncertain factor. Automatic gauges were also in the experimental stage at this time, and the results are not quite as reliable as similar records at a later date.

The best determined single period at Fort Constitution is probably the 74 days of observations taken in 1898. By this time automatic gauges were reliable, and, the standard-time belts having been established about 1885, time was no longer a doubtful factor in the records. All values in the table have been reduced to mean values either by comparison with the Portland (Me.) or Boston (Mass.) observations, or by applying factors to correct for periodic variations. It is impossible to compare the records for 1851, 1852, and 1853 with any standard station, and the results have, therefore, been reduced to mean values by applying factors to correct for the known periodic variations.

In arriving at the weighted means given in Table 20, all observations prior to 1885 have been omitted. Beginning with the series of 1898, weights were given in accordance with the lengths of series.

for the various years shown. The best available values to date for tidal characteristics for Fort Constitution, N. H., are the weighted means of all observations since 1885 and are given in the last line of Table 20.

STATION D, KITTERY POINT, ME.

This station was located on Kittery Point, Pepperell Cove, Me. (latitude 43° 05′ N. and longitude 70° 42′ W.). There are two periods of observations available at this station—one in 1917, when 64 high waters and 64 low waters were recorded, and another in 1919, when 23 highs and 23 lows were obtained. In neither case were the observations from consecutive tides, but they were the high and low waters obtained from a series of daytime observations on a staff gauge, established in connection with hydrographic work in the harbor. The results from each series have been reduced to mean values by comparisons with simultaneous observations at Portland, Me. The results thus obtained are tabulated in Table 21. The best available values for this station are the weighted means of the two series as tabulated in the last line of the table. Each series was weighted in proportion to the number of days in the series.

STATION E, PORTSMOUTH NAVY YARD, ME.

This station is located at the ferry landing in the navy yard, on Seavy Island (latitude 43° 04.8′ N. and longitude 70° 44.5′ W.). The earliest series at this place is one started in 1902 by the navy-yard authorities to determine the elevations of the high and low water planes at the yard. Heights of high and low water were recorded for a period of 25 lunar months. The time relations for this period are not available. In 1919 a four-day series of observations was taken in connection with hydrographic work in the harbor. Late in August, 1926, an automatic gauge (United States Coast and Geodetic Survey three-roller type) was installed at the ferry landing, where it will be kept in continuous operation for a number of years. This gauge was installed and is maintained jointly by the navy-yard authorities and the Coast and Geodetic Survey. In the near future, when a two or three year series of observations is available at this station, the tidal characteristics for this station will be better established than at present and will probably be the best-determined values in the harbor.

The results from each series of observations is tabulated in Table 22. The values in the table have been reduced to mean values by comparison with the Portland (Me.) tide station or by correcting the results for periodic variations. The best available values to date for this station are the weighted means of all observations as shown in the last line of the table. Each series has been weighted in direct proportion to the number of days of observations in the series.

STATION F, COMMERCIAL WHARF, PORTSMOUTH, N. H.

This station was located on Commercial Wharf in the city of Portsmouth (latitude 43° 04.7′ N. and longitude 70° 45.1′ W.). There is only one series of observations available at this station. Daytime observations on a plain staff were made at this place in connection with hydrographic work in the harbor in 1903. Sixty-four high waters and 68 low waters were recorded during the series. The results from this series have been reduced to mean values by comparison with the station at Fort Constitution, N. H., and by applying factors to correct for periodic variations. The results of the reductions are tabulated in Table 23.

STATION G, ATLANTIC CORPORATION SHIPYARD, PORTSMOUTH, N. H.

This station was located on the docks of the Atlantic Corporation Shipyard, on the Piscataqua River (latitude 43° 05.4′ N. and longitude 70° 46.0′ W.). There are two series of observations available at this station, one of 10 days' duration in 1919 and another of 5 days in 1926. The results from each series have been reduced to mean values by comparison of simultaneous observations with the Portland (Me.) tide station. The results are tabulated in Table 24. The best available values to date for this station are the weighted means of the two series of observations which are given in the last line of the table.

STATION H, DOVER POINT, N. H.

There are two series of observations at this station, one in 1913 and one in 1926. The location of the gauge for each period was slightly different. In 1913 the gauge was located on a dock north of the railroad bridge. In 1926 the gauge was located on the center pier of the draw of the railroad bridge. The two locations are less than 400 yards apart, so the tidal action should be very nearly the same at both places. The 1913 series consists of daytime observations taken in connection with hydrographic work. Values were obtained for 41 high and 42 low waters. The 1926 series consists of six consecutive days of observations with an automatic gauge. The results from each series have been reduced to mean values by comparison with the Portland (Me.) tide station. The results of the comparisons are tabulated in Table 25.

The mean range for the two series, as shown in the table, agree very well, but the lunitidal intervals are quite different, both high water and low water occurring later in 1926 than in 1913. The relation between duration of rise and duration of fall is also quite different in the two series. The interval of rise was slightly greater than the interval of fall in 1913, while in 1926 the duration of fall was considerably larger than the duration of rise. This station is located well up the Piscataqua River where fresh-water discharge would have a considerable effect on the tidal action, and it is, therefore, quite probable that the difference in the time relations are due to this cause. The series of 1913 was taken in the midsummer months, when the run-off is generally small, while the 1926 series was taken in the early fall, when the run-off is larger.

The weighted means of the two series should give average conditions at this station and will, therefore, be accepted as the best available values to date for this station. The mean values thus computed, by weighting each series in direct proportion to its length, are tabulated in the last line of the table.

STATION I, SALMON FALLS RIVER HIGHWAY BRIDGE

This station was located on the highway toll bridge across the Salmon Falls River, near the city of Dover, N. H. (latitude 43° 11.4′ N. and longitude 70° 49.5′ W.). This bridge is very nearly at the head of navigation of the river, as the channel above the bridge shoals rapidly to 5 feet or less. The only observations available at this station are from a 6-day series taken in 1926 in connection with the tide and current survey of the harbor of that year. The results from this series have been reduced to mean values by comparison with the standard tide station at Portland, Me. The results of this comparison are shown in Table 26. The effect of fresh-water discharge at this station is very well shown by the intervals for duration of rise and fall, the duration of fall being 0.4 hour more than the duration of rise.

STATION J, EXETER RIVER ENTRANCE, N. H.

This station was located at the draw span of the Boston & Maine Railroad bridge across the Exeter River just above the head of Great Bay (latitude 43° 03.2′ N. and longitude 70° 54.7′ W.). The Exeter River is navigable above this station by light-draft vessels as far as the city of Exeter, N. H.

Tidal observations at this station were made only in 1926, when five days' record were obtained from an automatic gauge. The results of these observations have been reduced to mean values by comparison with the standard tide station at Portland, Me., and are tabulated in Table 27. The effect of fresh-water discharge on the tide is also shown at this station by the duration of fall being considerably longer than the duration of rise.

SUMMARY

The accepted values of tidal characteristics for each station in Portsmouth Harbor are for convenience collected and tabulated in Table 28. The accepted values for the standard tide station at Portland, Me., are also included in the table for purposes of comparison.

Tidal movements in coastal waters are rarely of a simple wave movement, but it is frequently of considerable value and interest in tide and current predictions to determine which type of wave movement is most nearly represented. The two principal types of wave movement are the stationary and the progressive. The stationary wave is one in which the tide oscillates about an axis, so that high water occurs at all stations on one side of the axis at the same time that low water occurs at all stations on the other side of the axis. The range of the tide generally increases toward the head of the bay, and slack water occurs at the time of high and low water. The progressive-wave movement is one in which the crest of the wave advances, so that the time of tide becomes later and the range generally decreases as the distance from the entrance of the bay increases. In this type of movement slack water occurs about halfway between the times of high and low water, with the maximum strength of flow at times of high and low water.

It is evident from an inspection of Table 28 that the tide in Portsmouth Harbor is not of the stationary-wave type of movement, for the time of the tide is different at every station in the harbor and the range decreases toward the head of the harbor.

If the movement is of the progressive-wave type, the range of the tide should decrease from the mouth to the head of the bay at approximately a uniform rate, and the time of tide should become later in accordance with the formula for the rate of advance of a progressive wave ($R = \sqrt{gd}$) where R is the rate of advance, g is the acceleration due to gravity, and d is the average depth of the channel below sea level.

The rate of decrease in range for the outer portion of the harbor, or between stations B and D on one shore and A and C on the other, is about 0.11 foot per mile. The rate of decrease for the inner portion of the harbor, or between stations C and F on one shore and stations D and E on the other, is about 0.51 foot per mile. The difference in rate of decrease of range in the two portions of the harbor is probably due to the configuration of the channel. The outer harbor is straight and free of obstructions and of nearly uniform depth, while the inner harbor has many obstructions in the channel and is variable in depth. In the lower reaches of the Piscataqua River, where the configuration of the channel is somewhat similar to that in the inner harbor, the rate of decrease in range is approximately equal to that for the inner harbor, the rate between stations E and H being about 0.42 foot per mile as compared with 0.51 for the inner harbor. The range at each of the two river stations above station H is slightly greater than that at H, which is no doubt caused by the constriction of the channel at each place. From the rate of decrease of range alone it is not evident whether the tide is of the progressive type or not.

The best test of the progressive wave is the time relations. From the formula ($R = \sqrt{gd}$) the tide should be 0.06 hour later at station C than at station A and from Table 28 the actual average difference is 0.05 hour. The theoretical difference in time between stations A and E is 0.13 hour, while the actual time is 0.24 hour. Therefore, for that portion of the harbor from the entrance to the navy yard the tidal movement is largely of the progressive-wave type. According to theory, the tide at station G should be 0.10 hour later than at station F, while the actual time difference is 0.26 hour. Between stations G and H the theoretical time is 0.22 hour, while the actual time is 0.90 hour. Therefore, between these stations it is evident that the movement of the tide is not entirely of the progressive-wave type. It is probable that the tidal movement in Portsmouth Harbor and tributaries is largely of the progressive-wave type, but because of the numerous obstructions in the channels and the varying depth and width of the channels the theory does not hold very well in some portions of the waterway.

The two river stations I and J each have a range of tide greater than station H, which is several miles downstream. This must be due to the constriction of the channel at each of these stations. At station H the channel has an average width of 400 yards and an average depth of 20 feet, while at station I the width has been reduced to 120 yards and the depth to 5 feet, and at station J the width is reduced to 100 yards and the depth to 6 feet.

Fresh-water discharge or river current has very little effect on the tidal action anywhere in Portsmouth Harbor and tributaries. The greatest effect is at the two up-river stations I and J, where the duration of fall is about 0.4 hour longer than the duration of rise. Nearly all of the observations in the waterway have been taken during summer months, when the run-off is small, and it is quite probable that observations taken at other times of the year would show the effect of run-off farther downstream. When a year of observations is available from the navy yard station the effect of freshets on the tidal action at that place during the year will be known.

Part II.—CURRENTS IN PORTSMOUTH HARBOR

By E. A. LE LACHEUR, *United States Coast and Geodetic Survey*

Part II of this publication deals with the tidal current in Portsmouth Harbor and its tributaries. The movements of the tidal current in the approaches to Portsmouth Harbor from the Atlantic Ocean are also included because of the relationship between such tidal current movements offshore and those in Portsmouth Harbor proper.

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

1. The current in the approaches to Portsmouth Harbor.
2. The current in Portsmouth Harbor entrance.
3. The current in Portsmouth Harbor, vicinity of Newcastle, N. H.
4. The current in Portsmouth Harbor, vicinity of Portsmouth, N. H.
5. The current in the Piscataqua River and tributaries.

APPROACHES TO PORTSMOUTH HARBOR

For convenience in discussing the tidal current in the approaches to Portsmouth Harbor, the entrance to the harbor is defined by a line joining Odiornes Point and Kitts Rocks whistle buoy. Current stations located north of this line are, therefore, in Portsmouth Harbor, and those located south of this line are in the approaches to Portsmouth Harbor. Figure 7 shows the locations of two current stations which have been occupied in the approaches to Portsmouth Harbor, the records of which are on file in the office of the Coast and Geodetic Survey.

The tidal current in Portsmouth Harbor is of the reversing type; that is, it floods or sets northerly or westerly for a period of about six hours and then ebbs, or sets southerly or easterly, for the following period of about six hours. Due to fresh-water run-off in the Piscataqua River and its tributaries, the period of the duration of the ebb is generally increased to about seven hours duration and that of 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.

Offshore, however, away from the immediate influences of the coast, the tidal current is quite different from the current found in inland tidal waters. Instead of setting in one general direction, or flooding,

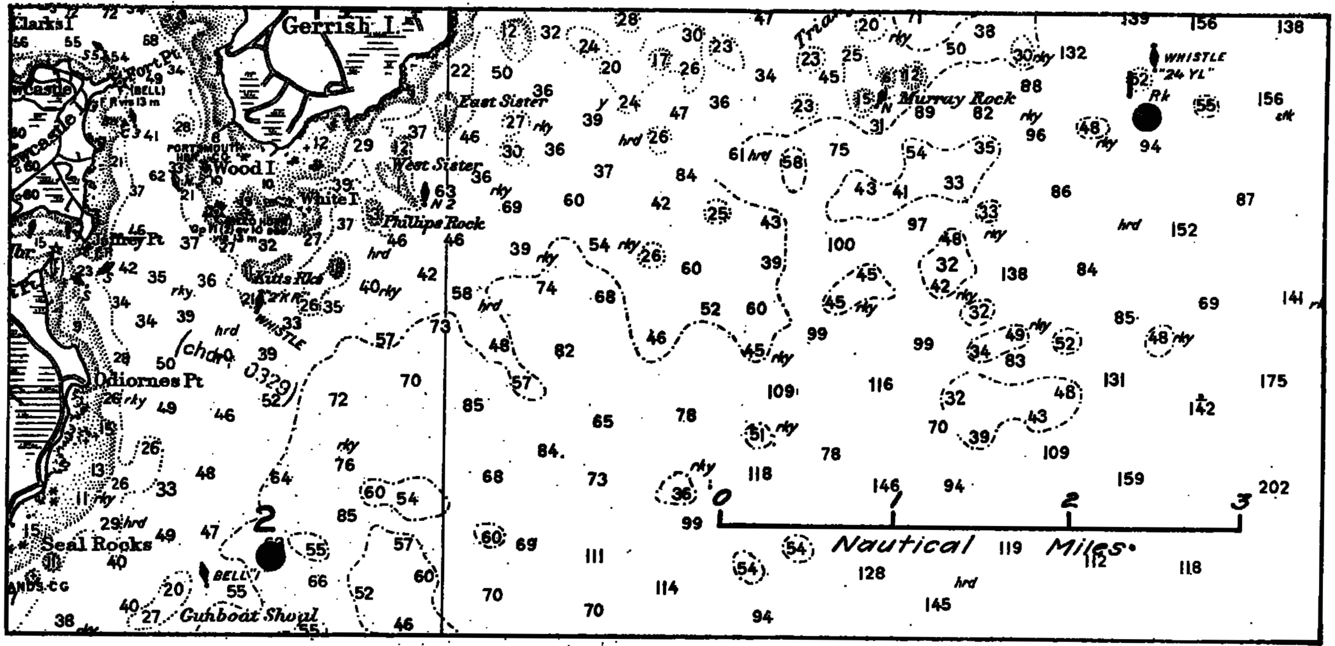

FIG. 7.—Current stations, approaches to Portsmouth Harbor

for a period of about 6 hours, and ebbing in the opposite direction during the following period of about 6 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 Portsmouth Harbor and the Piscataqua River. For more detailed information on the reversing, or rectilinear, and rotary types of current, see page 89 of the appendix to this publication.

At current stations 1 and 2, shown in Figure 7, 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.

Current data for stations 1 and 2 are given in Table 29. Observations were made continuously by means of pole and log line at hourly intervals. 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 each observation. Owing to the length of the current pole used, current data for stations 1 and 2 in Table 29 represent average current conditions at a depth of 7 feet, or, approximately, at the surface.

Current station 1 was located about one-half mile south of York Ledge whistle buoy 24YL and about 1½ miles east of Murray Rock, while current station 2 was located about one-half mile east of bell buoy 1, which marks the northeast end of Gunboat Shoal. The current at both stations is of the rotary type, turning clockwise, the flood setting southwesterly at station 1 and northwesterly at station 2. It is a weak current, however. It will be noted from Figure 7 that current station 1 is located about 5 miles from the entrance to Portsmouth Harbor, while station 2 is but a mile away from this entrance.

In Table 29 the time of the tidal current at stations 1 and 2 is referred to the time of predicted slack water before flood at Portsmouth Harbor entrance. This is the reference station for the times of the current at all current stations mentioned in this publication, and it is also one of the standard reference stations for which full predictions for every day in the year are given in the Atlantic Coast Current Tables, a serial publication of the United States Coast and Geodetic Survey. The times of strength of flood at stations 1 and 2 occur about two and one-half and one and one-half hours later, respectively, than the same phase of the current at Portsmouth Harbor entrance.

It will be noted that the velocity of the flood at these stations is rather small compared with that of about 1½ knots at Portsmouth Harbor entrance. Because of proximity to the harbor entrance, the velocity of the current at station 2 is obviously greater than that at station 1. The directions (true) of the flood strength at each station are given to the nearest 5° reckoned from 0° N., 90° E., 180° S., 270° W., and 360° N. This method of giving the direction of the current is used for pole observations at all current stations mentioned in this publication. The direction of the tidal current at the time of strength of ebb at stations 1 and 2 is approximately 45° and 145°, respectively.

The velocity and direction of the set, or nontidal current, for the 2-day observation period is also given for each station in Table 29. This current is largely due to winds, fresh-water run-off, or some other meteorological factor or factors in distinction from the tide which is an astronomical phenomenon. It will be noted that the set, or nontidal current, at each station is approximately as great in velocity as the tidal current. When strong winds occur it may completely mask a weak tidal current.

PORTSMOUTH HARBOR ENTRANCE

For all practical purposes Portsmouth Harbor entrance may be taken as the mouth of the Piscataqua River where the latter meets the Atlantic Ocean. This would include that portion of the waterway from the vicinity of Odiornes Point and Kitts Rocks to the vicinity of Pepperell Cove, off Fort Point, a 2-mile stretch of deep water.

In mid-channel depths of 40 to 70 feet are found. South and west of Gerrish Island several rocky reefs and islets occur. The eastern shore of Newcastle Island is also rocky. The channel is wide, deep, and free from shoals, having depths of 30 feet or more and widths of more than a quarter of a mile in its narrowest reaches off Wood Island and Fort Point. Depths of 1 foot or less at mean low water are found between Whaleback Reef and Wood Island and between the latter and Gerrish Island, making this portion of Portsmouth Harbor practically useless for navigation purposes.

Figure 8 shows the locations of 19 current stations occupied in Portsmouth Harbor entrance by the following field parties of the United States Coast and Geodetic Survey: C. H. Woodhull, in 1852; P. A. Welker, in 1898; J. H. Hawley, in 1919; and R. W. Woodworth, in 1926. Observations at a majority of these stations were made in the summer of 1926, when the Coast and Geodetic Survey made an extensive tide and current survey of Portsmouth Harbor and its tributaries. Currents were observed on cross sections of Portsmouth Harbor entrance in 1926, as follows:

1. Between Odiornes Point and Whaleback Reef—stations 2, 3, and 4.
2. Between Fort Point and Gerrish Island—stations 13 and 15.

Station 11 was a control station for current stations occupied in Portsmouth Harbor entrance in 1926, and continuous observations by current pole and log line and also by current meter were made at this station for a total of five and one-fourth days from August 11 to 13 and from August 30 to September 2. The data derived from current observations at these 19 stations in Portsmouth Harbor entrance are given in Table 30. 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.

The times of slack water and strengths of flood and ebb in Table 30 are given in hours and tenths of hours and are referred to the times of predicted slack water at Portsmouth Harbor entrance, one of the standard reference stations for which full predictions for every day in the year are given in the Atlantic Coast Current Tables. The location of this standard reference station is approximately that of current station 11, shown in Figure 8, located about one-fourth mile northwest of Whaleback Reef Light.

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 Portsmouth Harbor entrance is considerably greater than that of the flood, owing to fresh-water discharge. 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 earlier in the shallower reaches near the eastern and western shores of the harbor entrance than it does in mid-channel. This is shown very distinctly for flood observations at stations 1, 4, and 7, and ebb observations at stations 2, 5, and 7. The depths of water at stations 5 and 7 at mean low water are but 14 or 15 feet as compared with depths of 40 to 50 feet at the mid-channel stations 3, 9, 11, 12, 14, 16, 18, and 19.

The greatest velocities of the current on the flood and ebb occur mainly at stations which are located on the axis of the channel. Under normal weather conditions, the average velocity of flood at time of strength at these stations is about 1¼ knots, although in mid-channel, off Fort Point, velocities of about 2 knots occur. Ebb strength averages about 1¾ knots at these stations and average velocities exceeding 2 knots obtain at certain points in the waterway. At stations along the eastern and western shores of Portsmouth Harbor entrance the strengths of flood and ebb average from about 0.65 to 0.85 knot, as will be readily seen from the data for stations 1, 2, 4, 5, 6, 7, and 17, given in Table 30.

The average duration of flood and ebb at station 11, Figure 8, for which daily current predictions are given in the Atlantic Coast Current Tables, are 5.8 and 6.6 hours, respectively. In mid-channel, at stations 3, 9, 11, 12, 14, 16, 18, and 19, the average durations of flood and ebb are about 5½ and 7 hours, respectively. With increased fresh-water run-off the duration of ebb is correspondingly increased and the duration of flood is decreased.

It will be noted from Table 30 that the duration and velocity of flood at station 18, north of Fort Point, is considerably greater than that at station 19, while on the ebb the converse is true. This phenomenon may be explained by the fact that the influence of the flood is felt more at station 18 than it is at station 19. Although the two stations are close together, the depth of water is greater at the former station. The flood, upon entering Portsmouth Harbor, is undoubtedly deflected by Fort Point, Fishing Islands, and the western shores of Gerrish Island, causing its influence to be felt more at station 18 than at station 19. This may also explain the rather small velocities of flood and ebb at station 17 at the entrance to Pepperell Cove. That the flood is deflected by Fort Point is brought out by the data for station 13 in Table 30 which show the direction of flood to be N. 5° E. (true), while the ebb direction at time of strength is 145° (true), or S. 35° E.

The unusually long ebb duration at station 5 and long flood durations at stations 1 and 4 may be explained by the locations of these stations. The flood at station 5 is interfered with by the many rocks and shoals south of Gerrish Island. It is interesting to note that at stations 1 and 4 the duration of flood is three hours longer than that of ebb, while at stations 2 and 6 on the other side of the harbor entrance the ebb runs three hours longer than the flood. The depths of water north of Wood Island indicate that the ebb is deflected toward Little Harbor entrance by Wood Island and Whaleback Reef. This is brought out by the long ebb durations at stations 2 and 6. While there is considerable interference to the flood at station 5, causing a flood duration of less than four hours, there is lesser interference to the ebb at this station, resulting in an ebb duration of nearly nine hours.

At the 11 current stations occupied by the field party of R. W. Woodworth in 1926, in Portsmouth Harbor entrance, observations of subsurface currents were also made by means of a Price current meter with telephone attachment. 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 31. The velocities of flood and ebb have been reduced to a mean range of tide and are given to the nearest hundredth of a knot for comparative purposes. The times of the current for each depth at each station are referred to the times of predicted slack water at Portsmouth Harbor entrance (approximately at station 11). The durations of flood and ebb as well as the times of current at each station are given to the nearest hundredth of an hour, also for comparative purposes, 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 at half-hour intervals for 25 consecutive hours. Stations 2, 3, 4, and 5 as well as stations 13 and 15 were located on cross sections of Portsmouth Harbor entrance. Station 10, located east of Newcastle Island, was occupied for two days, and the control station, No. 11, was occupied for more than five days. At all these stations the current is of the reversing, or rectilinear, type, and generally the ebb runs considerably longer than the flood with the exception of station 4, located southwest of Whaleback Reef Light.

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 where velocities were observed with the Price current meter. Bifilar subsurface current-direction observations were not obtained at station 2, however, off Odiornes Point. It will be noticed from Table 31 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.

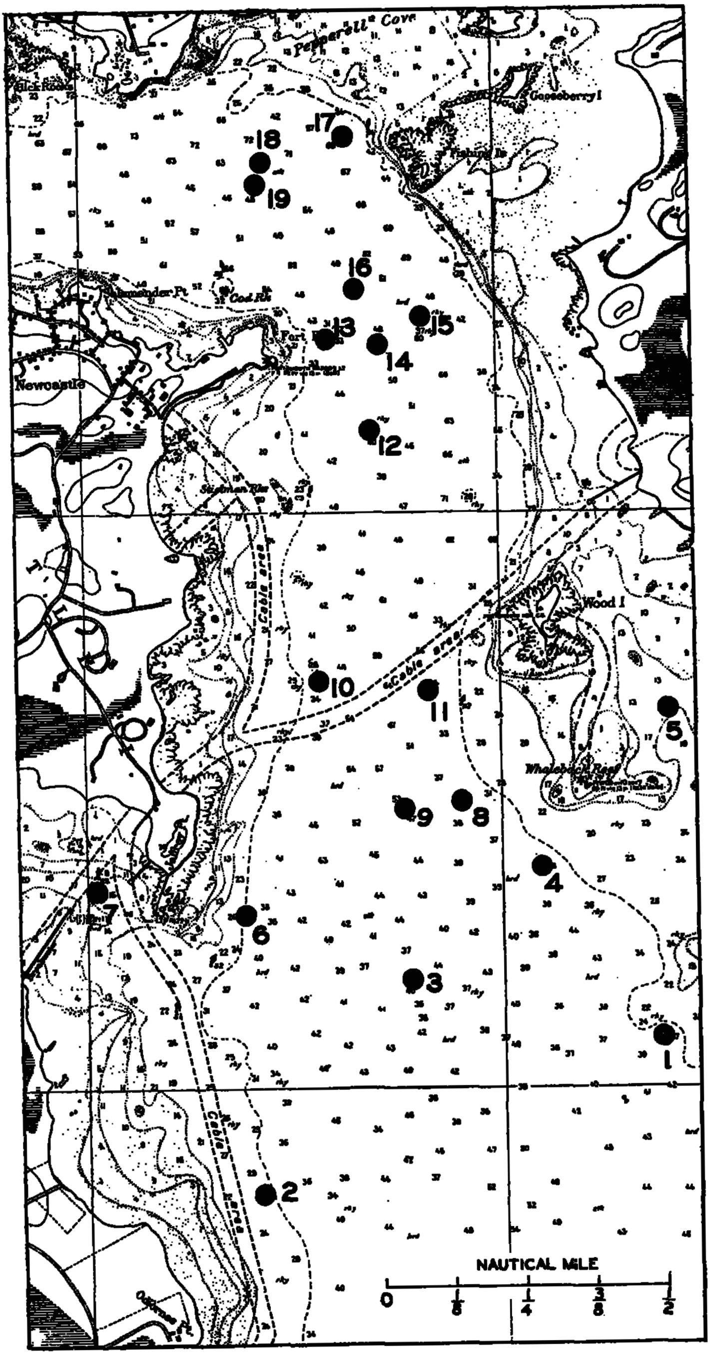

FIG. 8.—Current stations, Portsmouth Harbor Entrance

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 in Portsmouth Harbor entrance at times of ebb strength, as will be noted in Table 31 for all the stations at which current observations have been made. On the flood, however, as illustrated by the data for station 10 in Table 31, the velocity may show an increase from the surface downward for a considerable depth. It will be noted from Table 31 that at station 10, located east of Newcastle Island, the velocity of flood strengths at the lower depths is greater than that for ebb strengths.

The difference in the vertical distribution of the current velocity is evidently due to the nontidal or fresh-water discharge from the Piscataqua 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.

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 increased depth. This is clearly shown by the current data for stations 10 and 11 in Table 31. The stations are located in mid-channel in deep water off Newcastle Island. It will be noted that at station 10 the ebb runs about 20 minutes longer than the flood at the surface, while at station 11 it runs more than 50 minutes longer than the flood. At the bottom depth at each station, however, the flood runs half an hour longer than the ebb.

In addition to Price meter observations at station 10, Pettersson current-meter observations were also obtained at the middle depth of 19 feet. Whereas the Price meter is only used to obtain current velocities, the Pettersson meter is used to obtain current directions as well as velocities. The Price meter cups rotate with the current and cause an electric contact to be made with each complete rotation, or each five rotations, as the case may be. These contacts are audible to an observer with ear phones on board the observing boat and indicate the velocity of the current by their frequency.

The Pettersson meter is designed to give a photographic record of both the velocity and direction of the current and will operate automatically for a period of two weeks. A water-tight cylinder contains a small camera with a roll of film moved by clockwork, a small electric lamp with batteries, a glass velocity disk with numerals inscribed near the outer edge, and a glass compass disk carrying two magnetic needles and inscribed with numerals to indicate direction.

The compass dial is free to move so that the needles may assume a north-and-south direction. The velocity dial, through a system of reducing gears and parallel magnets, rotates with an anemometer wheel which is actuated by the current. At intervals of 30 minutes the electric lamp is automatically flashed and a picture is taken showing certain numerals on the velocity and compass dials. The numeral on the velocity dial indicates the accumulated motion of that dial due to the movement of the current. The difference between two successive readings, as interpreted by a rating table, gives the average velocity of the current for the half-hour period. The numeral on the compass dial indicates the direction of the current at the moment the picture was taken.

Pettersson meter observations were obtained continuously at station 10 for a period of two days from 9:20 a. m., August 30, 1926, to 10 a. m., September 1, 1926. The velocities observed during this series agree very closely with those obtained by means of the Price current meter, while the current directions observed agree favorably with those obtained by means of the bifilar suspension current-direction indicator.

PORTSMOUTH HARBOR, VICINITY OF NEWCASTLE, N. H.

The area covered by this section of Portsmouth Harbor is that lying northerly and northwesterly from the town of Newcastle, on Newcastle Island, and extending from Salamander Point to the vicinity of Sullivan Point, Seavy Island. In the Piscataqua River stretch of this section mid-channel depths of 50 to 80 feet obtain. East of Seavy Island are Jamaica and Clarks Islands, which are small in extent and very rocky on their westward shores. A narrow, 25-foot channel is located between these islands, uniting in the vicinity of Hicks Rocks with a similar channel located west of Kittery Point and north of Seavy Island. Between Salamander and Kittery Points the channel of the Piscataqua River is more than a quarter of a mile wide, but south of Clarks and Seavy Islands it narrows down to about half this width.

Figure 9 shows the locations of 10 current stations occupied in this portion of Portsmouth Harbor by the following field parties of the United States Coast and Geodetic Survey: P. A. Welker, in 1898; and R. W. Woodworth, in 1926. Observations at a majority of these stations were made in the summer of 1926, when the Coast and Geodetic Survey made an extensive tide and current survey of Portsmouth Harbor and its tributaries. Currents were observed on a cross section between Salamander and Kittery Points at stations 1, 2, and 3.

Station 2 was a control station for current stations occupied in this portion of Portsmouth Harbor in 1926, and continuous observations by current pole and log line and also by current meter were made at this station for a total of 11 days from August 16 to 27. The data derived from current observations at these 10 stations in Portsmouth Harbor are given in Table 32. 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.

The times of slack water and strengths of flood and ebb in Table 32 are given in hours and tenths of hours and are referred to the times of predicted slack water at Portsmouth Harbor entrance, one of the standard reference stations for which full predictions for every day in the year are given in the Atlantic Coast Current Tables.

The durations of flood and ebb are also given in hours and tenths of hours. 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°.

Most of the current stations in this section of Portsmouth Harbor were located in mid-channel either in the Piscataqua River proper or in the channels north and west of Hicks Rocks and Clarks Island. It will be noticed from the data in Table 32 that at station 6, off Kittery Point, Me., the time of slack water before flood and ebb occurs about one and one-half hours earlier than it does at Portsmouth Harbor entrance, off Whaleback Reef Light, while at station 5 it occurs half an hour earlier than it does at the harbor entrance. At both these stations the durations of flood and ebb are equal—6.2 hours each. At station 9 the duration of flood is slightly greater than that of ebb, indicating that at these three stations, 5, 6, and 9, fresh-water discharge from the Piscataqua River is not noticeable. It will also be noticed that at stations 3 and 4 similar conditions obtain.

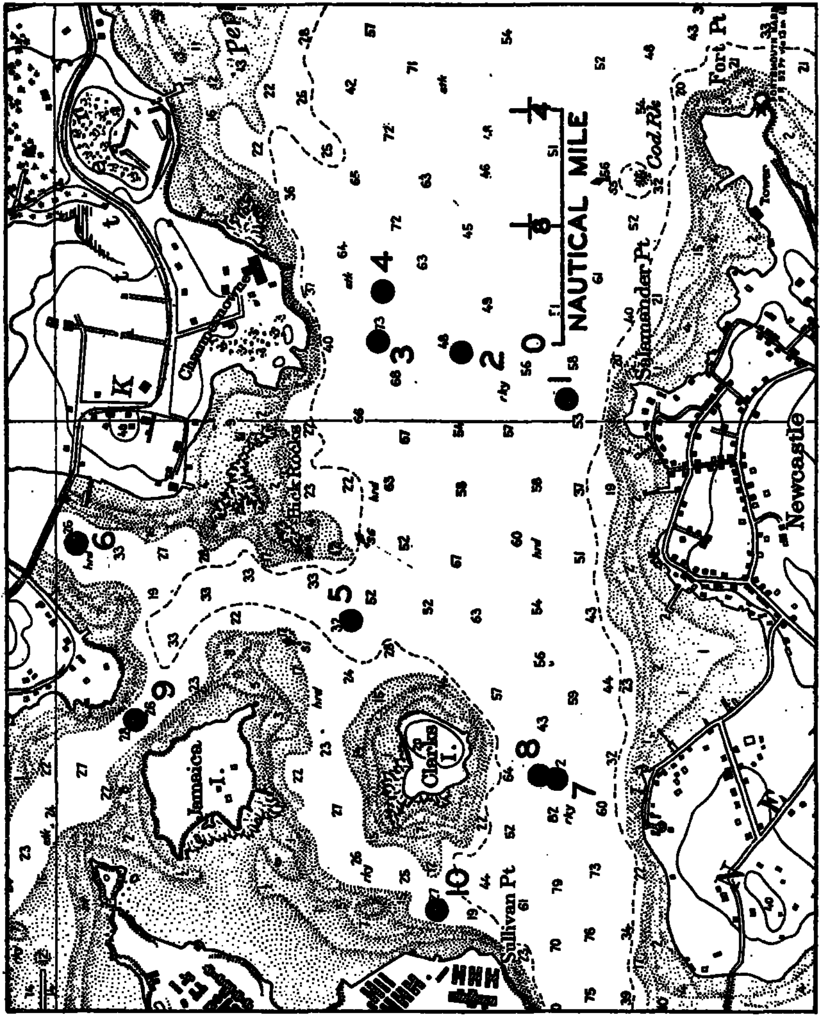

FIG. 9.—Current stations, Portsmouth Harbor, vicinity of Newcastle, N. H.

On the other hand, the duration of ebb at station 1, just north of Salamander Point, is relatively long, being about 10½ hours, while the strength is considerable, 2.4 knots, as compared with a flood duration of about 1¾ hours and strength of about ¾ knot, indicating that the flood is not noticeable to any extent off Newcastle and that fresh-water discharge from the Piscataqua River is felt considerably at this point. This is also borne out by the results of the long series of observations at the control station No. 2 (11 days). In mid-channel off Salamander Point, at station 2, the average velocities of flood and ebb at times of strength are about equal, being approximately 1¼ knots each, while the duration of ebb is but 0.4 hour longer than that of flood.

It is highly probable that this condition is due to the contour of the northeast coast of Newcastle Island in the vicinity of Fort Point. As the flood progresses northerly in Portsmouth Harbor from the entrance, it is deflected easterly by Fort Point, as shown by observations at various current stations and discussed at some length in the preceding section of this publication, under "Portsmouth Harbor entrance." On the other hand, there appears to be no interference to the progression of the ebb at station 1, off Newcastle. At this station slack before flood occurs about half an hour later than it does at the harbor entrance, while slack before ebb occurs nearly four hours earlier than the corresponding slack water at the entrance.

While stations 7 and 8, in mid-channel south of Clarks Island, were occupied at an interval of time of 30 years apart, the results of the observations, as given in Table 32, agree quite closely. Slack water occurs somewhat earlier at station 7 than it does at station 8, and the velocities of flood and ebb, especially the former, are considerably greater. This is most likely due to the locations of the two stations, considering the fact that the channel of the Piscataqua River is but an eighth of a mile wide at this point. Durations of flood and ebb are similar at both stations, in each case the ebb duration being approximately 15 minutes longer than that of the flood.

The results of current observations at station 10 are of interest in showing a duration of flood, or southerly current, of 11 hours as against an ebb duration, or northerly current, of but 1½ hours. The main progression of the flood in the Piscataqua River follows the deep channel between Clarks and Newcastle Islands, but the flood is divided by Clarks Island, so that a portion of it passes north of the island and then reaches the Piscataqua River after passing between Clarks and Seavy Islands. The average velocity of the flood strength at station 10 is nearly 2 knots, while that of the ebb, or northerly stream, is but one-tenth as great. The main ebb from the Piscataqua River, as shown from observations at stations 1, 2, 7, and 8, progresses between Clarks and Newcastle Islands, but part of it passes around Clarks Island to the northward. Again, the ebb from that branch of the Piscataqua River which flows northward and eastward of Seavy Island in the narrow channel between that island and the mainland probably divides in the vicinity north of Jamaica Island, so that some of its effect is felt as a southerly or flood current at station 10. The greater part of this ebb would follow the channel in the path of stations 9, 5, 1, and 2.

Slack before flood at station 10 occurs about two and three-fourths hours before local low water, or about the time of mean tide level. At this time, under average conditions, there is approximately an average depth of water of about 4 feet in the area between Jamaica and Seavy Islands, which area at the time of mean low water is dry, as shown in a section of the Coast and Geodetic Survey Chart No. 0329 (fig. 9). It will be noted from the data in Table 32 that slack before flood at station 9, northeast of Jamaica Island, occurs more than four hours later than it does at station 10. By inference, then, it follows that while the current is still ebbing at station 9 over a period of four hours, it is flooding, or running southerly, at station 10. This southerly current at station 10, however, is not a true flood, for at the same time that it is ebbing at station 9 it is also ebbing at stations 7, 8, 5, and 2, or running easterly. This southerly current at station 10 for the first four hours of the flood is due, therefore, to the fact that the area between Jamaica and Seavy Islands which has filled up with water at high tide empties into the Piscataqua River in a southerly direction. The velocity of the flood over this 4-hour interval averages about ½ knot, while during the following seven hours it increases to an average strength of about 1¾ knots.

At the eight current stations occupied by the field party of R. W. Woodworth in 1926 in this section of Portsmouth Harbor, observations of subsurface currents were also made by means of a Price current meter with telephone attachment. 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 33. The velocities of flood and ebb have been reduced to a mean range of tide and are given to the nearest hundredth of a knot for comparative purposes. The times of the current for each depth at each station are referred to the times of predicted slack water at Portsmouth Harbor Entrance (off Whaleback Reef Light). The durations of flood and ebb as well as the times of current at each station are given to the nearest hundredth of an hour, also for comparative purposes, 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 at half-hour intervals for 25 consecutive hours. Stations 1, 2, and 3 were located on a cross section of the harbor between Salamander Point, Newcastle Island, N. H., and Kittery Point, Me. Station 2 was also the control station for this portion of the harbor current survey of 1926, and continuous observations were obtained at this station for 11 days from August 16 to 27, 1926. Current station 5, located between Clarks Island and Hicks Rocks, was occupied for two days. At all these stations the current is of the reversing, or rectilinear, type. In most cases the duration of flood exceeds that of ebb.

In addition to the subsurface velocity determinations at each station, subsurface current directions were also observed by means of the bifilar suspension current-direction indicator, a device permitting simultaneous determinations of the direction of the current at the three depths at each station where velocities were observed with the Price current meter. At stations 1 and 7 bifilar observations were not made while the current was ebbing, owing to the swiftness of the ebb at times of strength.

In general, the velocity of the current decreases as the depth increases, in accordance with the distribution of velocity in ordinary hydraulic flow. In several cases, however, the data in Table 33 do not verify this general conclusion, for at some stations the strength of ebb appears to be rather constant at all depths, or even to increase somewhat. The data show such a condition at stations 1, 2, and 10, but this may be due to the individual locations of these stations. The data derived from observations at station 2 are based upon a series of considerable length, this being a control station for this area.

Similarly, the strength of ebb appears to be rather uniform for all depths at a majority of these stations or even to increase somewhat as the depth increases, notably at the control station No. 2. On the flood, the nontidal water or fresh-water run-off 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 obtained at some distance from the surface. Again, as the effect of the nontidal water diminishes with depth, the time of slack water before flood advances, as shown by the data in Table 33 for the representative mid-channel stations 2, 3, and 7, stations where fresh-water run-off is mainly encountered.

In consequence of the diminution of the flood strength near the surface by fresh water, and increase in the duration of the flood period may be expected with increased depth. This is clearly shown in Table 33 by the current data for the mid-channel stations 2, 3, and 7, referred to above. It will be noted that at the control station (station 2) the ebb runs about 20 minutes longer than the flood at the surface; at the middle depth (24 feet) the flood runs about 20 minutes longer than the ebb; while at the bottom depth (38 feet) the flood runs about 50 minutes, or nearly an hour, longer than the flood.

At station 3 the flood runs longer than the ebb by nearly two hours at the surface while at the bottom depth (40 feet) it runs three and three-fourths hours longer than the ebb. While the flood runs but a few minutes longer than the ebb at the surface at station 7, it runs an hour longer at the bottom depth, 48 feet. It will be further noted from the data in Table 33 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.

That the current in this portion of Portsmouth Harbor is rather irregular is indicated by notes from the current record of observations made at station 4 (fig. 9) in September, 1898, which state that the current was continually changing in direction from flood to ebb, as indicated by the swinging of the observing vessel while at anchor on station. It is possible, however, that the vessel was located in an eddy.

PORTSMOUTH HARBOR, VICINITY OF PORTSMOUTH, N. H.

This section of Portsmouth Harbor includes that portion of the Piscataqua River and its branches from the vicinity of Sullivan Point, Seavy Island, to the Portsmouth water front southwest of Badgers Island, a distance of about 1½ nautical miles. The prominent islands in this area—Seavy, Badgers, Newcastle, Goat, Marvin, and Pierces—have all been connected to the Maine and New Hampshire mainlands by means of bridges and breakwaters. No observations are available in the office of the Coast and Geodetic Survey for that shoal and little-used portion of Portsmouth Harbor south of the connected islands—Marvin, Goat, and Newcastle.

Most of the commerce in this section of Portsmouth Harbor follows the Piscataqua River proper, where mid-channel depths of over 60 feet are found. The approach to Kittery, Me., is in the narrow channel between Badgers and Squash Islands on the northwest and Pumpkin Island on the southeast. This channel as well as the one north of Seavy Island is used only by vessels of light draft.

Figure 10 shows the locations of 14 current stations occupied in this portion of Portsmouth Harbor by the following field parties of the United States Coast and Geodetic Survey: P. A. Welker, in 1898; W. E. Parker, in 1903; J. H. Hawley, in 1919; and R. W. Woodworth, in 1926. Observations at a majority of these stations were made in the summer of 1926, when an extensive tide and current survey of Portsmouth Harbor and its tributaries was made.

The control station for current stations occupied in this portion of Portsmouth Harbor in 1926 was station 2 of the preceding section (referred to above), located in mid-channel off Salamander Point in the vicinity of Newcastle, where continuous current observations by means of current pole and log line and also by current meter were made for a total of 11 days from August 16 to 27.

The data derived from observations at the 14 current stations in the vicinity of Portsmouth, N. H., are given in Table 34. 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. At station 11, however, located just north of the bridge connecting Pierces Island with the Portsmouth water front, it was impossible to use a current pole, owing to the congestion of boats at anchor in the stream. The current data for this station, therefore, are derived from meter observations at a depth of 5 feet.

The times of slack water and strengths of flood and ebb in Table 34 are given in hours and tenths of hours and are referred to the times of predicted slack water at Portsmouth Harbor Entrance (off Whaleback Reef Light), one of the standard reference stations for which full predictions for every day in the year are given in the Atlantic Coast Current Tables.

The durations of flood and ebb are also given in hours and tenths of hours. 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°.

Most of the current stations in this section of Portsmouth Harbor were located in mid-channel either in the Piscataqua River or in the channels leading northward and southward from the river proper.

In general, it will be noted from the table that at the mid-channel stations (stations 1, 3, 6, 7, 8, 9, and 14) slack water before flood occurs about 10 minutes later than the time of the corresponding slack water at the entrance to the harbor, while slack water before ebb occurs about 25 minutes later than the corresponding slack at the reference station off Whaleback Reef Light. Nearer the shores of a stream where shallow water prevails the current generally turns earlier than it does in mid-channel. This is indicated by flood observations at stations 4, 5, 12, and 13 and by ebb observations at stations 5 and 12. It will be noted from the data in Table 34 that at station 5, located in the narrow channel connecting the Piscataqua River with the great shoal body of water lying to the southward, the current turns nearly one and one-half hours earlier than it does at the entrance to Portsmouth Harbor on both the flood and the ebb.

It is interesting to note that the time of current at stations 9 and 10, off Seavy Island Navy Yard, is practically simultaneous, although the latter station is located in rather shoal water. The results are rather well determined, the series of observations being of two days' length at each station. While slack water is but 10 minutes earlier at station 10 than it is at station 9, the times of strength of current appear to be simultaneous.

At station 11, located in mid-channel north of the bridge connecting Pierces Island with the Portsmouth water front, the current conditions are very peculiar. The data for this station are comparable with those for station 9, located in mid-channel in the Piscataqua River, since observations were made simultaneously at both stations, August 19 to 20, 1926. Slack water before flood at station 11 occurs 0.9 hour, or about 55 minutes, later than it does at station 9, while there is little difference in the time of ebb at both stations. The strength of flood at station 11 likewise occurs an hour later than it does at station 9. The flood at station 11 sets northerly and the ebb southerly. On account of Pierces Island, a natural obstruction to the progression of the tidal current, the water flowing northerly at station 11 must have entered the shoal area in the vicinity of Little Island (see fig. 10) either from the narrow passage between Pierces and Marvin Islands or from the narrow channel between Marvin Island and Frame Point.

Referred to the times of local tides, slack water before flood at station 11 occurs three hours after low water, or about the time of mean tide level, when there is no interference to the flood entering the narrow passage between Pierces and Marvin Islands, since there is approximately 4 feet of water at that point at that time. Strength of flood at this station occurs one hour before high water, when there is approximately 8 feet of water in the above-mentioned passage. Slack before ebb occurs two hours after local high water, or near the time of mean tide level.

The current continues to ebb, or run southerly, at station 11, but at the same time the tide is falling, and at the time of mean low water the passage between Pierces and Marvin Islands dries. The water level in the Piscataqua River proper continues to fall until the water in the vicinity of Little Island is higher than that in the former locality. The water in the vicinity of Little Island therefore flows northward, making a secondary flood condition at station 11, and empties into the Piscataqua River.

Current conditions at station 11 are quite irregular, for while there is no apparent interference to the flood there is considerable interference to the ebb, at least under average tidal conditions such as obtained when currents were observed at this station in August, 1926. The data in Table 34 would give a flood duration of 5.3 hours, but the results of the above-mentioned observations indicate that the northerly current at station 11 obtains for about 10½ hours out of the half-tidal day of 12 hours 25 minutes. A considerable amount of this flood is really due to interference with the ebb as described above. The ebb at this station is very weak, having a velocity of about ¼ knot.

It will be noted from the data in Table 34 that there is very little difference in the time of current in mid-channel in this 1½-mile stretch of the Piscataqua River. This fact is evident from a comparison of the data for stations 1, off Sullivan Point, and 14, off Badgers Island, the results showing that the time of current at the latter locality occurs about 15 minutes later than it does off Sullivan Point.

At most of the mid-channel stations in this section of Portsmouth Harbor the duration of ebb is somewhat longer than that of flood.

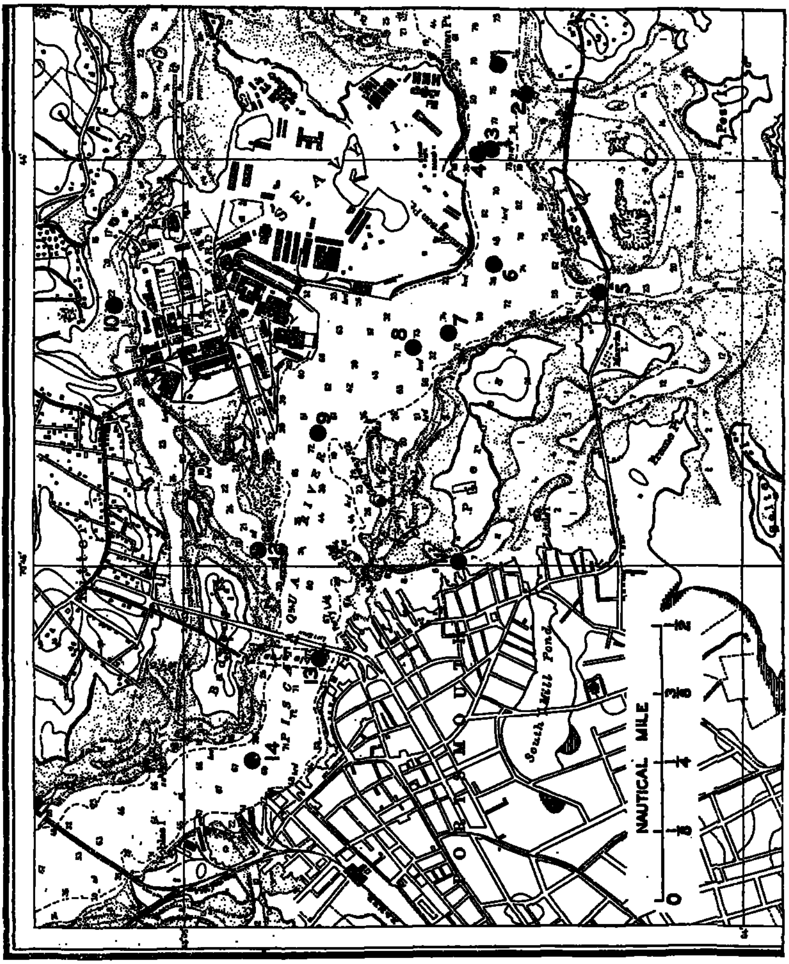

FIG. 10.—Current stations, Portsmouth Harbor, vicinity of Portsmouth, N. H.

This is likewise true at the smaller channel stations 5 and 10, shown in Figure 10. At some stations, however, flood runs longer than ebb. This is most likely due to the locations of these stations.

The tidal current in the Piscataqua River has considerable velocity especially in places where the channel is constricted. Average flood strengths of 3½ knots and average ebb strengths of 4 knots may be encountered in the river in the vicinity of Sullivan and Henderson Points, Seavy Island, and west of Badgers Island, as shown by the data in Table 34 for stations 1, 2, 3, 6, 7, 8, and 14. During spring tides currents of 5 to 6 knots may be encountered in this section of Portsmouth Harbor. The average strengths of flood and ebb at the mid-channel stations 1, 3, 6, 7, 8, 9, and 14 are 2.9 and 3.1 knots, respectively.

At the eight current stations occupied by the field party of R. W. Woodworth in 1926 in this section of Portsmouth Harbor, observations of subsurface currents were also made by means of a Price current meter with telephone attachment. These observations were made at three depths—0.2, 0.5, and 0.8 of the depth at each station with the exception of station 11, where a mean low water depth of but 10 feet obtained. The results of these observations are given in Table 35. The velocities of flood and ebb have been reduced to a mean range of tide and are given to the nearest hundredth of a knot for comparative purposes. The times of the current for each depth at each station are referred to the times of predicted slack water at Portsmouth Harbor entrance (off Whaleback Reef Light). The durations of flood and ebb as well as the times of current at each station are given to the nearest hundredth of an hour, also for comparative purposes, and the directions of the current at flood and ebb strengths are given to the nearest degree.

At stations 3, 9, 10, and 14 currents were observed at half-hour intervals for 50 consecutive hours, while at stations 5, 7, 11, and 12 (fig. 10) currents were observed for 25 consecutive hours. The mid-channel station off Salamander Point, Newcastle Island (station 2 of Tables 32 and 33), was the control station for this portion of the harbor current survey of 1926, and continuous observations were obtained at this station for 11 days from August 16 to 27, 1926. At all these stations the current is of the reversing, or rectilinear, type.

In addition to the subsurface velocity observations at each station, subsurface current directions were also observed at stations 5 and 10 by means of a bifilar suspension current-direction indicator. While the subsurface directions of the ebb, or northerly stream, at station 5 are rather uniform, those of the flood differ considerably. The flood at the bottom depth (20 feet) appears to set about 20° farther south than that near the surface. At station 10, in the channel north of Seavy Island, the subsurface directions of flood and ebb appear to be rather uniform, like those near 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. The data for the eight stations in Table 35 agree rather closely with this general statement. At all these stations the ebb decreases with increased depth, especially at the mid-channel stations in the Piscataqua River. Such decreases in velocity at stations 7, 9, and 14 are 15 ,13, and 12 per cent, respectively, for currents near the bottom of the river as compared with currents near the surface. At stations 12 and 10, in the channel northeasterly from Seavy Island, the velocity of the ebb, or easterly, stream decreases from the surface to the bottom by approximately 35 and 10 per cent, respectively.

On the flood, however, as illustrated by the data in Table 35 for stations 3 and 7, the velocity may show an increase from the surface downward for a considerable depth, or be rather uniform in velocity. At all depths at station 5 the flood, or southerly stream, is about twice as great in velocity as the ebb. At station 7 the flood current exceeds the ebb in velocity at all depths. Generally, however, the flood, like the ebb, decreases as the depth increases. At the mid-channel stations 9 and 14 such decreases in flood velocities are 9 and 4 per cent, respectively, for currents near the bottom as compared with currents near the surface. At station 12 this decrease is about 15 per cent. At mid-channel stations 3 and 7 there appears to be little, if any, decrease in flood velocity with increased depth. Ebb velocities at all depths are likewise rather uniform at station 3, south of Seavy Island.

PISCATAQUA RIVER AND TRIBUTARIES

The area covered by this section of Portsmouth Harbor is that above the city of Portsmouth, N. H., and comprises the Piscataqua River and its tidal tributaries such as Little Bay, Furber Strait, Great Bay, Bellamy River, Oyster River, and Exeter River—a drainage area of considerable extent. About 4 miles above Portsmouth, in the vicinity of Dover Point, the Piscataqua River is formed by two branches or forks—a northerly and a westerly branch. The natural channel of the river is wide and deep from Portsmouth to Dover Point, depths from 40 to 65 feet obtaining. The river varies in width from less than an eighth of a mile south of Spinney Creek entrance to more than half a mile in the vicinity of Frankfort Island and Mast Cove.

North of Dover Point the river, especially in the channel narrows considerably, and mean low-water depths of about 20 feet obtain. West of the railroad drawbridge at Dover Point, however, the channel is wide and deep, and depths of 35 to 65 feet may be carried for 5 miles to the vicinity of Furber Strait, which connects Little Bay with Great Bay. Little Bay is really only a wide stretch of waterway about 2 miles long from Fox Point to Adams Point, where the river has a width of about three-fourths of a mile. Great Bay, about 3½ miles in width, is very shoal.

Figure 11 shows the locations of seven current stations occupied in this portion of Portsmouth Harbor, as follows: Atlantic Corporation Shipyard, in 1919; and a field party of the United States Coast and Geodetic Survey in charge of R. W. Woodworth, in 1926. All stations, with the exception of station 2, were occupied by the latter field party.

Observations at station 2, made in the Piscataqua River in April to June, 1919, off the Atlantic Corporation Shipyard by officials of that concern, consist only of slack-water determinations. During this interval of time 37 ebb-slack observations were obtained and but 1 flood-slack observation.

Station 1 was located at the railroad drawbridge northwest of Nobles Island. Current conditions are rather peculiar at this locality in that the flood direction is northeasterly and the ebb southerly. This is due to the fact that a part of the flood which progresses northwesterly in the Piscataqua River off Portsmouth passes around Nobles Island to the southward and then rejoins the main flood in the river north of station 1.

The data derived from current observations at these seven stations in Portsmouth Harbor are given in Table 36. 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.

The times of slack water and strengths of flood and ebb in Table 36 are given in hours and tenths of hours and are referred to the times of predicted slack water at Portsmouth Harbor entrance, one of the standard reference stations for which full predictions for every day in the year are given in advance annually in the Atlantic Coast Current Tables.

The durations of flood and ebb are also given in hours and tenths of hours. 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°.

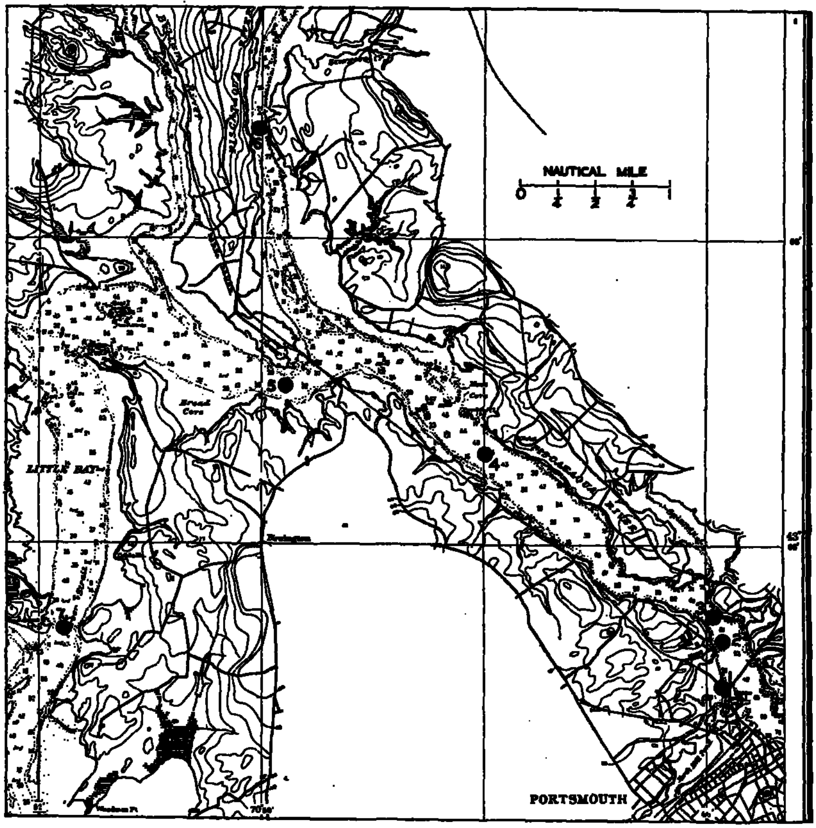

FIG. 11.—Current stations, Piscataqua River and tributaries

Stations 3, 4, 5, 6, and 7 were located in mid-channel, and at the first three stations continuous observations were made half-hourly for 52 hours. At stations 1, 6, and 7 observations were made for 26 hours.

At most of the stations in this section of Portsmouth Harbor slack water before ebb occurs from 10 to 30 minutes later than it does at Portsmouth Harbor entrance. This is likewise true of slack water before flood. However, at station 6, south of Sturgeon Creek entrance and about 10 miles above the entrance to the harbor, the current turns about 10 minutes earlier on both flood and ebb than it does at the latter place.

At stations 1, 2, and 6 the duration of ebb greatly exceeds that of flood, while at stations 3, 4, 5, and 7 the durations of flood and ebb are approximately equal. It will also be noted from the data in the table that while the ebb is greater in velocity than the flood at each station with the exception of station 1 the excess velocity in each case is rather small.

Regarding velocities, strong ebbs and floods are found at stations 3 and 5 owing to constrictions in the river at these points. The comparatively small velocities at stations 1 and 6 are chiefly due to their locations. The small ebb velocity at station 1 may be attributed to the prominent point to the northward, in the vicinity of the Atlantic Corporation Shipyard, which deflects the ebb to the eastward. Since the mean low water depth at station 1 was but 6 feet, it was necessary to use a short current pole instead of the standard 15-foot current pole.

At five of the current stations occupied by the field party of R. W. Woodworth in 1926, the mid-channel stations 3, 4, 5, 6, and 7, observations of subsurface currents were also made by means of a Price current meter. 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 37. The velocities of flood and ebb have been reduced to a mean range of tide and are given to the nearest hundredth of a knot for comparative purposes. The times of the current for each depth at each station are referred to the times of predicted slack water at Portsmouth Harbor entrance (off Whaleback Reef Light). The durations of flood and ebb as well as the times of current at each station are given to the nearest hundredth of an hour, also for comparative purposes, and the directions of the current at flood and ebb strengths are given to the nearest degree.

Owing to the great ebb velocities at station 5, no meter observations were obtained near the time of strength of the ebb current. The mean low water depth at this station averaged about 20 feet, but in spots depths up to 40 feet obtained because the observing vessel swung to considerable anchor chain. Whenever possible, meter readings at a depth of 25 feet were obtained, but the results of these observations checked quite closely with those obtained at a depth of 16 feet, which are given in the table. Currents were observed at this station, and also at stations 3 and 4, half-hourly for 52 consecutive hours. Stations 6 and 7 were occupied for 26 hours. At all of these stations the current is of the reversing, or rectilinear, type and is of considerable velocity.

The results of observations for station 7, in Furber Strait, are of interest in that the time of slack water on both flood and ebb is practically simultaneous at all depths. The time of strength of current, however, appears to become earlier as the depth increases. Again, the velocities of flood and ebb appear to be uniform at all depths, the ebb being but slightly stronger in velocity than the flood.

The same characteristics of the current are present to a certain extent at station 4, in the Piscataqua River, where the times at slack before ebb at all depths, and likewise the times of strength of ebb, are practically simultaneous. This condition is not apparent on the flood, the times of slack before flood and strength of flood generally becoming earlier as the depth increases.

The times of slack before flood at station 6 increase considerably with depth, the change from ebb to flood occurring an hour earlier at the bottom depth than it does at the surface. On the other hand, there is little difference in the time of slack before ebb at all depths at this station. There is likewise a diminution in the velocity of current at time of strength, especially on the ebb. This advancement of time of slack water with increased depth and difference in the vertical distribution of the current velocity is evidently due to the nontidal or fresh-water discharge from the Piscataqua and Salmon Falls Rivers. 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.

It will be noted in the data for station 6 in Table 37 that, while the ebb runs more than a half-hour longer than the flood at the surface, the flood runs nearly half an hour longer than the ebb at the middle depth and nearly one and one-half hours longer than the ebb at the bottom depth. Under normal conditions this is characteristic of a current station located in a river where considerable fresh-water run-off obtains.

On comparing the data for stations 3 and 4 it appears that the duration of ebb at all depths at station 3 is greater than that of flood, while at station 4, also in mid-channel and 2 miles farther upstream, the opposite is true. The latter condition is likewise true at stations 5 and 7.

In addition to the subsurface velocity observations at station 4, subsurface current directions were also observed by means of a bifilar current-direction indicator. At this station the direction of the current at time of strength appears to be rather uniform at all depths. Continuous bifilar observations were not made at stations 3 and 5, owing to the strong velocities of the current at time of strength.

CURRENT DIAGRAMS

The current movement in Portsmouth Harbor for each hour of the tide at Portsmouth, N. H., is represented diagrammatically in Figures 12 to 23, which are based primarily upon observations made in 1926. The general direction in which the current is flowing is represented by arrows and the average velocities in knots and tenths of knots by small figures accompanying the arrows. At times of spring and perigean tides the velocities will usually be greater and at times of neap and apogean tides less than indicated. Winds and other meteorological conditions may also affect both the velocity and direction of the current.

It will be noted from Figures 12 to 23 that the strengths of flood and ebb, or times of maximum current in this waterway, occur about five hours after the time of local low water and high water, respectively, or near the times of high and low water. The direction of the flood in Portsmouth Harbor and the Piscataqua River is northerly and westerly, while in Furber Strait and also in the channel between Marvin and Goat Islands it is southerly.

The average velocity of flood and ebb in mid-channel at the harbor entrance is about 1 to 1½ knots. Off Fort Point it increases to approximately 2 knots. Strong average velocities of 3 to 4 knots obtain south of Seavy Island and between Badgers Island and the Portsmouth water front, while average velocities of 3½ to 4½ knots occur in the Piscataqua River off the Atlantic Corporation Shipyard and also in the vicinity of Dover Point.

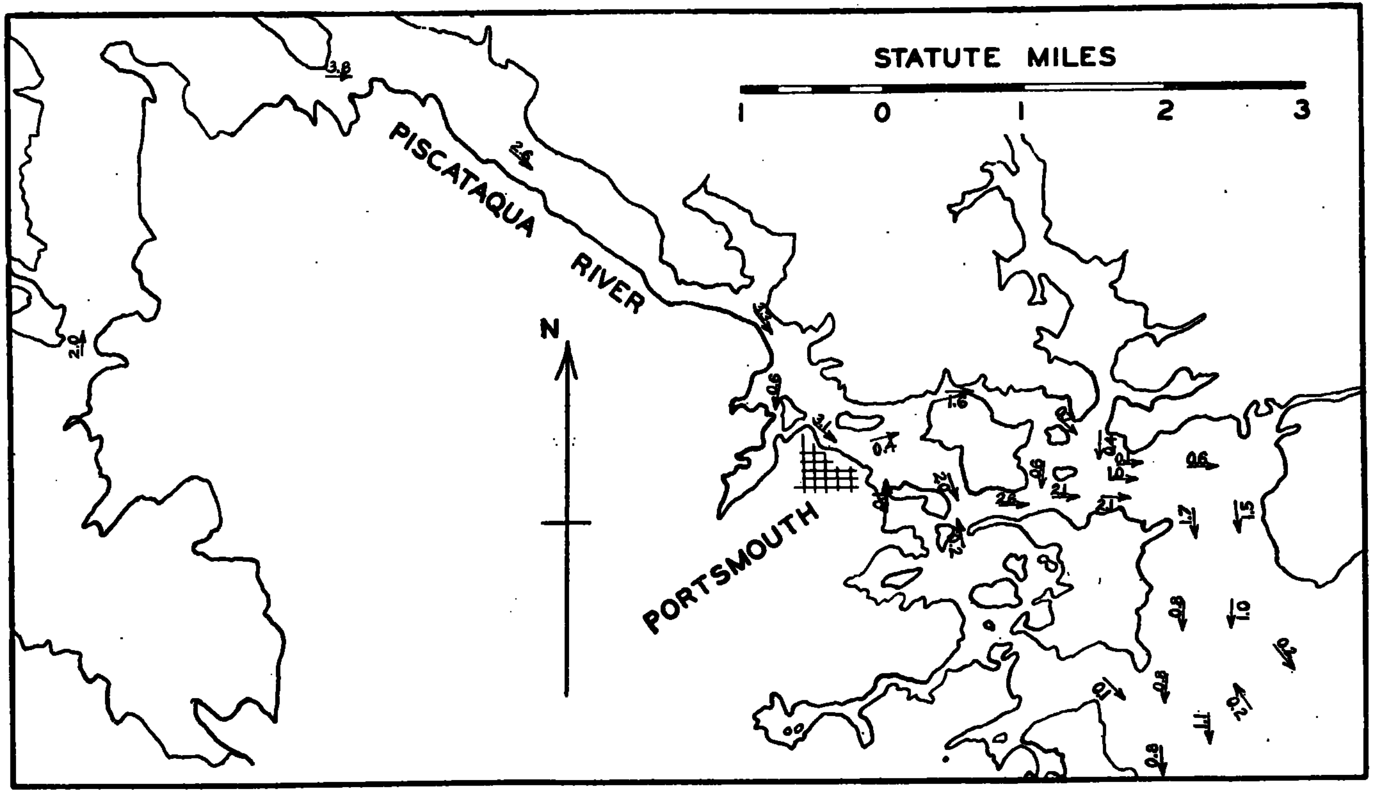

Fig. 12.—Currents at time of low water at Portsmouth, N. H.

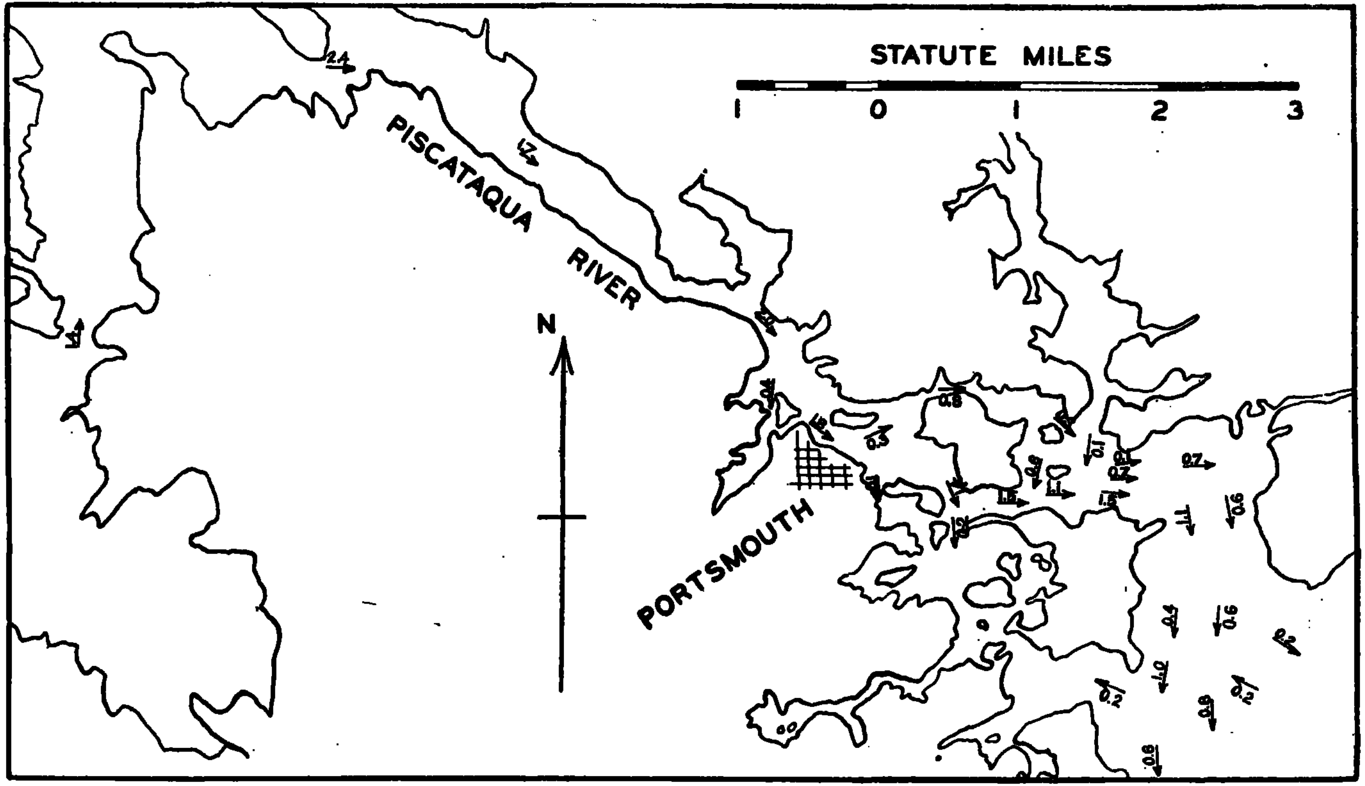

FIG. 13.—Currents one hour after low water at Portsmouth, N. H.

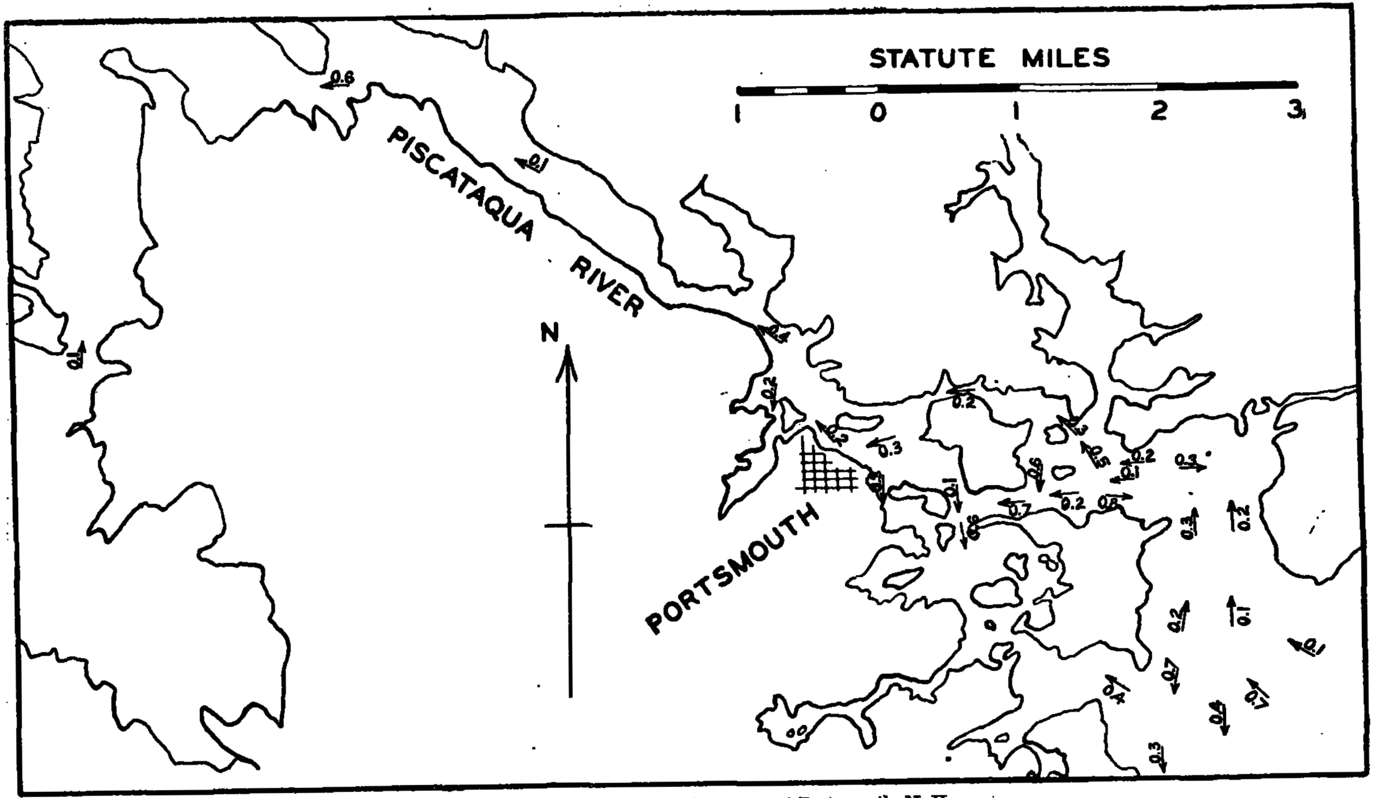

Fig. 14.—Currents two hours after low water at Portsmouth, N. H.

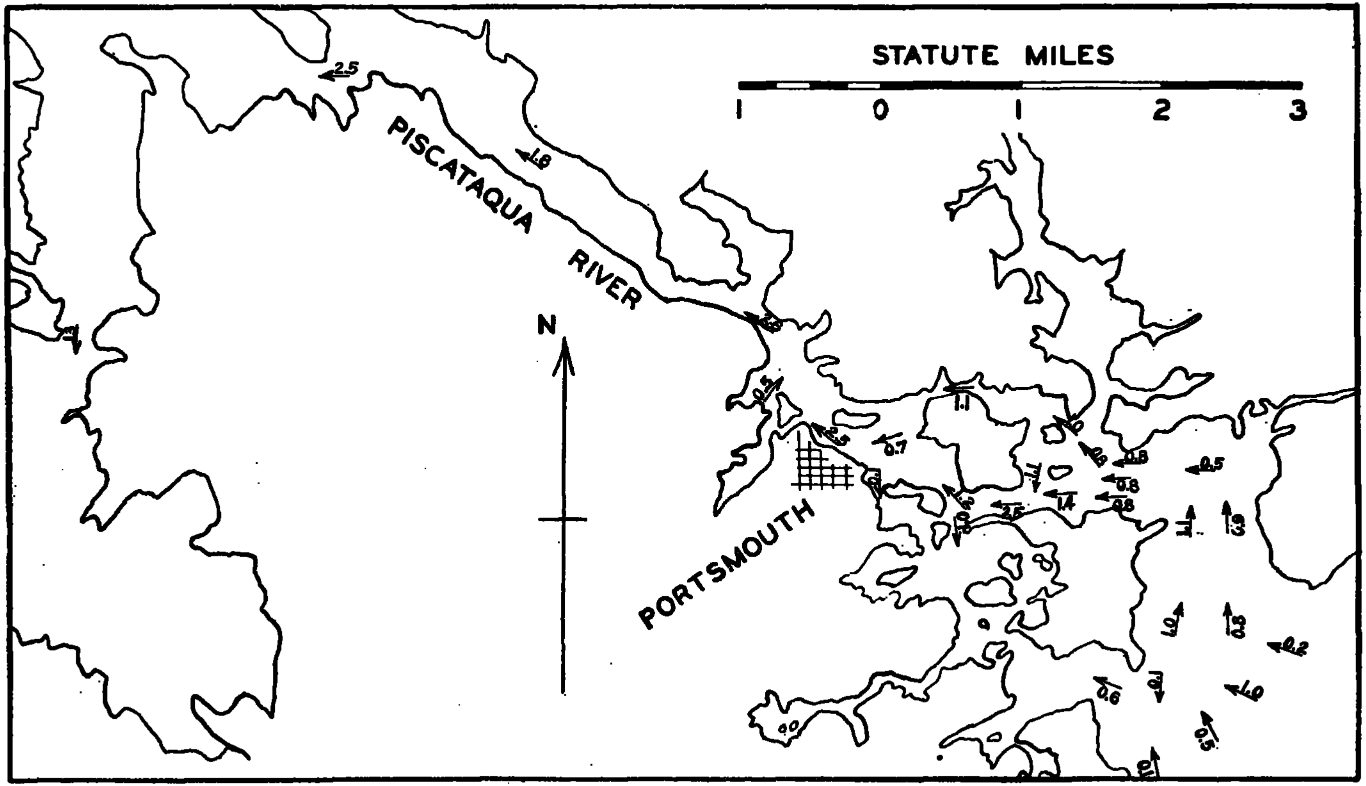

FIG. 15.—Currents three hours after low water at Portsmouth, N. H.

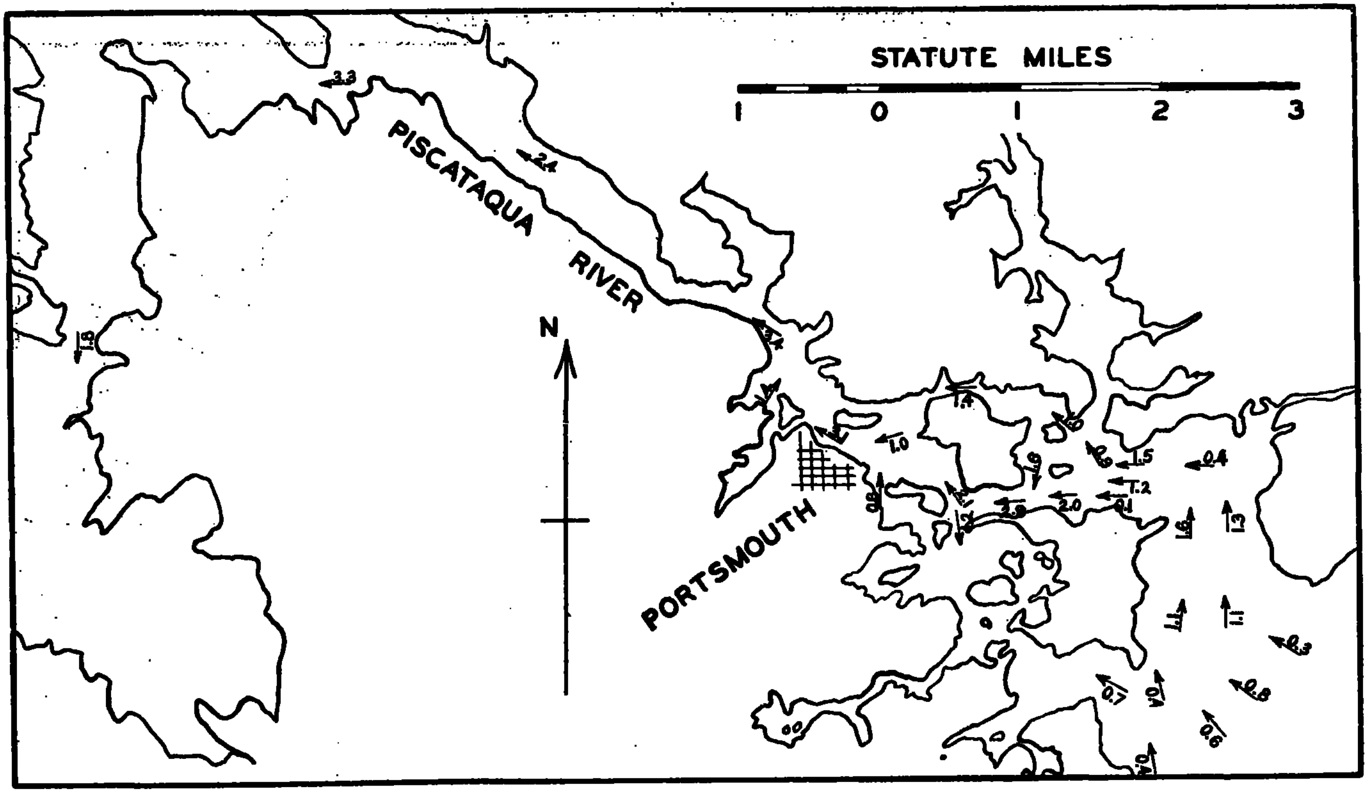

FIG. 16.—Currents four hours after low water at Portsmouth, N. H.

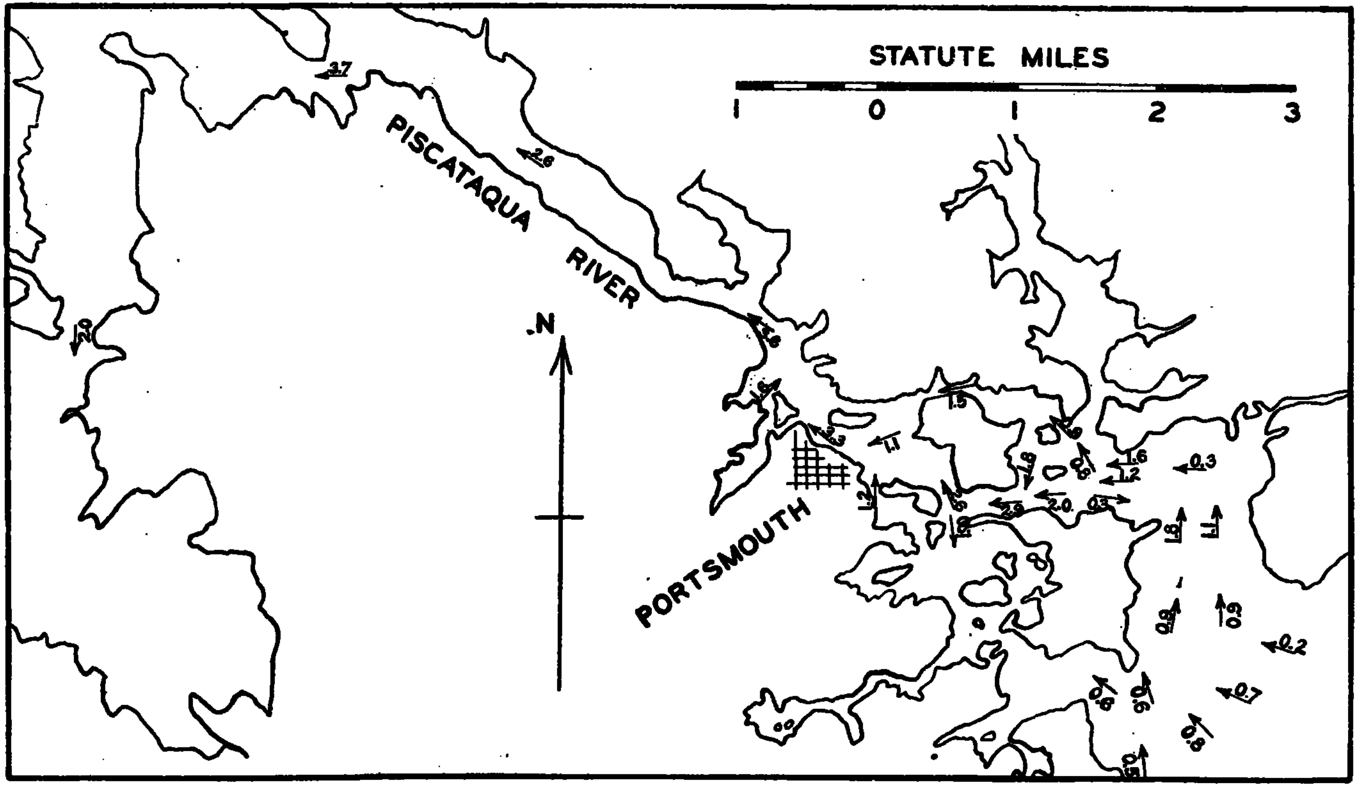

FIG. 17.—Currents five hours after low water at Portsmouth, N. H.

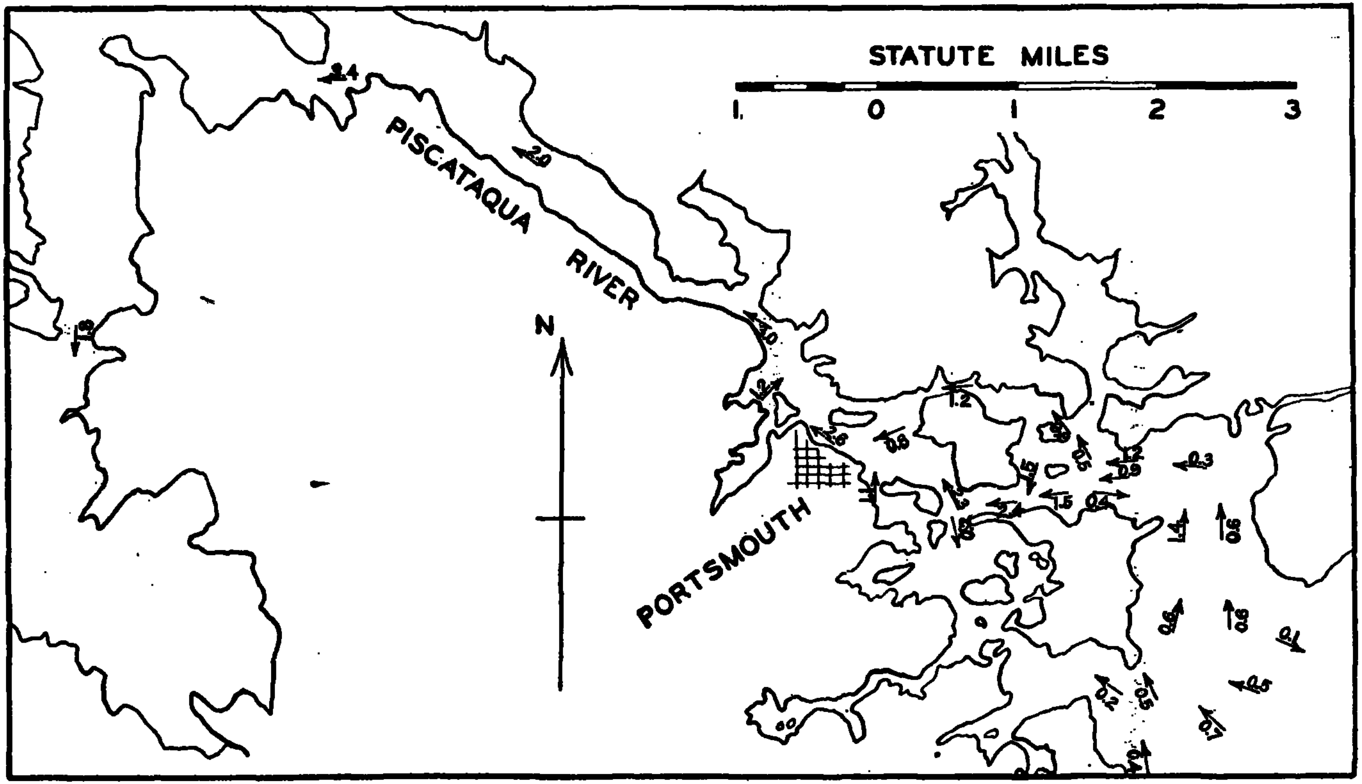

FIG. 18.—Currents at time of high water at Portsmouth, N. H.

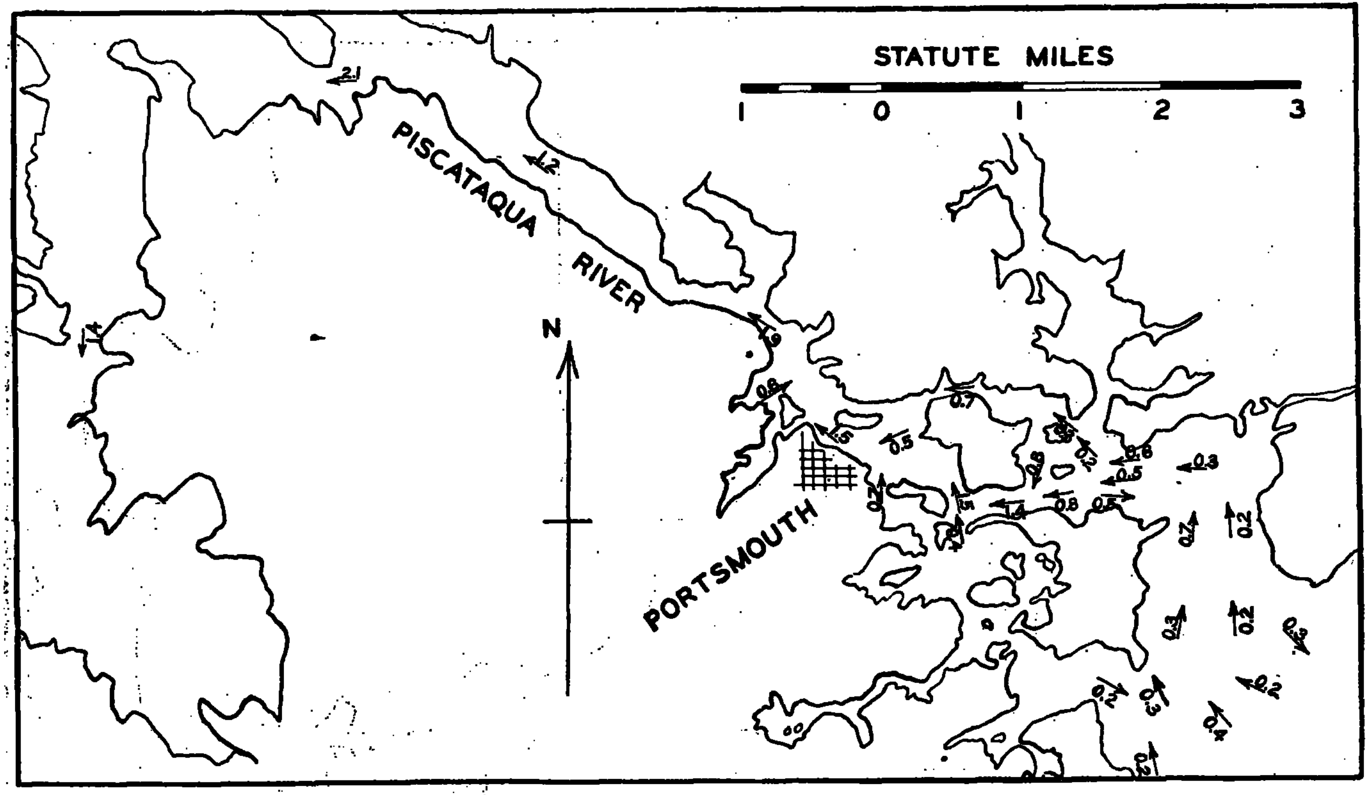

FIG. 19.—Currents one hour after high water at Portsmouth, N. H.

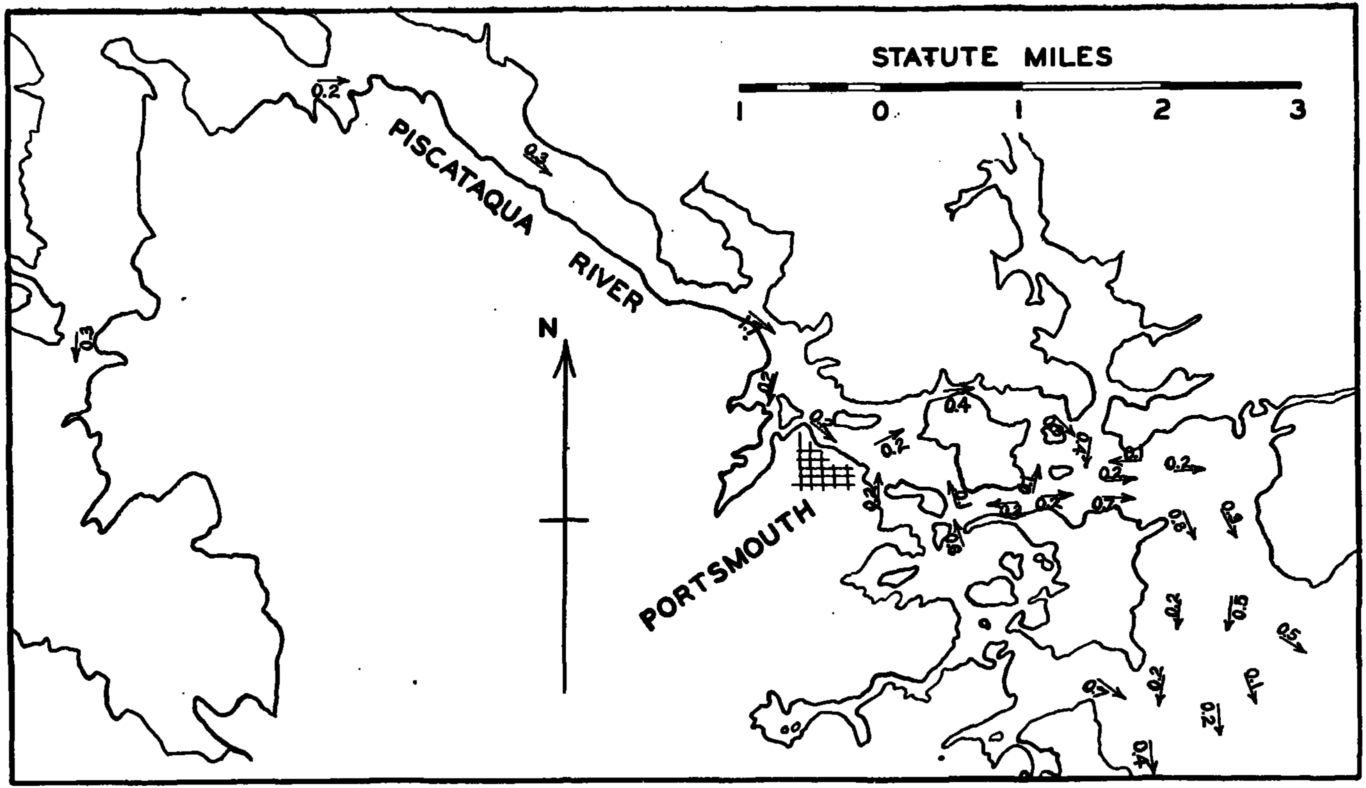

Fig. 20.—Currents two hours after high water at Portsmouth, N. H.

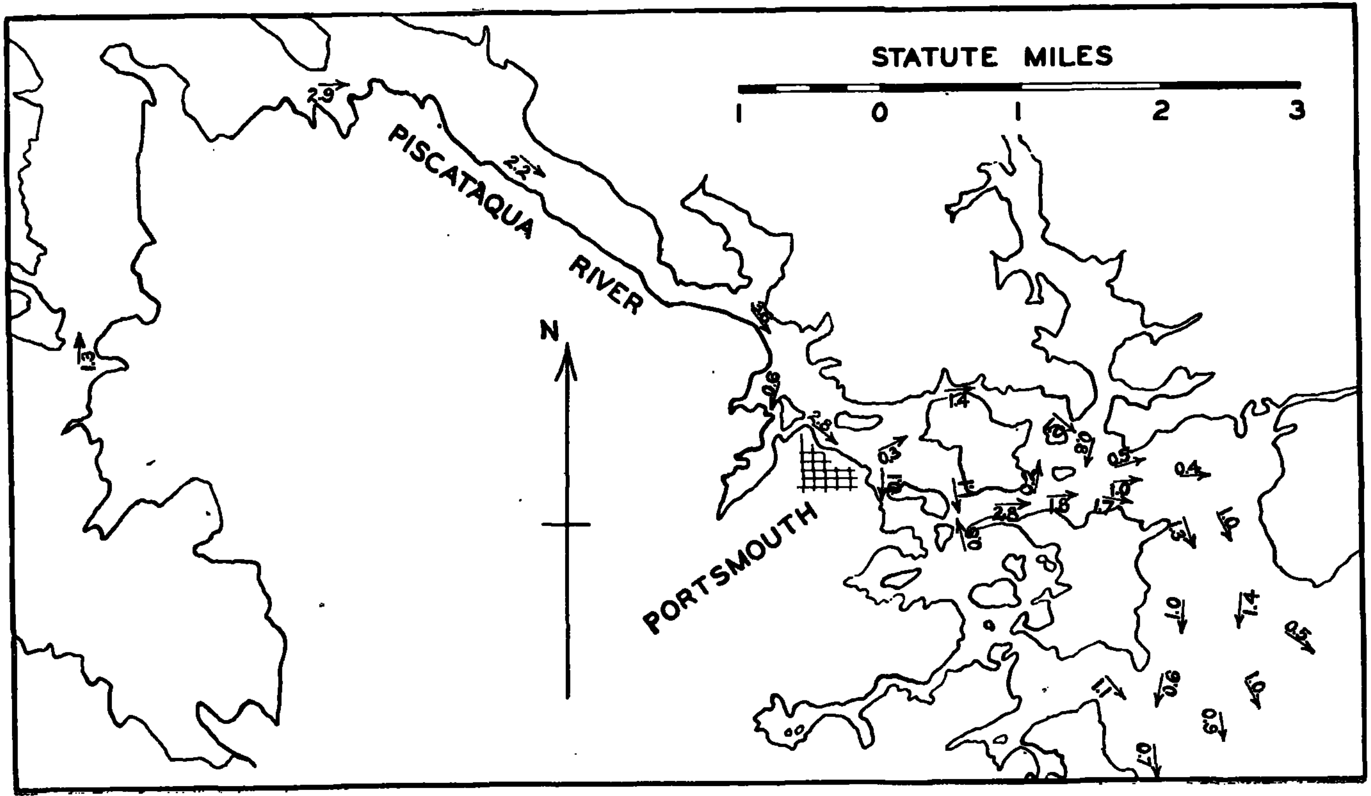

Fig. 21.—Currents three hours after high water at Portsmouth, N. H.

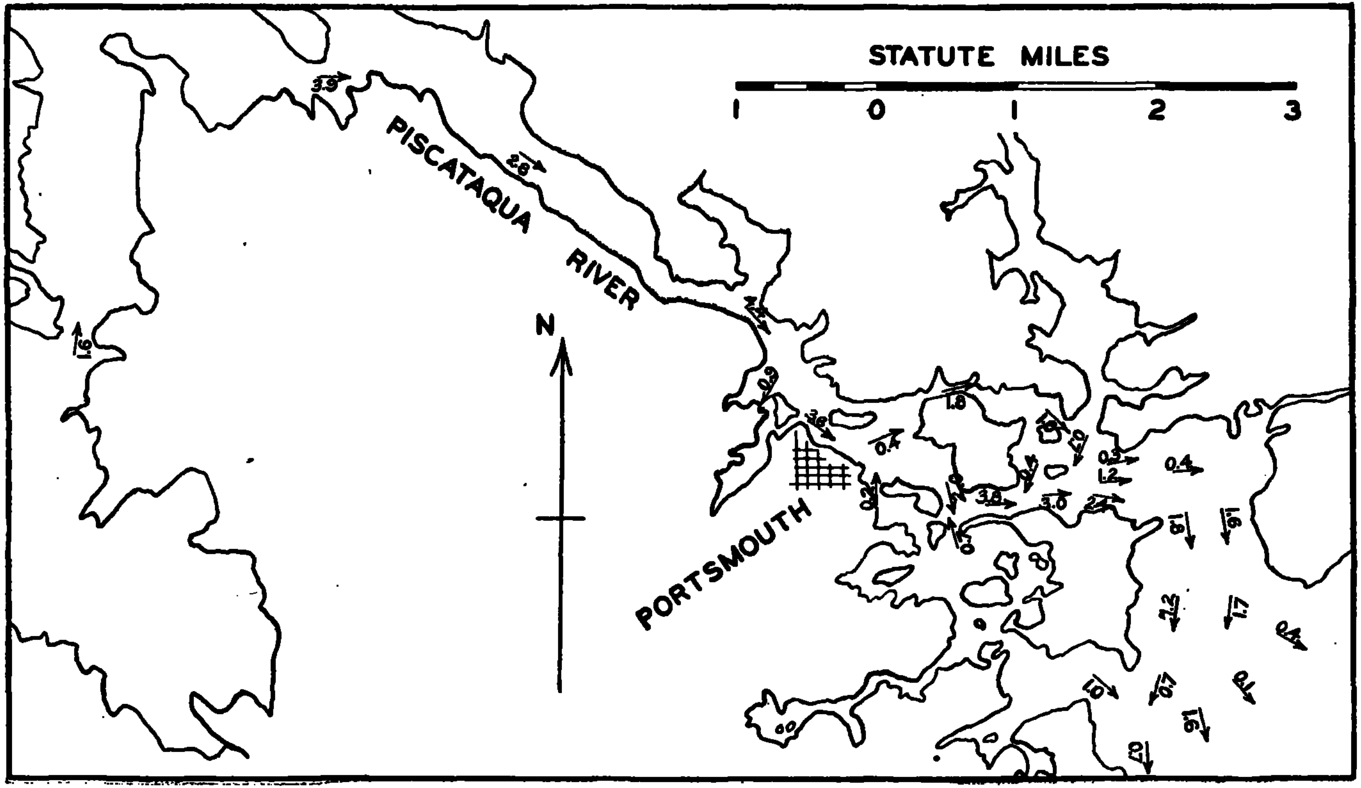

Fig. 22.—Currents four hours after high water at Portsmouth, N. H.

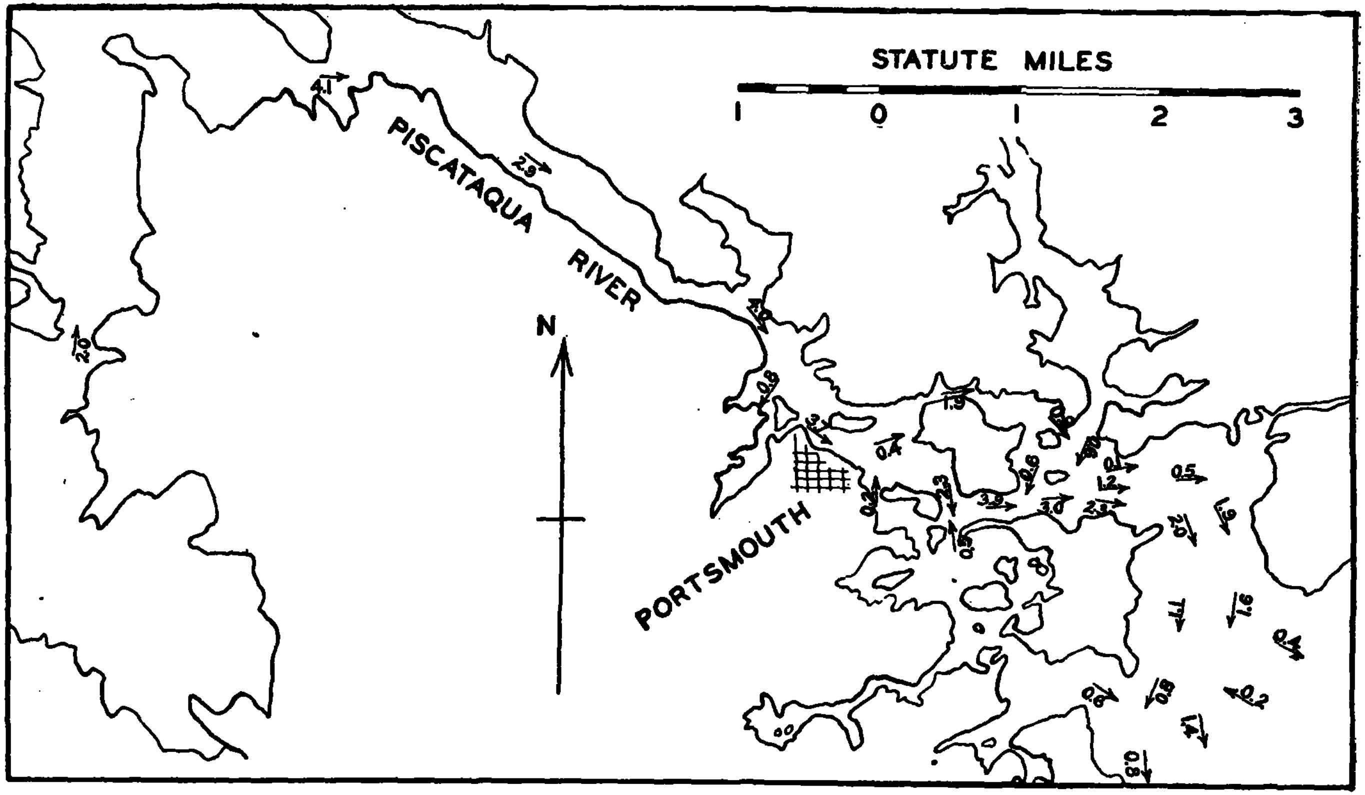

FIG. 23.—Currents five hours after high water at Portsmouth, N. H.

TABLE 1.—*High and low waters at Portland, Me., August, 1926*

Date	Moon's transit, meridian of Greenwich	Time of—		Lunitidal interval		Duration of—		Height of—		Range	
		High water	Low water	High water	Low water	Rise	Fall	High water	Low water	Rise	Fall
	Hours	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Feet*	*Feet*	*Feet*	*Feet*
Aug. 1	6.3	4.7	11.0	(10.9)	4.7		6.3	17.5	8.5		9.0
	(18.7)	17.3	23.5	11.0	(4.8)	6.3	6.2	17.9	8.5	9.4	9.4
2	7.1	6.0	11.8	(11.3)	4.7	6.5	5.8	16.9	8.9	8.4	8.0
	(19.5)	18.3		11.2		6.5		17.8		8.9	
3	7.9	6.7	0.5	(11.2)	(5.0)	6.2	6.2	16.8	8.8	8.0	9.0
	(20.3)	19.2	12.6	11.3	4.7	6.6	5.9	18.1	9.4	8.7	7.4
4	8.8	8.0	1.5	(11.7)	(5.2)	6.5	6.3	16.7	8.6	8.1	9.5
	(21.2)	20.3	13.7	11.5	4.9	6.6	5.7	17.9	9.4	8.5	7.3
5	9.6	9.0	2.5	(11.8)	(5.3)	6.5	6.2	16.7	8.4	8.3	9.5
	(22.0)	21.0	14.7	11.4	5.1	6.3	5.7	17.9	9.3	8.6	7.4
6	10.5	9.7	3.4	(11.7)	(5.4)	6.3	6.4	16.9	8.4	8.5	9.5
	(22.9)	22.0	15.8	11.5	5.3	6.2	6.1	18.0	9.2	8.8	7.7
7	11.3	10.5	4.4	(11.6)	(5.5)	6.1	6.4	16.9	8.5	8.4	9.5
	(23.7)	22.5	16.0	11.2	4.7	6.5	5.5	18.2	9.3	8.9	7.6
8	12.1	10.9	5.0	(11.2)	(5.3)	5.9	6.5	17.1	9.0	8.1	9.2
		23.4	17.0	11.3	4.9	6.4	6.1	17.7	8.7	9.0	8.4
9	(0.5)	11.7	5.5	(11.2)	(5.0)	6.2	6.1	17.4	8.6	8.8	9.1
	12.9		17.6		4.7		5.9		8.9		8.5
10	(1.2)	0.0	6.0	11.1	(4.8)	6.4	6.0	17.7	8.4	8.8	9.3
	13.6	12.5	18.3	(11.3)	4.7	6.5	5.8	17.0	8.9	8.6	8.1
11	(1.9)	0.5	6.7	10.9	(4.8)	6.2	6.2	17.5	8.4	8.6	9.1
	14.3	13.0	18.7	(11.1)	4.4	6.3	5.7	16.9	9.0	8.5	7.9
12	(2.6)	1.0	7.4	10.7	(4.8)	6.3	6.4	17.2	8.3	8.2	8.9
	15.0	13.5	19.5	(10.9)	4.5	6.1	6.0	16.7	9.0	8.4	7.7
13	(3.3)	1.6	8.0	10.6	(4.7)	6.1	6.4	17.0	8.8	8.0	8.2
	15.7	14.4	20.2	(11.1)	4.5	6.4	5.8	16.9	9.2	8.1	7.7
14	(4.0)	2.6	8.6	10.9	(4.6)	6.4	6.0	17.0	9.1	7.8	7.9
	16.4	15.0	21.0	(11.0)	4.6	6.4	6.0	16.9	9.2	7.8	7.7
15	(4.7)	3.3	9.4	10.9	(4.7)	6.3	6.1	16.6	9.1	7.4	7.5
	17.1	15.6	21.6	(10.9)	4.5	6.2	6.0	17.0	9.3	7.9	7.7
16	(5.5)	4.0	10.0	10.9	(4.5)	6.4	6.0	16.2	9.4	6.9	6.8
	17.9	16.5	22.6	(11.0)	4.7	6.5	6.1	17.1	9.3	7.7	7.8
17	(6.3)	5.0	11.0	11.1	(4.7)	6.4	6.0	16.4	9.6	7.1	6.8
	18.7	17.4		(11.1)		6.4		17.4		7.8	
18	(7.1)	6.0	0.0	11.3	5.3	6.0	6.6	16.3	9.4	6.9	8.0
	19.6	18.2	11.8	(11.1)	(4.7)	6.4	5.8	17.6	9.6	8.0	6.7
19	(8.1)	7.0	0.5	11.4	4.9	6.5	6.3	16.6	8.9	7.7	8.7
	20.6	19.3	13.0	(11.2)	(4.9)	6.3	6.0	18.0	9.3	8.7	7.3
20	(9.1)	8.0	1.6	11.4	5.0	6.4	6.3	16.8	8.5	8.3	9.5
	21.6	20.3	14.0	(11.2)	(4.9)	6.3	6.0	18.2	8.9	9.3	7.9
21	(10.1)	8.7	2.6	11.1	5.0	6.1	6.3	17.1	7.7	9.4	10.5
	22.6	21.0	14.5	(10.9)	(4.4)	6.5	5.8	18.6	8.1	10.5	9.0
22	(11.1)	9.6	3.5	11.0	4.9	6.1	6.5	17.6	7.1	10.5	11.5
	23.6	22.0	15.4	(10.9)	(4.3)	6.6	5.8	19.0	7.4	11.6	10.2
23	(12.1)	10.5	4.3	10.9	4.7	6.2	6.3	18.1	6.4	11.7	12.6
		23.0	16.5	(10.9)	(4.4)	6.5	6.0	19.6	7.2	12.4	10.9
24	0.6	11.4	5.0	10.8	4.4	6.4	6.0	18.8	6.5	12.3	13.1
	(13.1)	23.5	17.4	(10.4)	(4.3)	6.1	6.0	19.9	7.3	12.6	11.5
25	1.5	12.3	6.0	10.8	4.5	6.3	6.5	19.0	6.6	12.4	13.3
	(14.0)		18.4		(4.4)		6.1		7.2		11.8
26	2.4	0.4	7.0	(10.4)	4.6	6.0	6.6	19.6	7.0	12.4	12.6
	(14.9)	13.0	19.3	10.6	(4.4)	6.0	6.3	19.0	7.1	12.0	11.9
27	3.3	1.5	7.5	(10.6)	4.2	6.2	6.0	19.0	7.4	11.9	11.6
	(15.7)	14.0	20.0	10.7	(4.3)	6.5	6.0	19.0	7.8	11.6	11.2
28	4.1	2.5	8.5	(10.8)	4.4	6.5	6.0	18.6	8.0	10.8	10.6
	(16.6)	15.0	21.3	10.9	(4.7)	6.5	6.3	18.6	7.9	10.6	10.7
29	5.0	3.3	9.6	(10.7)	4.6	6.0	6.3	18.1	8.6	10.2	9.5
	(17.4)	15.8	22.3	10.8	(4.9)	6.2	6.5	18.4	8.4	9.8	10.0
Sums				619.3	265.8	347.5	342.1	989.4	473.7	506.6	515.7
Means				11.06	4.75	6.32	6.11	17.67	8.46	9.21	9.21
Correction to intervals				+0.15	+0.15						
Corrected intervals				11.21	4.90						

TABLE 2.—*Lunitidal intervals, Portland, Me.: Monthly and yearly means from 1912 to 1919*

HIGH-WATER INTERVALS

	1912	1913	1914	1915	1916	1917	1918	1919
	Hours	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*
January	11.13	11.18	11.13	11.21	11.10	11.09	11.21	11.16
February	11.02	11.05	11.11	11.20	11.27	11.10	11.19	11.12
March	11.08	11.04	11.01	11.09	11.22	11.16	11.14	11.14
April	11.10	11.05	11.01	11.04	11.18	11.14	11.22	11.09
May	11.11	11.23	11.01	11.12	11.12	11.16	11.30	11.14
June	11.16	11.07	11.20	11.18	11.05	11.15	11.14	11.23
July	11.22	11.22	11.16	11.07	11.10	11.23	11.15	11.18
August	11.09	11.09	11.24	11.18	11.12	11.19	11.15	11.22
September	11.30	11.13	11.19	11.17	11.18	11.17	11.08	11.31
October	11.18	11.20	11.23	11.18	11.15	11.27	11.13	11.21
November	11.19	11.19	11.22	11.17	11.13	11.17	11.21	11.22
December	11.15	11.07	11.25	11.12	11.13	11.24	11.21	11.10
Mean	11.14	11.13	11.15	11.14	11.15	11.17	11.18	11.18

Mean of the yearly means, 11.16.

LOW-WATER INTERVALS

	1912	1913	1914	1915	1916	1917	1918	1919
	Hours	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*
January	4.93	4.92	5.02	4.93	4.91	4.94	5.05	4.91
February	4.97	4.91	4.96	4.93	4.96	4.92	5.00	4.90
March	4.93	4.93	4.89	4.85	4.95	4.97	4.91	4.93
April	4.89	4.94	4.89	4.87	4.92	5.00	5.00	4.91
May	4.92	4.95	4.85	4.96	4.91	4.91	4.90	4.83
June	4.92	4.91	4.94	4.75	4.85	4.91	4.83	4.95
July	5.07	4.98	4.93	4.99	4.89	4.90	4.89	4.90
August	5.27	4.93	5.03	4.89	4.94	4.85	4.86	4.96
September	5.27	4.94	5.01	4.90	4.98	5.08	4.92	5.03
October	4.94	4.93	4.94	5.20	4.95	5.12	4.98	5.04
November	4.93	4.98	4.94	5.12	4.94	4.97	4.81	4.95
December	4.96	5.01	4.92	4.90	4.91	4.95	4.91	4.89
Mean	5.00	4.94	4.94	4.94	4.93	4.96	4.92	4.93

Mean of the yearly means, 4.94.

TABLE 3.—*Duration of rise and fall at Portland, Me.: Monthly and yearly means for the years 1912 and 1919*

	Duration of—		Duration of—	
	Rise	Fall	Rise	Fall
	1912		1919	
	Hours	*Hours*	*Hours*	*Hours*
January	6.20	6.22	6.25	6.17
February	6.05	6.37	6.22	6.20
March	6.05	6.37	6.21	6.21
April	6.21	6.21	6.18	6.24
May	6.19	6.23	6.31	6.11
June	6.24	6.18	6.28	6.14
July	6.15	6.27	6.28	6.14
August	5.82	6.60	6.26	6.16
September	6.03	6.39	6.28	6.14
October	6.24	6.18	6.17	6.25
November	6.26	6.16	6.27	6.15
December	6.19	6.23	6.21	6.21
Mean	6.14	6.28	6.25	6.17

TABLE 4.—*Duration of rise and fall at Portland, Me.: Yearly means from 1912 to 1919*

	1912	1913	1914	1915	1916	1917	1918	1919	Mean
	Hours	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*
Duration of rise	6.14	6.19	6.21	6.20	6.22	6.21	6.26	6.25	6.21
Duration of fall	6.28	6.23	6.21	6.22	6.20	6.21	6.16	6.17	6.21

TABLE 5.—*Daily sea level on tide staff, Portland, Me., June, 1919*

Date	Feet	Date	Feet	Date	Feet
June 1	13.56	June 11	12.98	June 21	13.56
June 2	13.61	June 12	12.94	June 22	13.45
June 3	13.56	June 13	13.00	June 23	13.48
June 4	13.41	June 14	13.01	June 24	13.52
June 5	13.58	June 15	13.16	June 25	13.23
June 6	13.39	June 16	13.13	June 26	13.08
June 7	13.57	June 17	13.22	June 27	13.09
June 8	13.49	June 18	13.29	June 28	12.90
June 9	13.31	June 19	13.00	June 29	12.80
June 10	12.51	June 20	13.20	June 30	12.74
Sum	133.99	Sum	130.93	Sum	131.85
Mean	13.40	Mean	13.09	Mean	13.18

TABLE 6.—*Sea level on tide staff at Portland, Me.: Monthly and yearly means*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual means
	Feet	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*
1912	12.72	12.87	12.73	13.07	13.14	13.24	13.32	13.36	13.36	13.14	13.16	12.85	13.08
1913	12.87	12.86	12.64	12.98	13.00	13.21	13.17	13.14	13.01	13.32	13.07	13.09	13.03
1914	13.28	12.81	13.00	12.92	13.07	13.01	13.23	13.19	13.29	13.18	13.12	13.03	13.09
1915	12.96	13.06	13.18	12.92	13.31	13.12	13.29	13.23	13.21	13.17	13.22	13.32	13.17
1916	12.94	13.02	13.07	13.25	13.28	13.39	13.11	13.27	13.16	12.98	13.08	13.01	13.13
1917	13.01	12.97	13.05	13.01	13.42	13.28	13.23	13.22	13.08	13.29	13.11	13.02	13.14
1918	13.30	13.03	13.06	13.12	13.05	13.23	13.18	13.07	13.15	13.08	13.20	13.25	13.14
1919	12.96	13.17	13.08	13.22	13.32	13.24	13.33	13.32	13.29	13.20	13.55	13.10	13.23
1920	13.07	13.04	12.80	13.38	13.15	13.31	13.23	13.16	13.25	13.40	13.21	13.30	13.19
1921	13.25	13.13	12.90	13.09	13.33	13.23	13.17	12.95	13.16	13.22	13.21	13.06	13.14
1922	12.62	12.85	13.00	13.18	12.95	13.10	13.05	13.10	13.04	13.20	13.18	12.96	13.02
1923	13.27	13.06	13.01	13.11	13.12	13.16	13.00	12.98	12.89	13.04	13.20	13.01	13.07
1924	12.76	13.03	13.37	13.17	13.22	13.18	13.06	13.18	13.09	13.09	13.03	12.82	13.08
1925	12.98	12.88	12.87	12.98	13.10	13.10	13.11	12.99	13.06	13.06	12.97	12.88	13.00
Monthly means	13.00	12.98	12.98	13.10	13.18	13.20	13.18	13.15	13.15	13.17	13.16	13.05	13.11

TABLE 7.—*Low water on tide staff at Portland, Me.: Monthly and yearly means*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual means
	Feet	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*
1912	8.23	8.39	8.19	8.57	8.65	8.85	8.88	8.91	9.06	8.79	8.81	8.55	8.66
1913	8.45	8.51	8.27	8.71	8.81	8.90	8.77	8.75	8.62	8.93	8.83	8.79	8.70
1914	9.12	8.47	8.52	8.53	8.66	8.53	8.76	8.69	8.82	9.03	8.98	8.73	8.74
1915	8.60	8.68	8.89	8.45	8.85	8.71	8.88	8.85	8.84	8.80	8.89	8.92	8.78
1916	8.54	8.61	8.56	8.74	8.80	8.95	8.65	8.78	8.71	8.64	8.73	8.62	8.69
1917	8.48	8.50	8.58	8.65	9.06	8.82	8.74	8.67	8.47	8.74	8.73	8.68	8.68
1918	8.84	8.59	8.59	8.67	8.58	8.75	8.67	8.53	8.45	8.60	8.79	8.74	8.65
1919	8.64	8.40	8.66	8.74	8.80	8.80	8.73	8.77	8.78	8.79	9.04	8.69	8.78
1920	8.54	8.45	8.12	8.75	8.54	8.73	8.63	8.60	8.67	8.82	8.64	8.61	8.59
1921	------	8.54	8.30	8.48	8.79	8.67	8.55	8.32	8.54	8.63	8.69	8.57	8.55
1922	8.07	8.25	8.40	8.57	8.38	8.46	8.38	8.41	8.41	8.64	8.69	8.48	8.43
1923	8.87	8.50	8.30	8.41	8.50	8.54	8.39	8.39	8.36	8.47	8.66	8.46	8.49
1924	8.20	8.46	8.77	8.54	8.64	8.62	8.53	8.64	8.37	8.54	8.47	8.26	8.50
1925	8.47	8.33	8.34	8.53	8.66	8.56	8.53	8.38	8.50	8.43	8.46	8.44	8.47
Monthly means	8.54	8.51	8.46	8.60	8.69	8.71	8.66	8.62	8.61	8.70	8.74	8.60	8.62

TABLE 8.—*Low water below sea level, Portland, Me.: Annual means*

Year	Feet	Year	Feet	Year	Feet
1912	4.42	1917	4.46	1922	4.59
1913	4.33	1918	4.49	1923	4.58
1914	4.35	1919	4.45	1924	4.58
1915	4.39	1920	4.60	1925	4.53
1916	4.44	1921	4.59		

Mean, 1912 to 1925, 4.49. Mean, 1913 to 1922, 4.47.

TABLE 9.—*Low water below sea level at Portland, Me.: Annual means corrected for variation in longitude of the moon's node*

Year	Feet	Year	Feet	Year	Feet
1912	4.54	1917	4.48	1922	4.46
1913	4.46	1918	4.47	1923	4.45
1914	4.47	1919	4.38	1924	4.47
1915	4.49	1920	4.50	1925	4.44
1916	4.51	1921	4.46		

Mean, 1912 to 1925, 4.47.

TABLE 10.—*High water on tide staff at Portland, Me.: Monthly and yearly means*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual means
	Feet	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*
1912	17.15	17.31	17.24	17.51	17.57	17.60	17.64	17.47	17.44	17.45	17.50	17.14	17.42
1913	17.29	17.12	16.98	17.28	17.40	17.49	17.51	17.47	17.38	17.73	17.39	17.45	17.37
1914	17.60	17.13	17.45	17.27	17.45	17.45	17.68	17.59	17.64	17.47	17.39	17.26	17.45
1915	17.26	17.38	17.49	17.35	17.64	17.50	17.66	17.62	17.55	17.33	17.46	17.74	17.50
1916	17.40	17.34	17.53	17.68	17.68	17.79	17.46	17.71	17.50	17.33	17.44	17.44	17.52
1917	17.33	17.40	17.49	17.27	17.78	17.67	17.67	17.74	17.49	17.66	17.49	17.35	17.53
1918	17.64	17.39	17.46	17.53	17.42	17.70	17.68	17.37	17.66	17.53	17.56	17.65	17.55
1919	17.33	17.50	17.44	17.67	17.77	17.69	17.79	17.68	17.59	18.03	17.59	17.59	17.66
1920	17.56	17.59	17.42	17.95	17.69	17.84	17.75	17.66	17.28	17.62	17.69	17.86	17.73
1921		17.70	17.44	17.65	17.85	17.74	17.77	17.53	17.73	17.81	17.70	17.49	17.67
1922	17.15	17.45	17.54	17.75	17.51	17.68	17.69	17.75	17.63	17.75	17.64	17.35	17.57
1923	17.65	17.59	17.70	17.26	17.69	17.71	17.58	17.53	17.40	17.57	17.68	17.49	17.61
1924	17.28	17.57	17.96	17.77	17.75	17.67	17.56	17.68	17.76	17.64	17.55	17.39	17.63
1925	17.44	17.40	17.36	17.40	17.51	17.61	17.65	17.54	17.64	17.56	17.47	17.22	17.48
Monthly means	17.39	17.42	17.46	17.56	17.62	17.65	17.65	17.60	17.59	17.60	17.57	17.46	17.55

TABLE 11.—*High water above sea level, Portland, Me.: Yearly means*

Year	Feet	Year	Feet	Year	Feet
1912	4.34	1917	4.39	1922	4.55
1913	4.34	1918	4.41	1923	4.54
1914	4.36	1919	4.43	1924	4.55
1915	4.33	1920	4.54	1925	4.48
1916	4.39	1921	4.53		

Mean, 1912 to 1925, 4.44. Mean, 1913 to 1922, 4.43.

TABLE 12.—*High water above sea level, Portland, Me.: Annual means corrected for variation in longitude of the moon's node*

Year	Feet	Year	Feet	Year	Feet
1912	4.46	1917	4.41	1922	4.42
1913	4.47	1918	4.39	1923	4.41
1914	4.48	1919	4.36	1924	4.44
1915	4.43	1920	4.44	1925	4.39
1916	4.46	1921	4.40		

Mean, 1912 to 1925, 4.43.

TABLE 13.—*Range of the tide, Portland, Me.: Yearly means*

Year	Feet	Year	Feet	Year	Feet
1912	8.76	1917	8.85	1922	9.14
1913	8.67	1918	8.90	1923	9.12
1914	8.71	1919	8.88	1924	9.13
1915	8.72	1920	9.14	1925	9.01
1916	8.83	1921	9.12		

Mean, 1912 to 1925, 8.93. Mean, 1913 to 1922, 8.90.

TABLE 14.—*Range of the tide at Portland, Me.: Annual means corrected for the longitude of the moon's node*

Year	Feet	Year	Feet	Year	Feet
1912	9.01	1917	8.89	1922	8.87
1913	8.92	1918	8.86	1923	8.86
1914	8.95	1919	8.75	1924	8.90
1915	8.92	1920	8.94	1925	8.84
1916	8.96	1921	8.86		

Mean, 1912 to 1925, 8.90.

TABLE 15.—*Harmonic constants, Portland, Me.*

Component	1864-1865		1915		1916		1925		Mean of the 4-year series	
	H	κ	H	κ	H	κ	H	κ	H	κ
	Feet	*Degrees*	*Feet*	*Degrees*	*Feet*	*Degrees*	*Feet*	*Degrees*	*Feet*	*Degrees*
J_1	(0.027)	(141.9)	(0.029)	(140.8)	(0.025)	(142.4)	(0.028)	(140.7)	(0.027)	(141.4)
K_1	0.473	131.5	0.452	132.0	0.452	132.7	0.457	131.3	0.458	131.9
K_2	0.221	357.6	0.192	351.2	0.154	357.5	0.211	0.1	0.194	356.6
L_2	0.232	21.2	0.141	355.6	0.118	23.0	0.151	3.7	0.160	10.9
M_1	0.027	141.7	0.009	122.3	0.013	115.2	0.018	147.3	0.017	131.6
M_2	4.341	323.5	4.385	324.3	4.408	324.0	4.336	322.4	4.368	323.6
M_3	0.005	293.6	0.008	170.1	0.005	186.4	0.004	322.8	0.006	243.2
M_4	0.034	75.3	0.031	118.1	0.033	83.4	0.026	70.1	0.031	86.7
M_6	0.042	70.7	0.052	81.3	0.052	74.3	0.045	67.1	0.048	73.4
M_8	0.013	263.1	0.014	285.2	0.015	308.1	0.008	249.6	0.012	276.5
N_2	0.912	292.1	0.976	296.0	0.941	292.5	0.930	291.9	0.940	293.1
2N	(0.121)	(260.7)	0.156	266.1	(0.125)	(261.1)	(0.124)	(261.4)	(0.132)	(262.3)
O_1	0.344	110.7	0.362	114.5	0.360	113.1	0.359	112.6	0.356	112.7
OO	(0.015)	(152.3)	(0.016)	(149.5)	(0.014)	(152.2)	(0.015)	(150.0)	(0.015)	(151.0)
P_1	0.138	131.3	0.142	123.5	0.137	127.7	0.152	134.9	0.142	119.4
Q_1	0.065	83.2	0.067	104.8	0.058	75.2	0.064	96.2	0.064	89.8
2Q	(0.009)	(89.9)	(0.009)	(97.0)	(0.009)	(93.7)	(0.009)	(93.9)	(0.009)	(93.6)
R_2	(0.005)	(0.0)	(0.006)	(0.8)	(0.006)	(359.8)	(0.006)	(355.1)	(0.006)	(358.9)
S_1	0.035	111.2	0.027	102.7	0.024	88.9	0.020	102.1	0.026	101.2
S_2	0.685	0.0	0.705	0.8	0.714	359.8	0.717	355.1	0.705	358.9
S_4	0.004	240.4	0.007	179.9	0.003	184.6	0.002	119.9	0.004	181.2
S_6	0.006	123.7	0.006	163.5	0.005	109.0	0.006	95.3	0.006	122.9
T_2	(0.040)	(0.0)	0.192	293.1	0.042	0.0	0.163	50.5	(0.109)	(355.9)
λ_2	(0.030)	(340.4)	0.069	354.2	0.077	347.0	0.087	344.3	0.066	346.5
μ_2	0.003	231.6	0.005	98.5	0.018	193.5	0.053	204.0	0.020	181.9
ν_2	0.217	301.6	0.205	307.1	0.225	298.4	0.209	302.5	0.214	302.4
ρ_1	(0.013)	(101.8)	(0.014)	(107.0)	(0.014)	(104.7)	(0.014)	(104.6)	(0.014)	(104.8)
Sa	0.203	177.6	0.093	153.8	0.132	137.0	0.111	128.5	0.135	149.2
Ssa	0.013	181.7	0.048	141.8	0.068	121.6	0.050	119.7	0.045	141.2
MS	--------	--------	--------	--------	--------	--------	0.008	116.4	0.008	116.4

TABLE 16.—*Extreme tides on tide staff, Portland, Me., 1912 to 1925*

Year	Storm high water	Storm low water	Highest high water		Lowest low water	
	Feet	*Feet*	*Feet*	*Date*	*Feet*	*Date*
1912	19.67	6.73	20.6	Jan. 5	6.0	Mar. 2
1913	19.52	6.70	20.7	Oct. 2	5.9	Mar. 23
1914	19.73	6.59	20.6	Dec. 14	5.6	Apr. 13
1915	19.68	6.74	20.6	Dec. 7	5.4	Oct. 8
1916	19.63	6.69	20.2	Jan. 5	6.1	Feb. 4
1917	19.52	6.78	20.3	Dec. 14	6.2	Jan. 24
1918	19.92	6.82	21.1	Nov. 19	6.4	Sept. 22
1919	20.08	7.05	21.1	Dec. 7	6.4	Dec. 11
1920	19.86	6.76	20.3	June 16	5.9	Dec. 25
1921	19.70	6.78	20.3	Nov. 29	6.4	Aug. 5
1922	19.56	6.46	20.7	Apr. 11	5.8	Feb. 14
1923	19.67	6.51	20.1	Apr. 30	5.4	Apr. 3
1924	19.68	6.47	20.1	July 17	5.5	Dec. 27
1925	19.38	6.42	19.9	June 9	6.0	Aug. 5
Mean	19.69	6.68	20.47		5.93	

	Feet
Storm range	13.01
Extreme range	14.54
Greatest range	15.7

TABLE 17.—*Relation between meteorological changes and extreme tides, Portland, Me., 1926*

Date	Height of high water			Barometric pressure			Wind	
	Observed	Astronomical	Difference	Average daily value	Annual mean	Difference	Prevailing direction	Average velocity per hour
	Feet	*Feet*	*Feet*	*Inches*	*Inches*	*Inches*	*True*	*Miles*
Jan. 15	20.1	19.6	0.5	29.57	29.92	−0.35	SW	7
Feb. 15	20.0	19.2	0.8	29.53	29.92	−0.39	NE	12
Mar. 13	19.4	19.1	0.3	29.82	29.92	−0.10	N	9
Apr. 1	18.9	17.8	1.1	29.26	29.92	−0.66	NE	13
May 10	19.1	19.0	0.1	29.56	29.92	−0.36	E	4
June 26	19.2	19.2	0.0	29.82	29.92	−0.10	SW	9
July 25	19.2	19.5	−0.3	29.96	29.92	0.04	N	7
Aug. 24	19.9	19.7	0.2	29.81	29.92	−0.11	S	8
Sept. 22	19.6	19.5	0.1	30.00	29.92	0.08	S	7
	Height of low water							
Jan. 16	5.9	6.5	−0.6	30.11	29.92	0.19	SW	8
Feb. 13	6.2	6.4	−0.2	29.84	29.92	−0.08	S	6
Mar. 14	6.2	6.6	−0.4	29.93	29.92	0.01	N	8
Apr. 13	6.1	6.9	−0.8	30.14	29.92	0.22	S	14
May 29	6.8	7.5	−0.7	30.22	29.92	0.30	SE	8
June 28	6.7	7.1	−0.4	29.86	29.92	−0.06	NW	10
July 27	6.4	6.8	−0.4	30.10	29.92	0.18	S	6
Aug. 23	6.4	7.0	−0.6	30.11	29.92	0.19	S	10
Sept. 23	6.4	6.8	−0.4	30.13	29.92	0.21	NE	7

TABLE 18.—*Tidal characteristics, station A, Jaffrey Point, N. H.*

Year	Length of series	Range	Lunitidal intervals		Duration of—	
			High water	Low water	Rise	Fall
		Feet	*Hours*	*Hours*	*Hours*	*Hours*
1903	10 days	9.13	11.17	4.81	6.36	6.06
1919	2 days	8.68	11.26	5.05	6.21	6.21
1926	6 days	8.63	11.23	4.95	6.28	6.14
Weighted means		8.91	11.20	4.88	6.32	6.10

TABLE 19.—*Tidal characteristics, station B, Gerrish Island Wharf, Me.*

Year	Length of series	Range	Lunitidal intervals		Duration of—	
			High water	Low water	Rise	Fall
		Feet	*Hours*	*Hours*	*Hours*	*Hours*
1926	7 days	8.66	11.22	5.01	6.21	6.21

TABLE 20.—*Tidal characteristics, station C, Fort Constitution, N. H.*

Year	Length of series	Range	Lunitidal intervals		Duration of—	
			High water	Low water	Rise	Fall
		Feet	*Hours*	*Hours*	*Hours*	*Hours*
1851	86 days	8.79	11.36	5.08	6.28	6.14
1852	48 days	8.21	11.38	5.06	6.32	6.10
1853	166 days	8.70	11.38	5.05	6.33	6.09
1898	74 days	8.72	11.23	4.91	6.32	6.10
1903	2 days	8.82	11.37	4.97	6.40	6.02
1909	5 days	8.75	11.06	4.69	6.37	6.05
1919	3 days	8.46	11.31	5.13	6.18	6.24
1926	13 days	8.56	11.31	5.13	6.18	6.24
Weighted means		8.69	11.24	4.94	6.30	6.12

TABLE 21.—*Tidal characteristics, station D, Kittery Point, Me.*

Year	Length of series	Range	Lunitidal intervals		Duration of—	
			High water	Low water	Rise	Fall
		Feet	*Hours*	*Hours*	*Hours*	*Hours*
1917	32 days	8.74	11.28	5.17	6.11	6.31
1919	22 days	8.55	11.25	4.94	6.31	6.11
Weighted means		8.66	11.27	5.08	6.19	6.23

TABLE 22.—*Tidal characteristics, station E, Portsmouth Navy Yard, Seavy Island, Me.*

Year	Length of series	Range	Lunitidal intervals		Duration of—	
			High water	Low water	Rise	Fall
		Feet	*Hours*	*Hours*	*Hours*	*Hours*
1902–1904	700 days	8.01				
1919	4 days	7.91	11.41	5.06	6.35	6.07
1926	120 days	7.95	11.34	5.23	6.11	6.31
Weighted means		8.00	11.34	5.22	6.12	6.30

TABLE 23.—*Tidal characteristics, station F, Commercial Wharf, Portsmouth, N. H.*

Year	Length of series	Range	Lunitidal intervals		Duration of—	
			High water	Low water	Rise	Fall
		Feet	*Hours*	*Hours*	*Hours*	*Hours*
1903	32 days	7.80	11.50	5.17	6.33	6.09

TABLE 24.—*Tidal characteristics, station G, Atlantic Corporation Shipyard, Portsmouth, N. H.*

Year	Length of series	Range	Lunitidal intervals		Duration of—	
			High water	Low water	Rise	Fall
		Feet	*Hours*	*Hours*	*Hours*	*Hours*
1919	10 days	7.12	11.69	5.38	6.31	6.11
1926	5 days	7.12	11.93	5.54	6.39	6.03
Weighted means		7.12	11.77	5.43	6.34	6.08

TABLE 25.—*Tidal characteristics, station H, Dover Point, N. H.*

Year	Length of series	Range	Lunitidal intervals		Duration of—	
			High water	Low water	Rise	Fall
		Feet	*Hours*	*Hours*	*Hours*	*Hours*
1913	48 days	6.34	12.59	6.34	6.25	6.17
1926	6 days	6.39	12.88	6.75	6.13	6.29
Weighted means		6.35	12.62	6.39	6.23	6.19

TABLE 26.—*Tidal characteristics, station I, Salmon Falls River Highway Bridge*

Year	Length of series	Range	Lunitidal intervals		Duration of—	
			High water	Low water	Rise	Fall
		Feet	*Hours*	*Hours*	*Hours*	*Hours*
1926	6 days	6.56	12.90	6.88	6.02	6.40

TABLE 27.—*Tidal characteristics, station J, Exeter River Railroad Bridge, N. H.*

Year	Length of series	Range	Lunitidal intervals		Duration of—	
			High water	Low water	Rise	Fall
		Feet	*Hours*	*Hours*	*Hours*	*Hours*
1926	5 days	6.90	13.69	7.64	6.05	6.37

TABLE 28.—*Tidal characteristics for stations in Portsmouth Harbor and tributaries*

Station	Location	Latitude	Longitude	Mean range	Lunitidal intervals		Duration of—	
					High water	Low water	Rise	Fall
		North ° ′	*West* ° ′	*Feet*	*Hours*	*Hours*	*Hours*	*Hours*
A	Jaffrey Point (Fort Stark), N. H	43 03.3	70 42.9	8.91	11.20	4.88	6.32	6.10
B	Gerrish Island Wharf, Me	43 04.0	70 41.8	8.66	11.22	5.01	6.21	6.21
C	Fort Constitution, N. H	43 04.3	70 42.7	8.69	11.24	4.94	6.30	6.12
D	Kittery Point, Me	43 05.0	70 42.0	8.66	11.27	5.08	6.19	6.23
E	Portsmouth Navy Yard, Me	43 04.8	70 44.5	8.00	11.34	5.22	6.12	6.30
F	Commercial Wharf, Portsmouth, N. H	43 04.7	70 45.1	7.80	11.50	5.17	6.33	6.09
G	Atlantic Corporation Shipyard, Portsmouth, N. H.	43 05.4	70 46.0	7.12	11.77	5.43	6.34	6.08
H	Dover Point, N. H	43 07.3	70 49.5	6.35	12.62	6.39	6.23	6.19
I	Salmon Falls River highway bridge	43 11.4	70 49.5	6.56	12.90	6.88	6.02	6.40
J	Exeter River entrance, N. H	43 03.2	70 54.7	6.90	13.69	7.64	6.05	6.37
	Standard tide station, Portland, Me	43 39.2	70 15.1	8.90	11.16	4.94	6.21	6.21

TABLE 29.—*Tidal and nontidal current in the approaches to Portsmouth Harbor, party of J. W. Hawley*

[Referred to time of predicted slack before flood at Portsmouth Harbor entrance]

Station No.	Date of observations	Observations with—	Depth	Tidal current, strength of flood			Nontidal current		Length of observations
				Time	Velocity	Direction (true)	Velocity	Direction (true)	
	1919		*Feet*	*Hours*	*Knots*	*Degrees*	*Knots*	*Degrees*	*Days*
1	June 2-4	Pole	7	+4.8	0.2	225	0.16	175	2
2	May 29-31	do	7	+4.0	0.4	325	0.31	170	2

TABLE 30.—*Current data, Portsmouth Harbor entrance, from results of observations near the surface*

[Referred to times of predicted slack water at Portsmouth Harbor entrance]

Station No.	Location	Party of—	Date	Slack before flood	Flood strength			Flood duration	Slack before ebb	Ebb strength			Ebb duration	Length of observations
					Time	Direction (true)	Velocity			Time	Direction (true)	Velocity		
				Hours	*Hours*	*Degrees*	*Knots*	*Hours*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Days*
1	South of Kitts Rocks	C. H. Woodhull	October, 1852	−2.6	1.8	305	0.7	9.1	+0.6	2.5	155	0.9	3.3	1
2	Off Odiornes Point	R. W. Woodworth	August, 1926	+0.9	3.4	350	0.5	4.7	−0.2	3.6	170	0.8	7.7	1
3	Mid-channel, off Kitts Rocks	do	do	+0.5	2.6	325	0.8	5.6	+0.2	2.6	175	1.6	6.8	1
4	Southwest of Whaleback Reef	do	do	−4.0	1.2	300	1.0	10.1	+0.2	1.6	150	1.0	2.3	1
5	Northeast of Whaleback Reef	do	do	+0.3	1.8	295	0.3	3.6	−2.0	0.8	120	0.5	8.8	1
6	Off Jaffrey Point	do	do	+1.3	3.5	345	0.6	4.8	+0.2	5.4	195	1.0	7.6	1
7	Entrance to Little Harbor	do	do	−1.8	1.9	310	0.7	6.8	−0.8	1.8	130	1.1	5.6	1
8	Off Whaleback Reef	P. A. Welker	October, 1898	+0.3	2.7	350	0.8	5.8	+0.7	2.2	175	1.3	6.6	½
9	Mid-channel, off Whaleback Reef	J. H. Hawley	May, 1919	+0.5	2.7	350	0.6	5.5	0.0	2.8	185	1.7	6.9	2
10	Off Newcastle Island	R. W. Woodworth	August, 1926	−0.1	1.9	20	1.1	6.2	+0.2	2.4	190	1.2	6.2	2
11	Off Wood Island	do	do	+0.1	1.9	355	1.1	5.8	0.0	2.7	190	1.8	6.6	5¼
12	Off Stielman Rocks	P. A. Welker	October, 1898	+0.8	3.4	5	1.2	5.5	−0.1	2.6	175	1.4	6.9	½
13	Off Fort Point	R. W. Woodworth	September, 1926	−0.1	3.1	5	1.8	6.2	+0.1	4.4	145	2.0	6.2	1
14	Mid-channel, off Fort Point	P. A. Welker	October, 1898	+0.2	1.9	335	1.7							¼
15	do	R. W. Woodworth	September, 1926	−0.2	1.9	355	1.3	6.0	−0.1	3.4	185	1.9	6.4	1
16	do	J. H. Hawley	May, 1919	+0.4	3.0	330	1.5	5.1	−0.4	2.6	120	2.0	7.3	2
17	Northwest of Fishing Islands	R. W. Woodworth	August, 1926	+0.5	3.4	275	0.6	6.0	+0.6	5.8	80	0.7	6.4	1
18	Off Cod Rock	C. H. Woodhull	October, 1852	+0.4	3.7	305	1.8	5.9	+0.4	4.9	70	1.3	6.5	1
19	do	P. A. Welker	September, 1898	+0.5	2.8	300	1.4	4.8	−0.6	2.6	115	2.2	7.6	1

TABLE 31.—*Results from current observations at various depths, Portsmouth Harbor entrance, party of R. W. Woodworth*

[Referred to times of predicted slack water at Portsmouth Harbor entrance]

Station No.	Location	Date	Observations with—	Depth	Slack before flood	Flood strength			Flood duration	Slack before ebb	Ebb strength			Ebb duration	Length of observations
						Time	Direction (true)	Velocity			Time	Direction (true)	Velocity		
		1926		*Feet*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Days*
2	Off Odiornes Point	Aug. 11–12	Pole	7	+0.92	3.42	348	0.54	4.75	−0.25	3.55	168	0.84	7.67	1
			Meter	5	+0.97	3.17	--------	0.49	4.55	−0.40	4.35	--------	0.84	7.87	1
			do	14	+1.02	3.27	--------	0.48	4.60	−0.30	4.65	--------	0.73	7.82	1
			do	22	+0.97	3.22	--------	0.53	4.60	−0.35	4.85	--------	0.63	7.82	1
3	Mid-channel, off Kitts Rocks	do	Pole	7	+0.52	2.62	324	0.82	5.65	+0.25	2.62	177	1.57	6.77	1
			Meter	8	+0.62	2.87	320	0.82	5.65	+0.35	2.38	169	1.54	6.77	1
			do	21	+0.67	3.22	319	0.76	5.35	+0.10	2.85	167	1.23	7.07	1
			do	34	+0.72	2.92	336	0.64	5.55	+0.35	3.12	169	0.94	6.87	1
4	Southwest of Whaleback Reef	do	Pole	7	−3.98	1.22	302	0.96	10.10	+0.20	1.55	152	1.01	2.32	1
			Meter	7	−4.02	1.27	312	0.85	10.24	+0.30	1.60	134	1.05	2.18	1
			do	17	−3.95	1.72	314	0.75	10.12	+0.25	1.70	148	0.95	2.30	1
			do	28	−3.78	1.82	306	0.64	9.35	−0.35	1.45	135	0.84	3.07	1
5	Northeast of Whaleback Reef	Aug. 30–31	Pole	7	+0.32	1.77	294	0.27	3.60	−2.00	0.80	118	0.52	8.82	1
			Meter	3	+0.42	1.42	276	0.37	3.65	−1.85	1.65	136	0.57	8.77	1
			do	7	+0.37	1.87	279	0.32	3.70	−1.85	0.85	82	0.57	8.72	1
			do	11	+0.57	2.12	280	0.27	3.55	−1.80	0.80	104	0.42	8.87	1
6	Off Jaffrey Point	Aug. 12–13	Pole	7	+1.32	3.52	346	0.63	4.85	+0.25	5.35	196	1.03	7.57	1
			Meter	7	+1.37	3.52	345	0.63	4.91	+0.35	4.55	196	0.98	7.51	1
			do	19	+1.37	3.67	6	0.57	4.86	+0.30	4.50	188	0.82	7.56	1
			do	32	+1.37	3.67	28	0.51	4.81	+0.25	5.00	192	0.63	7.61	1
7	Entrance to Little Harbor	do	Pole	7	−1.78	1.92	309	0.74	6.85	−0.85	1.75	130	1.14	5.57	1
			Meter	3	−1.48	2.12	302	0.75	6.65	−0.75	1.70	128	1.25	5.77	1
			do	7	−1.53	2.17	311	0.74	6.55	−0.90	1.75	131	1.09	5.87	1
			do	11	−1.43	2.22	314	0.68	6.55	−0.80	1.55	120	0.98	5.87	1
10	Off Newcastle Island	Aug. 30–Sept. 1	Pole	7	−0.08	1.87	18	1.10	6.15	+0.15	2.45	188	1.18	6.27	2
			Meter	8	+0.02	1.73	357	1.17	5.97	+0.07	2.32	194	1.26	6.45	2
			do	19	−0.28	1.70	359	1.24	6.27	+0.07	2.42	202	1.19	6.15	2
			do	30	−0.38	1.77	4	1.21	6.43	+0.13	2.42	198	1.12	5.99	2
11	Off Wood Island	Aug. 11–13; Aug. 30–Sept. 2.	Pole	7	+0.08	1.93	355	1.11	5.61	−0.03	2.67	191	1.77	6.61	5¼
			Meter	9	−0.02	2.08	357	1.04	5.76	−0.18	2.63	202	1.69	6.66	5¼
			do	22	−0.40	1.70	358	1.08	6.15	−0.17	2.63	204	1.55	6.27	5¼
			do	35	−0.63	2.02	357	0.95	6.47	−0.08	2.68	198	1.32	5.95	5¼
13	Off Fort Point	Sept. 1–2	Pole	7	−0.13	3.12	6	1.76	6.17	+0.12	4.45	143	1.96	6.25	1
			Meter	6	−0.18	2.92	353	1.71	6.10	0.00	4.45	149	2.03	6.32	1
			do	15	−0.18	2.87	355	1.81	6.05	−0.05	4.25	148	1.96	6.37	1
			do	24	−0.18	2.77	0	1.69	6.00	−0.10	4.05	144	1.84	6.42	1

TABLE 31.—*Results from current observations at various depths, Portsmouth Harbor entrance, party of R. W. Woodworth*—Continued

Station No.	Location	Date	Observations with—	Depth	Slack before flood	Flood strength			Flood duration	Slack before ebb	Ebb strength			Ebb duration	Length of observations
						Time	Direction (true)	Velocity			Time	Direction (true)	Velocity		
		1926		*Feet*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Days*
15	Mid-channel, off Fort Point	Sept. 1-2	Pole	7	−0.18	1.92	355	1.27	6.00	−0.10	3.45	136	1.92	6.42	1
			Meter	8	−0.33	1.77	343	1.32	5.95	−0.30	3.65	130	1.92	6.47	1
			do	21	−0.38	2.02	350	1.32	5.85	−0.45	2.95	147	1.82	6.57	1
			do	34	−0.38	2.02	357	1.15	5.85	−0.45	3.45	216	1.80	6.57	1
17	Northwest of Fishing Islands	Aug. 31-Sept. 1	Pole	7	+0.52	3.42	275	0.58	5.95	+0.55	5.85	80	0.73	6.47	1
			Meter	10	+0.62	3.67	275	0.68	5.95	+0.65	5.95	80	0.53	6.47	1
			do	25	+0.62	2.87	300	0.63	5.85	+0.55	5.95	80	0.73	6.57	1
			do	40	+0.12	2.82	320	0.73	6.35	+0.55	5.95	75	0.63	6.07	1

TABLE 32.—*Results from current observations near the surface, Portsmouth Harbor, vicinity of Newcastle, N. H.*

[Referred to times of predicted slack water at Portsmouth Harbor entrance]

Station No.	Location	Party of—	Date	Slack before flood	Flood strength			Flood duration	Slack before ebb	Ebb strength			Ebb duration	Length of observations
					Time	Direction (true)	Velocity			Time	Direction (true)	Velocity		
				Hours	*Hours*	*Degrees*	*Knots*	*Hours*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Days*
1	Off Salamander Point	R. W. Woodworth	August, 1926	+0.4	1.3	260	0.8	1.8	−3.7	3.0	105	2.4	10.6	1
2	Mid-channel, off Salamander Point	do	do	+0.2	2.4	260	1.3	6.0	+0.3	2.5	85	1.2	6.4	11
3	South of Kittery Point	do	do	−0.7	3.0	260	1.6	7.1	+0.6	1.6	65	0.5	5.3	1
4	do	P. A. Welker	September, 1898	0.0	3.0	262	1.9	6.5	+0.6	4.1	60	1.4	5.9	1
5	Northeast of Clarks Island	R. W. Woodworth	August, 1926	−0.7	1.6	335	0.9	6.2	−0.4	1.8	195	0.8	6.2	2
6	Southwest of Kittery Point Bridge	do	do	−1.8	1.6	20	0.8	6.2	−1.5	1.6	200	1.1	6.2	1
7	South of Clarks Island	do	do	+0.1	2.7	260	2.1	6.1	+0.3	3.0	80	3.1	6.3	1
8	do	P. A. Welker	October, 1898	+0.6	2.4	260	1.3	6.0	+0.6	3.0	90	2.7	6.4	½
9	Northeast of Jamaica Island	R. W. Woodworth	August, 1926	−0.4	1.9	315	1.0	6.3	0.0	2.1	135	1.0	6.1	1
10	West of Clarks Island	do	do	−4.7	3.3	200	1.8	11.0	+0.4	1.0	10	0.2	1.4	1

TABLE 33.—*Results from current observations at various depths, Portsmouth Harbor, vicinity of Newcastle, N. H., party of R. W. Woodworth*

[Referred to times of predicted slack water at Portsmouth Harbor entrance]

Station No.	Location	Date	Observations with—	Depth	Slack before flood	Flood strength			Flood duration	Slack before ebb	Ebb strength			Ebb duration	Length of observations
						Time	Direction (true)	Velocity			Time	Direction (true)	Velocity		
		1926		*Feet*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Days*
1	Off Salamander Point	Aug. 20–21	Pole	7	0.42	1.27	260	0.82	1.82	−3.68	3.05	104	2.42	10.60	1
			Meter	10	0.52	1.27	256	1.01	1.82	−3.58	3.15	--------	2.41	10.60	1
			do	25	0.42	1.52	248	0.96	2.12	−3.38	3.10	--------	2.36	10.30	1
			do	40	0.42	1.52	255	0.86	2.08	−3.42	3.05	--------	2.46	10.34	1
2	Mid-channel, off Salamander Point	Aug. 16–27	Pole	7	0.22	2.42	262	1.30	6.02	0.32	2.53	83	1.24	6.40	11
			Meter	9	0.18	2.37	273	1.26	6.06	0.32	2.40	97	1.09	6.36	11
			do	24	−0.10	2.65	275	1.34	6.39	0.37	2.08	100	1.09	6.03	11
			do	38	−0.32	2.72	274	1.40	6.62	0.38	1.88	98	1.09	5.80	11
3	South of Kittery Point	Aug. 20–21	Pole	7	−0.68	3.02	260	1.64	7.15	0.55	1.60	66	0.54	5.27	1
			Meter	10	−0.78	3.12	262	1.54	7.15	0.45	1.75	58	0.59	5.27	1
			do	25	−1.73	3.02	270	1.54	8.20	0.55	1.45	58	0.54	4.22	1
			do	40	−1.88	3.12	272	1.54	8.10	0.30	1.55	62	0.69	4.32	1
5	Northeast of Clarks Island	Aug. 23–25	Pole	7	−0.67	1.62	337	0.87	6.22	−0.37	1.77	194	0.77	6.20	2
			Meter	7	−0.73	1.80	312	0.64	6.32	−0.33	1.77	167	0.74	6.10	2
			do	18	−0.70	1.54	334	0.75	5.67	−0.95	1.97	172	0.68	6.75	2
			do	29	−0.48	2.00	328	0.74	5.47	−0.93	2.03	164	0.58	6.95	2
6	Southwest of Kittery Point Bridge	Aug. 26–27	Pole	7	−1.83	1.57	18	0.76	6.25	−1.50	1.60	202	1.06	6.17	1
			Meter	5	−1.68	1.52	28	0.68	5.95	−1.65	1.70	191	1.03	6.47	1
			do	13	−1.73	1.57	31	0.76	6.00	−1.65	1.70	199	0.96	6.42	1
			do	21	−1.78	1.52	35	0.70	6.10	−1.60	1.80	204	0.90	6.32	1
7	South of Clarks Island	Aug. 16–17	Pole	7	0.07	2.67	262	2.07	6.15	0.30	3.05	82	3.12	6.27	1
			Meter	12	0.17	2.67	249	1.93	6.15	0.40	2.50	--------	2.83	6.27	1
			do	29	−0.03	2.62	260	2.03	6.30	0.35	2.95	--------	2.78	6.12	1
			do	48	−0.33	2.17	272	1.91	6.70	0.45	2.70	--------	2.61	5.72	1
9	Northeast of Jamaica Island	Aug. 25–26	Pole	7	−0.38	1.87	314	1.04	6.35	0.05	2.10	136	1.04	6.07	1
			Meter	5	−0.38	2.07	302	0.99	6.30	0.00	2.55	136	0.84	6.12	1
			do	13	−0.38	2.02	311	1.07	6.30	0.00	2.35	134	0.87	6.12	1
			do	21	−0.43	2.67	318	1.04	6.35	0.00	2.00	140	0.79	6.07	1
10	West of Clarks Island	Aug. 23–24	Pole	7	−4.68	3.32	198	1.83	11.00	0.40	1.05	9	0.18	1.42	1
			Meter	4	−4.73	3.32	193	1.82	11.20	0.55	1.25	356	0.22	1.22	1
			do	10	−4.53	3.42	193	1.74	10.80	0.35	1.20	359	0.24	1.62	1
			do	16	−4.63	3.32	203	1.65	10.90	0.35	1.15	356	0.25	1.52	1

TABLE 34.—*Results from current observations near the surface, Portsmouth Harbor, vicinity of Portsmouth, N. H.*

[Referred to times of predicted slack water at Portsmouth Harbor entrance]

Station No.	Location	Party of—	Date	Slack before flood	Flood strength			Flood duration	Slack before ebb	Ebb strength			Ebb duration	Length of observations
					Time	Direction (true)	Velocity			Time	Direction (true)	Velocity		
				Hours	*Hours*	*Degrees*	*Knots*	*Hours*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Days*
1	Off Sullivan Point	J. H. Hawley	June, 1919	+0.3	2.7	265	2.6	5.8	+0.2	2.8	80	3.1	6.6	2¼
2	do	W. E. Parker	September, 1903	+0.2	3.0	280	2.8	6.4	+0.7	3.7	100	4.0	6.0	⅓
3	South of Seavy Island	R. W. Woodworth	August, 1926	−0.1	2.5	260	3.0	6.6	+0.6	2.8	90	3.8	5.8	2
4	do	P. A. Welker	October, 1898	−0.2	2.3	265	2.8							¼
5	Between Goat and Marvin Islands	R. W. Woodworth	August, 1926	−1.4	2.1	155	1.2	5.8	−1.4	1.8	340	0.8	6.6	1
6	Off Henderson Point	W. E. Parker	September, 1903	−0.2	2.2	310	3.4	6.0	−0.1	3.6	110	3.1	6.4	⅓
7	Northeast of Pierces Island	R. W. Woodworth	August, 1926	+0.2	3.3	340	2.6	6.5	+0.8	3.4	170	2.3	5.9	1
8	do	P. A. Welker	October, 1898	+0.5	2.4	310	3.2	6.1	+0.7	3.8	140	2.8	6.3	½
9	North of Pierces Island	R. W. Woodworth	August, 1926	+0.3	2.6	280	2.1	6.1	+0.5	3.6	110	3.0	6.3	2
10	Channel north of Seavy Island	do	do	+0.1	2.6	260	1.5	6.1	+0.3	3.7	80	1.9	6.3	2
11	Off Portsmouth water front	do	do	+1.2	3.6	(1)	1.2	(2)	+0.6	(2)	(3)	0.2	(2)	1
12	Southeast of Badgers Island	do	do	−0.2	2.9	240	1.1	6.4	+0.3	3.4	50	0.4	6.0	1
13	West of Portsmouth-Kittery Bridge	W. E. Parker	September, 1903	0.0	3.0	290	1.3	6.4	+0.5	3.6	110	3.3	6.0	⅓
14	Southwest of Badgers Island	R. W. Woodworth	August, 1926	+0.1	2.9	330	3.3	6.2	+0.4	3.2	125	3.7	6.2	2

[1] Northerly.

[2] See explanation on p. 43.

[3] Southerly.

TABLE 35.—*Results from current observations at various depths, Portsmouth Harbor, vicinity of Portsmouth, N. H., party of R. W. Woodworth*

[Referred to times of predicted slack water at Portsmouth Harbor entrance]

Station No.	Location	Date	Observations with—	Depth	Slack before flood	Flood strength			Flood duration	Slack before ebb	Ebb strength			Ebb duration	Length of observations
						Time	Direction (true)	Velocity			Time	Direction (true)	Velocity		
		1926		*Feet*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Days*
3	South of Seavy Island	Aug. 16–18	Pole	7	−0.08	2.54	260	2.97	6.60	+0.60	2.85	88	3.85	5.82	2
			Meter	12	−0.08	2.77	--------	2.91	6.67	+0.67	2.90	--------	3.48	5.75	2
			do	30	−0.08	2.60	--------	2.93	6.57	+0.57	3.03	--------	3.43	5.85	2
			do	48	−0.06	2.54	--------	2.98	6.58	+0.60	3.13	--------	3.43	5.84	2
5	Between Goat and Marvin Islands	Aug. 24–25	Pole	7	−1.38	2.07	154	1.22	5.85	−1.45	1.85	341	0.77	6.57	1
			Meter	5	−1.53	2.12	162	1.27	6.00	−1.45	1.75	337	0.67	6.42	1
			do	12	−1.58	2.02	169	1.23	6.00	−1.50	1.95	337	0.68	6.42	1
			do	20	−1.43	2.17	177	1.11	5.90	−1.45	2.05	344	0.66	6.52	1
7	Northeast of Pierces Island	Aug. 17–28	Pole	7	+0.22	3.32	341	2.65	6.45	+0.75	3.45	170	2.30	5.97	1
			Meter	10	+0.12	3.22	--------	2.61	6.50	+0.70	3.20	--------	2.46	5.92	1
			do	25	−0.05	3.17	--------	2.25	6.67	+0.70	2.90	--------	2.15	5.75	1
			do	40	+0.02	2.72	--------	2.62	6.55	+0.65	3.00	--------	2.02	5.87	1
9	North of Pierces Island	Aug. 18–20	Pole	7	+0.27	2.60	282	2.11	6.12	+0.47	3.55	110	3.01	6.30	2
			Meter	10	+0.30	2.60	--------	2.14	6.22	+0.60	4.03	--------	2.77	6.20	2
			do	25	+0.34	2.67	--------	2.07	6.21	+0.63	4.03	--------	2.72	6.21	2
			do	40	+0.34	2.67	--------	1.92	6.21	+0.63	4.10	--------	2.52	6.21	2
10	Channel north of Seavy Island	Aug. 25–27	Pole	7	+0.10	2.64	262	1.47	6.12	+0.30	3.70	81	1.87	6.30	2
			Meter	4	+0.10	2.57	258	1.45	6.05	+0.23	3.67	77	1.78	6.37	2
			do	9	+0.14	2.64	254	1.44	6.05	+0.27	3.77	76	1.74	6.37	2
			do	15	+0.14	2.80	257	1.38	6.08	+0.30	3.80	80	1.68	6.34	2
11	Off Portsmouth water front	Aug. 19–20	Meter	5	+1.22	3.57	(1)	1.21	(2)	+0.65	(2)	(3)	0.24	(2)	1
			do	8	+1.17	3.27	(1)	1.31	(2)	+0.65	(2)	(3)	0.19	(2)	1
12	Southeast of Badgers Island	Aug. 18–19	Pole	7	−0.23	2.87	242	1.09	6.45	+0.30	3.45	50	0.44	5.97	1
			Meter	4	−0.23	2.72	--------	0.94	6.55	+0.40	3.35	--------	0.54	5.87	1
			do	9	−0.28	2.62	--------	0.88	6.65	+0.45	3.25	--------	0.38	5.77	1
			do	14	−0.48	2.77	--------	0.87	6.90	+0.50	2.90	--------	0.32	5.52	1
14	Southwest of Badgers Island	Aug. 18–20	Pole	7	+0.14	2.90	331	3.30	6.21	+0.43	3.25	123	3.67	6.21	2
			Meter	10	+0.10	2.80	--------	2.89	6.32	+0.50	3.02	--------	3.52	6.10	2
			do	25	+0.07	2.54	--------	3.01	6.35	+0.50	2.92	--------	3.36	6.07	2
			do	40	+0.22	2.42	--------	2.98	6.20	+0.50	3.02	--------	3.15	6.22	2

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(1) Northerly.

(2) See explanation on p. 43.

(3) Southerly.

TABLE 36.—*Results from current observations near the surface, Piscataqua River and tributaries*

[Referred to times of predicted slack water at Portsmouth Harbor entrance]

Station No.	Location	Party of—	Date	Slack before flood	Flood strength			Flood duration	Slack before ebb	Ebb strength			Ebb duration	Length of observations
					Time	Direction (true)	Velocity			Time	Direction (true)	Velocity		
				Hours	*Hours*	*Degrees*	*Knots*	*Hours*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Days*
1	Northwest of Nobles Island	R. W. Woodworth	September, 1926	+0.7	3.1	50	1.6	5.5	+0.3	3.2	200	0.9	6.9	1
2	Off Atlantic Corporation Shipyard	Atlantic Corporation Shipyard.	April–June, 1919	[1] +0.5				5.6	[1] +0.2				6.8	[1] 37
3	do	R. W. Woodworth	September, 1926	0.0	3.2	305	3.6	6.1	+0.2	3.1	140	4.4	6.3	2⅛
4	Mid-channel, southeast of Frankfort Island.	do	do	+0.1	3.1	310	2.6	6.2	+0.4	3.2	130	2.9	6.2	2⅛
5	Mid-channel, south of Dover Point	do	do	0.0	3.5	270	3.8	6.3	+0.4	3.7	95	4.2	6.1	2⅛
6	South of Sturgeon Creek entrance	do	do	−0.2	2.3	355	1.5	5.9	−0.2	2.8	175	1.9	6.5	1
7	Mid-channel, off Adams Point, Furber Strait.	do	do	+0.2	3.2	185	2.0	6.2	+0.5	3.9	10	2.1	6.2	1

[1] Slack before flood, 1 observation; slack before ebb, 37 observations.

TABLE 37.—*Results from current observations at various depths, Piscataqua River and tributaries, party of R. W. Woodworth*

[Referred to times of predicted slack water at Portsmouth Harbor entrance]

Station No.	Location	Date	Observations with—	Depth	Slack before flood	Flood strength			Flood duration	Slack before ebb	Ebb strength			Ebb duration	Length of observations
						Time	Direction (true)	Velocity			Time	Direction (true)	Velocity		
		1926		*Feet*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Days*
3	Off Atlantic Corporation Shipyard	Sept. 2-4	Pole	7	+0.04	3.24	306	3.57	6.05	+0.17	3.13	141	4.40	6.37	2⅙
			Meter	12	0.00	3.30		3.53	6.09	+0.17	3.23		4.50	6.33	2⅙
			do	30	+0.04	3.12		3.57	6.08	+0.20	3.13		4.37	6.34	2⅙
			do	48	+0.02	3.37		3.52	6.05	+0.15	3.23		4.36	6.37	2⅙
4	Mid-channel, southeast of Frankfort Island	do	Pole	7	+0.10	3.07	309	2.58	6.25	+0.43	3.23	132	2.90	6.17	2⅙
			Meter	9	+0.02	2.94	317	2.30	6.33	+0.43	3.27	141	2.75	6.09	2⅙
			do	23	+0.02	2.67	319	2.34	6.33	+0.43	3.27	142	2.64	6.09	2⅙
			do	36	−0.10	2.80	314	2.21	6.45	+0.43	3.20	141	2.29	5.97	2⅙
5	Mid-channel, south of Dover Point	do	Pole	7	+0.04	3.47	270	3.83	6.28	+0.40	3.70	97	4.17	6.14	2⅛
			Meter	4	0.00	3.27		3.23	6.27	+0.35			(1)	6.15	2⅛
			do	10	−0.02	3.12		3.37	6.31	+0.37			(1)	6.11	2⅛
			do	16	+0.04	3.07		3.45	6.31	+0.43			(1)	6.11	2⅛
6	South of Sturgeon Creek entrance	Sept. 3-4	Pole	7	−0.18	2.32	354	1.52	5.90	−0.20	2.80	174	1.87	6.52	1
			Meter	5	−0.38	2.42		1.39	6.00	−0.30	2.50		1.54	6.42	1
			do	12	−0.73	2.42		1.38	6.45	−0.20	2.45		1.43	5.97	1
			do	20	−1.08	2.37		1.37	6.90	−0.10	2.20		1.27	5.52	1
7	Mid-channel, off Adams Point, Furber Strait.	Sept. 2-3	Pole	7	+0.17	3.22	186	2.01	6.25	+0.50	3.90	12	2.11	6.17	1
			Meter	9	+0.17	3.42		1.96	6.25	+0.50	3.60		2.06	6.17	1
			do	22	+0.17	3.37		1.95	6.25	+0.50	3.70		2.00	6.17	1
			do	36	+0.17	3.27		1.96	6.30	+0.55	3.65		2.11	6.12	1

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[1] Meter observations not made near time of strength of ebb.

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. 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.

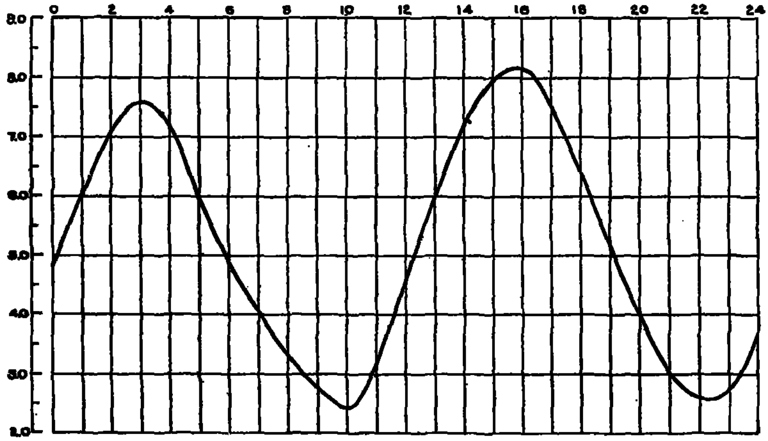

FIG. A.—Tide curve for Fort Hamilton, N. Y., July 4, 1922

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 give 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.

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 the 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 the equatorial tides occurred, these differences pertaining both to the time and the height. Instead of 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 than 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 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 declination 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.

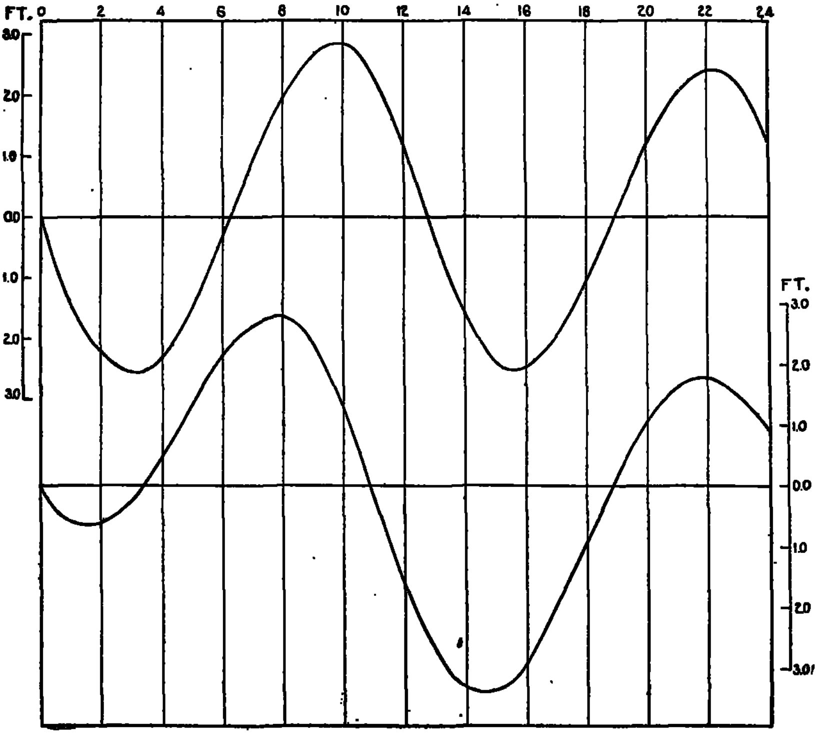

FIG. B.—Tide curves, San Francisco, Calif., October 18 and 24, 1922

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 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 $h=A\cos(at+\alpha)+B\cos(bt+\beta)+\ \ldots$ 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 $\frac{360°}{24\times 13.66}=1°.098$. The mean of the speeds of these two components must be that of the apparent diurnal movement of the moon about the earth, or $\frac{360°}{24.84}=14°.49$. The speeds are therefore derived from the equations $\frac{K_1+O_1}{2}=14°.49$ and $K_1-O_1=1°.098$, from which $K_1=15°.04$ and $O_1=13°.94$.

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 $\frac{M_2°}{28.98}$. The various ages of the tide can likewise be readily determined. Approximately, the ages in hours are: Phase age, $S_2°-M_2°$; parallax age, $2(M_2°-N_2°)$; diurnal age, $K_1°-O_1°$. 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.

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

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

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.

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.

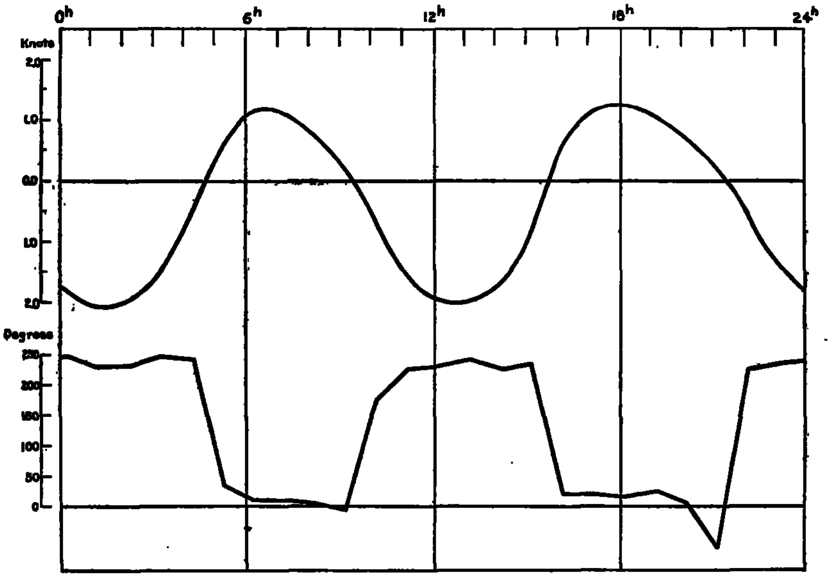

FIG. C.—Velocity and direction curves for the current, Hudson River, July 22, 1922

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 entrances 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.

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.

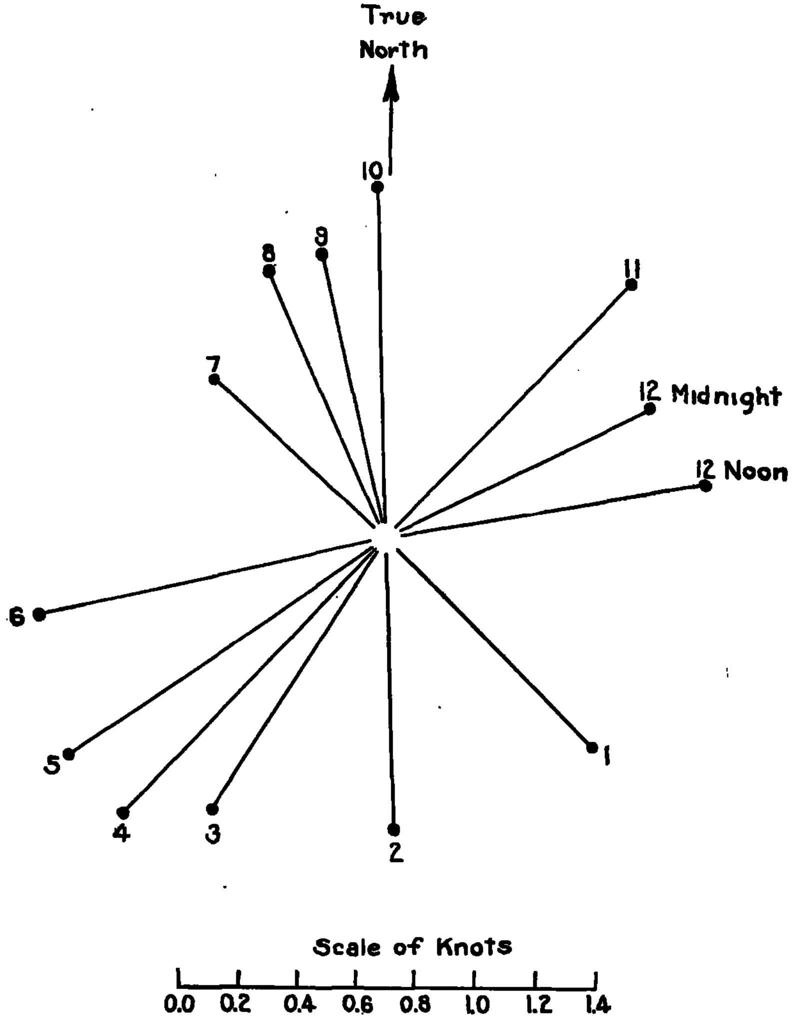

FIG. D.—Rotary current, Nantucket Shoals Light Vessel, afternoon of September 24, 1919

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.

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.

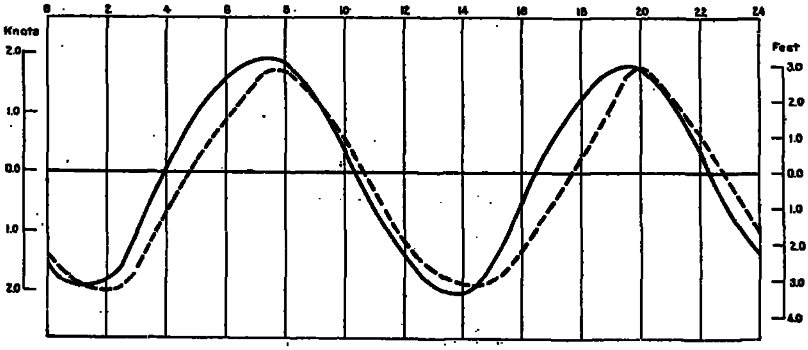

FIG. E.—Tide and current curves, New York Harbor, October 9, 1919

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 the 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 *AB*, flood velocities being plotted above the line and ebb velocities below.

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

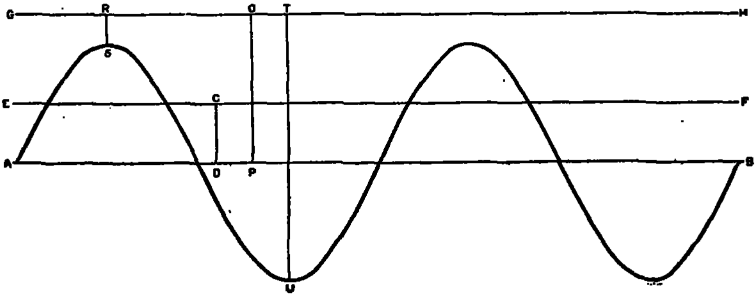

FIG. F.—Effect of nontidal current on tidal current

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 *GH*, parallel with the line *AB* and passing through the point *O*, 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 immediately 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 momentary, 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 analogous 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

$$M'_2 : S'_2 : N'_2 : K'_1 : O'_1 = m_2 M''_2 : s_2 S''_2 : n_2 N''_2 : k_1 K''_1 : o_1 O''_1$$

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 mean range of the tide divided by the range for the period of observations. 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 strength 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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Manual of Tides, by R. A. Harris. This publication was issued in separate parts as appendices to the Annual Reports of the United States Coast and Geodetic Survey for the years 1894, 1897, 1900, 1904, and 1907. These reports are no longer available for distribution but may be consulted in any of the larger libraries.	
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